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Review

# Cloud manufacturing: Strategic vision and state-of-the-art[☆]

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## ABSTRACT

Cloud manufacturing, a service oriented, customer centric, demand driven manufacturing model is explored in both its possible future and current states. A unique strategic vision for the field is documented, and the current state of technology is presented from both industry and academic viewpoints. Key commercial implementations are presented, along with the state of research in fields critical to enablement of cloud manufacturing, including but not limited to automation, industrial control systems, service composition, flexibility, business models, and proposed implementation models and architectures. Comparison of the strategic vision and current state leads to suggestions for future work, including research in the areas of high speed, long distance industrial control systems, flexibility enablement, business models, cloud computing applications in manufacturing, and prominent implementation architectures.

**Contents**

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## 1. Introduction

The force of globalization has served to instantaneously connect peoples from all across the globe, bringing with it game-changing opportunities to share knowledge and expertise to benefit in a collective manner (sometimes called share-to-gain). Friedman [1] explains that the latest globalization phase, which he coins Globalization 3.0, began around the year 2000 and was enabled by the expansion of the internet on a global basis during the dot-com boom. According to Friedman, Globalization 3.0 is defined by individuals and small groups from across the globe collaborating in areas once dominated by less-connected western economies.

Tapscott and Williams [2] explain that the advent of the internet has led to the development of cooperative collaboration networks, resulting in a power-shift from the once mighty hierarchical business model. These traditional business models, according to the authors, can no longer sustain successful innovation: “In an age where mass collaboration can reshape an industry overnight, the old hierarchical ways of organizing work and innovation do not afford the level of agility, creativity, and connectivity that companies require to remain competitive in today’s environment.” Simply put, industry is going to have to rethink the traditional models of business operation, as the amount of internal expertise they hold is dwarfed by that held by the global mass of peoples connected through globalization.

Many engineering paradigms have evolved as result of Globalization 3.0, some of which are mentioned by Tapscott and Williams (mass collaboration and self-organization, for example). Of the many paradigm shifts still in their infancy, cloud manufacturing (CM) will be the focus of this paper [6,8]. CM, as will be defined shortly, benefits from the share-to-gain philosophy as a wide number of manufacturing resources and expertise are shared to provide consumers with enhanced experiences. CM follows naturally from the introduction and success of cloud computing, for which the National Institute of Standards and Technology (NIST) offers the following definition [3]:

> “Cloud computing is 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.”

Building on NIST’s definition of cloud computing, many authors have proposed definitions of CM, including Li et al. [41], Zhang et al. [42], Zhang et al. [5], Xu [6], Wu et al. [7], and Schaefer et al. [8]. The term, cloud manufacturing, was first used by Li et al. [41] in 2010. Xu discerns between two forms of cloud manufacturing: the introduction of cloud-computing technologies into the manufacturing environment and cloud manufacturing. The latter is a replication of the cloud-computing environment using physical manufacturing resources in lieu of computing resources – this idea will be the focus of this paper. Using the work of the NIST [3] and Smith [4] as a foundation, the following definition of CM is offered:

> “Cloud Manufacturing (CM) is a customer-centric manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource loading in response to variable-demand customer generated tasking.” [54]

This paper will focus on developing a strategic vision for the CM environment, documenting the current state of academic research and industry implementation, and then making recommendations for future research.

## 2. Strategic vision

### 2.1. Provider–consumer interaction model

CM will require interaction between three groups: the users (consumers), application providers, and physical resource providers. The needs of users will be matched with the capabilities of resource providers through the application layer. This tri-group model represents the simple supply-demand market that will motivate the existence of CM. The provider–consumer model is shown in Fig. 1.

#### 2.1.1. Users

Users are the consumers in CM; these individuals or groups have the need to manufacture something, but do not possess the capabilities to do so, or they possess the capabilities but stand to gain a competitive advantage by utilizing CM. Users can range anywhere from individuals to large OEMs – any group that can generate engineering requirements to be used in a manufacturing setting can participate in CM partnerships. These engineering requirements, which describe the desired object and its final conditions, are provided to the cloud based application layer for interpretation.

#### 2.1.2. Application providers

The cloud based application layer is responsible for managing all aspects of the CM environment and interprets user requirements into data required for production of the desired objects. For example, a user desired product may require the development of a CNC tool path program and process planning to achieve a final desired plating condition – these would be created by the cloud based applications. Furthermore, production planning and sequencing can be carried out through automated applications that determine the numerous production paths that could lead to the desired object. Finally, the application layer is responsible for locating the required resources, pending them to the engineering job, and managing resources in the event of a service interruption. The application layer will be managed and controlled by application providers, who offer their services as an intermediary

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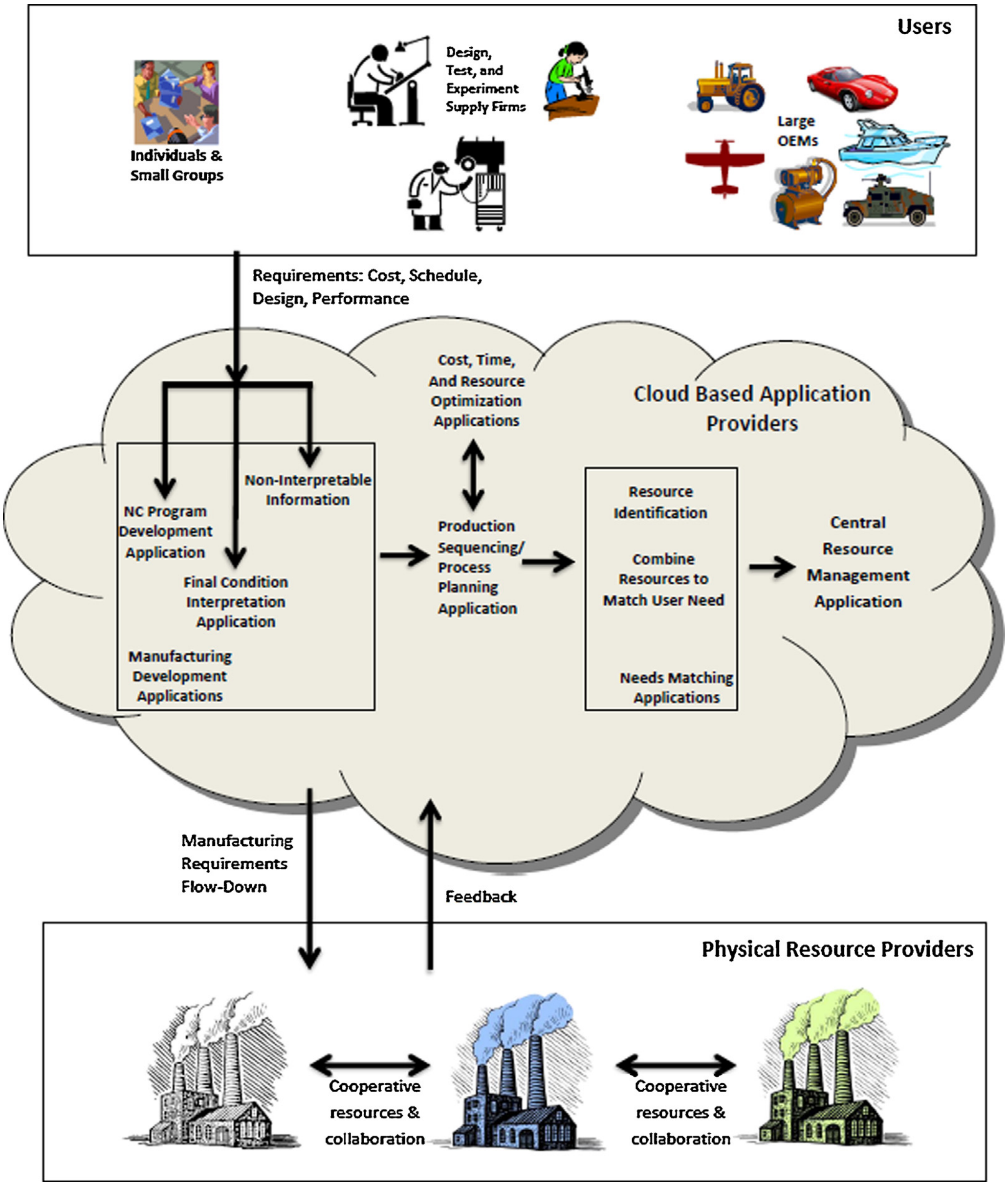

**Fig. 1.** Strategic vision for CM.

between users and resource providers for a portion of the product profit.

### 2.1.3. Physical resource providers (PRPs)

Physical resource providers (PRPs) own and operate manufacturing equipment, including but not limited to machining technologies, finishing technologies, inspection technologies, packaging technologies, and testing resources. In addition to owning physical resources, PRPs have the know-how and experience to utilize these machines effectively and efficiently. These PRPs are not limited by geographic location; rather, PRPs join the CM network based upon their expertise alone. Ideally as a whole, the PRP network would represent every type of manufacturing capability available in the marketplace, offering users instantaneous access to manufacturing capabilities provided through the cloud as a service. The input to the PRP group is the manufacturing data created by the cloud based applications, and the output is a finalized product in conformance with user requirements.

## 2.2. Key characteristics

### 2.2.1. Customer centricity

21st century industry is dominated by hierarchical supply chains in which requirement originating parties flow down product level requirements to suppliers, who can then engage sub-tier suppliers to assist with the product development process. A classic example of this relationship is that of an original equipment manufacturer (OEM) who develops product level requirements from the perspective of technology function and integration (specifications and drawings, for example). These requirements are then contractually enforced with a first-tier supplier, who can then contract out sections of the work to sub-tier suppliers based upon the nature of the work and core competencies. While often these relationships can be fruitful for all parties involved, the opportunity to enhance the consumer experience (reduce costs, improve quality, etc.) are severely limited by their rigid nature. Furthermore, when traditional supplier relationships prove to be undesirable, they can often prove to be difficult and costly to dissolve.

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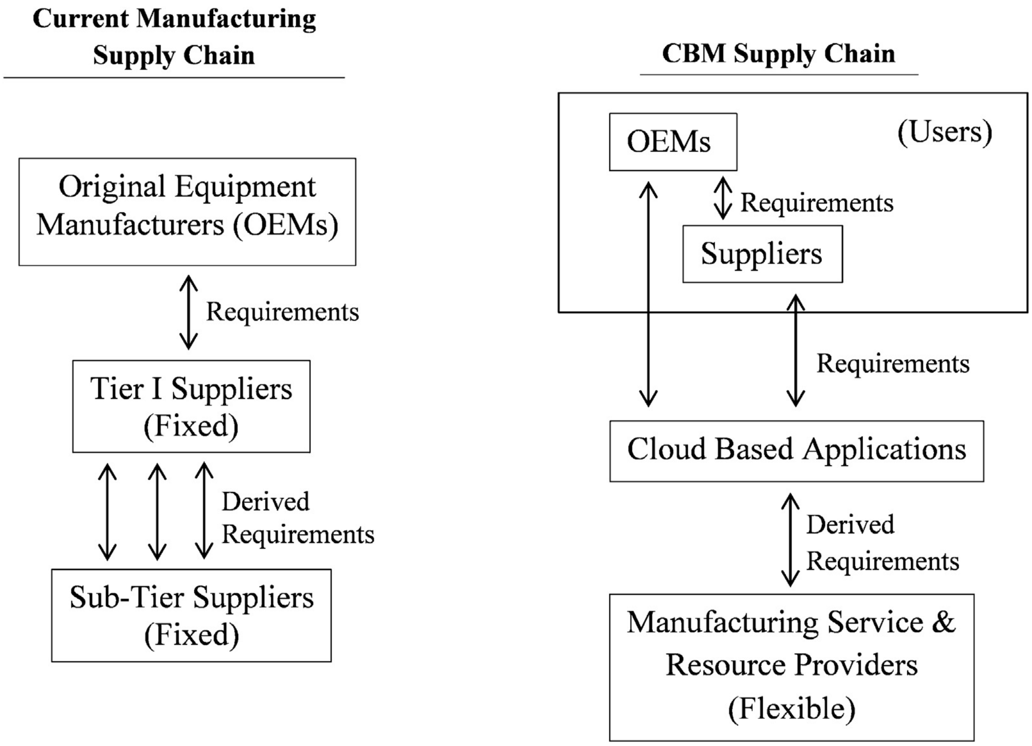

**Fig. 2.** Comparison of CM and traditional supply chains.

In the CM environment, manufacturing supply chain relationships will be customer-centric, defined by enhanced efficiency, reduced cost, increased flexibility, and improved capabilities for the user. These benefits will be derived from the creation of flexible manufacturing sequences enabled by the pooling of resources from many different PRPs. Solutions will be customer, or even task, specific, as the cloud based application layer can be used to generate numerous options for the users based upon their specifications (the user would be allowed to specify key aspects of the desired job, such as cost, lead time, and quality, and different choices that fit within those ranges would be provided for consideration). The key goal of a CM environment is linking users, with needs, to resource providers who can fulfill those needs while meeting cost, schedule, and quality objectives of the user. See Fig. 2 for a comparison of supply chains in traditional and CM environments. In addition, it is also crucial to understand collaborative relationships between cloud service providers and consumers and identify key information and resource owners within CM supply chain networks. Wu et al. [53] introduce a new framework to visualize such implicit collaboration structures and propose some essential metrics to measure the power and importance of individual suppliers and providers based on social network analysis.

### 2.2.2. *Temporary, reconfigurable, dynamic*

Another distinguishing characteristic of CM is the dynamic, flexible nature of resource provisioning. CM production lines are meant to be temporary in nature, allowing for the production of small lots but not excluding the opportunity for longer production runs as well. The ability to quickly reconfigure and repurpose manufacturing resources allows for high efficiency, minimized down time, and instant response to demand.

System flexibility will rely upon the ability to rapidly reconfigure and repurpose manufacturing equipment across multiple dispersed manufacturing sites with minimized down time. To accomplish such a task, a high level of automation will be required to ensure that the division of tasks can be properly flowed down to multiple, distributed shop floors with minimal effort. The integration of automation, which in many industries is already present today, does not necessarily imply the absence of human beings. Depending upon the application, the entire manufacturing process may be automated, and in other instances humans will still interact as a measure of quality assurance and error prevention.

In order to flow manufacturing requirements from the cloud to automated resources, industrial control systems (ICSs) will also be required. These control systems will act as the central nervous system, monitoring and controlling resources at the shop floor level to ensure multi-resource cooperation. The ICS will coordinate and distribute tasks among manufacturing locations, ensuring compatibility of efforts and final products.

### 2.2.3. *Turn no job away*

Due to the wide range of PRPs connected, jobs that were once not economically viable will be enabled through the flexibility of the CM environment. Cloud based applications can develop multiple cost and schedule scenarios for consideration by the consumer, utilizing access to a wide range of resources to enable saving opportunities not realizable in traditional isolated manufacturing settings. Where transportation is a cost driver, for example, the cloud based application layer can initiate searches for alternative manufacturing protocols that would result in lower cost. The CM environment can optimize the manufacturing environment to the point where no job would be turned away. In addition, the CM environment matches tasks with PRPs based upon their equipment availability and overall capacity, allowing for efficient processing of small jobs without disruption of larger jobs. This increased efficiency should increase the ability and willingness of PRPs to take on small jobs that were once too disruptive and costly to tackle.

### 2.2.4. *Demand driven, demand intelligent*

Like any manufacturing entity today, the extent to which the CM environment is exercised will be driven by user demand. Unlike traditional manufacturing enterprises, however, the CM environment

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will be "demand intelligent" in that the inherent system flexibility will be utilized to ensure even load sharing across equivalent or interchangeable manufacturing resources. For example, if manufacturing resource "A" is more heavily utilized than others in the network, yet the desired process can be performed by combining manufacturing resources "B" and "C", the CM environment will automatically realize and capitalize upon this alternative to avoid excessive loading of manufacturing resource "A". An example of such a scenario would be the requirement for a 6-axis CNC machine, when a combination of vertical and horizontal mills could be used to process the same job.

### 2.2.5. *Shared burden, shared benefit*

Traditional business organizations and relationships rely upon a tiered structure of control, which acts together to create value. Business organizations often vary widely across industries, and can even be different across corporations within the same industry. The organization of a business often defines a company as much as does the product or service it offers. For example, Amazon is not just a discount product marketplace; it is an online discount product marketplace. Mari Sako explains that business models define business operation: "a business model articulates the customer value proposition; it identifies a market segment; it defines the structure of the value chain; it specifies the revenue generation mechanisms; it describes the positioning within the value network or ecosystem; and it also elaborates on competitive strategy by which the firm gains and holds advantage over rivals" [40]. A business model is the argument as to why the company will succeed – it explains critical things such as who the customers are, why they care about your product or service, how you are going to add value to the product, and how you will make money.

The organizing business models that will someday define CM, while not unprecedented altogether, will require a shift from traditional business models of today to ones based on the share-to-gain philosophy. Value chains, which describe how value is added to a product, will be highly flexible in CM. Value will be added by resource providers sharing expertise and collaborating to provide users with the products they desire while utilizing less resources through efficient processes. CM will require the formation of new business models altogether (by all vested parties), and will require propositions as to what value the customer will receive, what market there is for such a business and so on. The appropriate business model for CM may be difficult to determine when it comes to value chain structure and revenue models. In traditional business models, the value chain and revenue models are firmly defined – each value adder is separated from the others, and they are compensated based upon the value they can add to the product. In a CM environment, collaboration between suppliers will be required to successfully complete a project. How will value added be determined when 3 different manufacturers combine resources to complete a build-to-print order? Will the overall value of the final parts be divided evenly between suppliers, or will it be shared based upon time and resources spent? These are the questions that will determine how value chains are structured and how wealth sharing will occur.

CM will likely cause a shift in the revenue models currently used by design firms and manufacturers alike. The introduction of the cloud will cause a shift in how value is added to the product, as the cloud will take over some of the activities that contribute to the revenue models of both the users and resource providers. For one, the cloud will introduce a change in how users calculate the cost of doing business. Secondly, the cloud will remove some opportunity for service providers to add value to products, requiring them to adjust their business models accordingly.

CM will also require the reversal of traditional beliefs held regarding intellectual property. Traditionally, data rights are easily understood – design authorities own the rights to product designs, and manufacturers of those designs own the manufacturing data that is used to produce them. Consider now that cloud based applications will be used to generate much of the value once produced by manufacturers (tool path programming, process planning, etc.). Users may claim that data produced by the cloud is their property because they paid for access to the cloud-based applications. Those firms managing the cloud-based applications will certainly argue that it is their property for distribution to whomever they like. The physical resource layer might also try and argue it is their data, because without their expertise it would be of little use. CM will be defined by an IP sharing model that aids in cooperation and collaboration.

### 2.3. *Cloud manufacturing topics map*

As CM is as of yet a relatively undefined field of study, the number of research areas within this field is only limited by the imagination. In order to discover and document possible areas of key interest, a brainstorming tool was used to record areas of research that would be critical to those using CM resources, those providing the resources, and those that help match users and providers. The result is shown in Fig. 3.

Fig. 3 shows a converging mind map, which can be read from the core outwards or from the outward fringes toward the center. Starting in the center of the map, one can see that CM (shown in a yellow cell) is composed mainly of cloud users (shown in a red cell), physical resource providers (shown in a green cell), and application providers (shown in a blue cell). These three groups converge to enable CM. Following the physical resource provider branch of the map, we can further see that physical resource providers will be enabled in the CM field by automation, data compatibility, information security, and business models. From there, enabling issues are broken down further where appropriate. For example, the development of enabling business models will be concerned with data ownership and promoting effective collaboration.

Not all of the topics shown in Fig. 3 are addressed in this report, however, most are. Specifically, the current state of quality assurance (QA), configuration management, cloud robustness, and information security were not researched nor documented. QA and configuration management were omitted due to the wide range of accepted industry specifications regarding these subjects and their already wide application to distributed suppliers in industry today. QA and configuration management as applied to CM environments will likely not differ significantly from their implementation in today's distributed environments. Cloud robustness and information security are two very important enabling aspects for CM, however they are far out of the core competencies of the authors. For this reason, these issues will be left for other researchers to explore.

In addition to those topics listed in Fig. 3, this report documents the numerous architectures and frameworks envisioned for implementation of CM. Through documentation of this work, many research topics as shown in Fig. 3 are indirectly addressed.

## 3. Current state

As CM is in the juvenile stages of development, the current state of the field must be collected from many different specialties which, in their combination, provide a foundation for the advancement of CM. Numerous fields of study were used to compile the following current status information, including but not limited to distributed manufacturing, virtual enterprises, and business management. The work that follows in no way defines the full extent of any particular field of study; rather, it documents those aspects most important to the enablement of CM.

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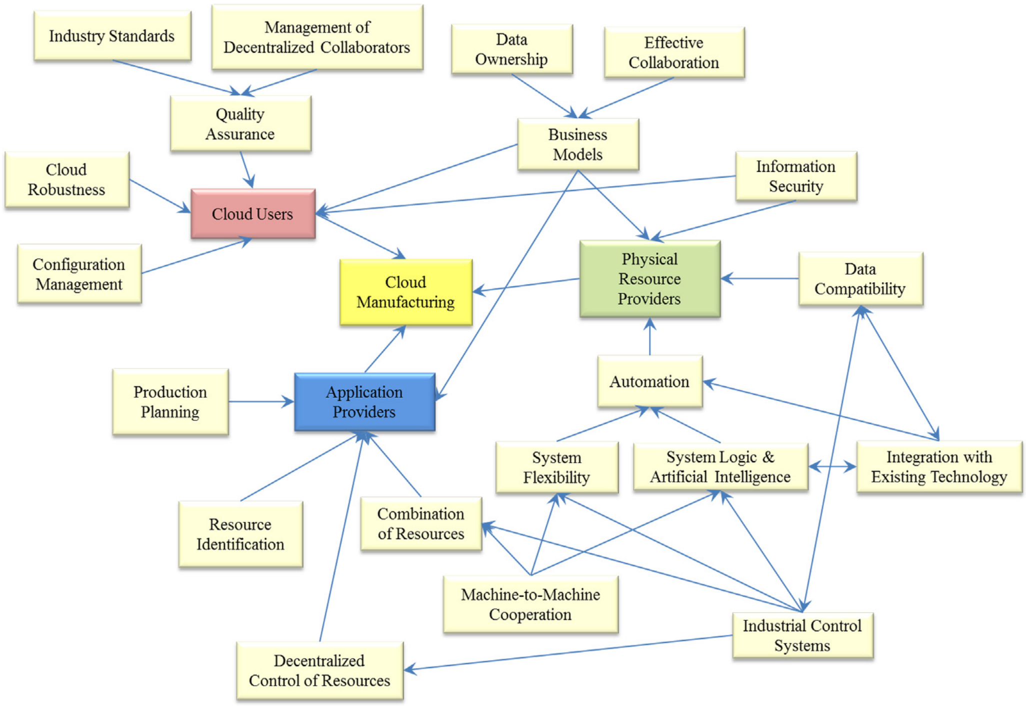

**Fig. 3.** CM topics map.

### 3.1. History

Surprisingly, significant literature on manufacturing-as-a-service was created in the late 1990s. It is expected that much of this literature was developed as part of the dot-com boom, which ended in the year 2000. It is likely that internet capabilities (speed, data transfer capability, etc.) were not able to accommodate the visions presented by these papers at the time of their creation, and as such CM has been awaiting arrival of today's internet for implementation.

In an article from 1990, Goldhar and Jelinek [35] discuss future implications of computer integrated manufacturing (CIM). These authors discuss transformation of the factory from a mechanical focused operation to one driven by information technology, and also discuss the ability for mass customization as a result of CIM. Much of the future envisioned by Goldhar and Jelinek matches the strategic vision for CM, including the ability to fulfill any demanded job regardless of size, and the ability to make the factory floor intelligent. While Goldhar and Jelinek envision the "smart" factory, they fail to realize the potential of networking multiple factories together into a virtual "smart" enterprise. This is undoubtedly due the year in which the document was written, as the internet was not yet prominent in the year 1990 and inter-factory cooperation may have not been a reality at that time. Regardless, this work represents a significant precursor to the vision of CM presented in this paper.

A 1998 source published by Rajagopalan et al. discusses the implications of the internet for design and rapid manufacturing technologies [36]. These authors discuss an internet infrastructure that connects designers and manufacturing services. Like so many of the more recent papers which will be reviewed in this report, these authors describe the existence of design clients, manufacturing services, and process brokers which act as intermediaries. The stated purpose for such an infrastructure is to allow for the separation of design and manufacturing – both in a geographic and organizational manner. In the described work, the design client uses software that augments traditional CAD programs and allows connection with the process broker to communicate design requirements to the manufacturing services providers. This work is very clearly applicable to the vision of CM presented in this report and represents a significant advancement toward understanding the possible capabilities and advantages of a CM style environment.

A 1996 source by Erkes et al. [34] discusses the implementation of manufacturing services available over the internet, and discusses the creation of integrated products and processes through similar interfaces. These authors have a similar vision to that presented in this report, showing how networked manufacturing networks could lead to exploitation of various enterprises based upon their competencies.

The DLA Piper legal group [28] explains that internet enabled manufacturing, crowd funding, and advertising through social media represent a revolutionary method of value production in today's marketplace. Instead of dealing with unknown market conditions, difficult to find financing, and strict vendor relationships, cloud-based activities offer flexibility and enable competiveness in a cutthroat marketplace.

In the 2000s, the concept of the manufacturing grid was proposed, which in some respect is similar to that of CM [48,62,63]. The idea of the manufacturing grid is to apply grid computing to product design, manufacturing resource integration and allocation, enterprise information management, and scheduling. Tao et al. [65] provided a review of the application of grid technology in manufacturing.

### 3.2. Current implementations

#### 3.2.1. Commercially viable implementations

A limited number of commercial companies have implemented CM systems, most notably in the consumer product industry with rapid prototyping manufacturing resources. These companies utilize the foundations of CM as enabling technologies for their ventures, and connect designers with manufacturing resources over the internet. According to The Economist [31], Quirky offers

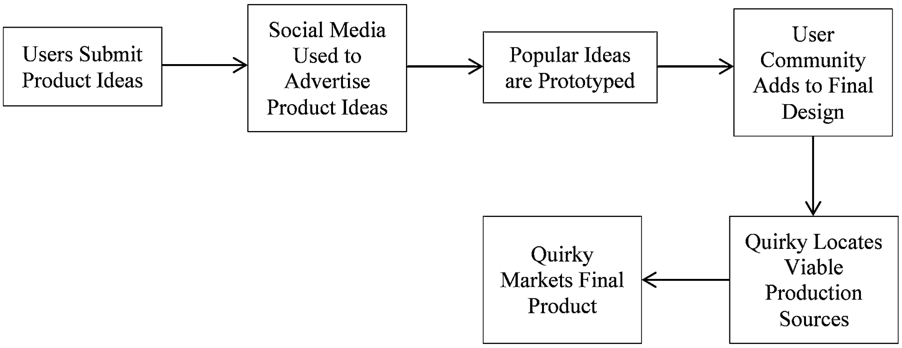

**Fig. 4.** Quirky development process. Simplified version of artwork shown in [31].

users with access to a complete product creation enterprise, as summarized in Fig. 4 below.

While not a pure cloud-based manufacturing environment, Quirky is enabled by manufacturing resources virtualized over the internet and available for use by distributed designers. The Quirky business model incorporates the originating designers into the wealth sharing model and provides them with a portion of the profits that their products yield. The Economist [31] also discusses Shapeways, a company which offers 3D printing services over the internet. In contrast to the vetting process used in the Quirky business model, Shapeways offers users immediate access to 3D printers to make any object which they desire.

Chafkin of Inc. Magazine discusses Ponoko, a product creation website which providers designers with access to the manufacturing resources they need to realize their products. This company prices products based upon the materials they require and the amount of machine time needed to make the part [32]. Review of the Ponoko website [38] shows that a number of 2D and 3D manufacturing services are offered to designers, and the website even enables manufacture of electronic components by offering access to hundreds of electronic components which the designer can specify and create designs with.

One of the most promising CM companies is MFG.com, which connects consumers with over 200,000 manufacturers in 50 states [31]. According to MFG.com, buyers request services by providing technical product specifications, which are communicated to appropriate suppliers for quoting. Suppliers are selected based upon their manufacturing capabilities, expertise, and instantaneous production capacity. The MFG.com platform hosts all activities from creating the Request for Quote to the shipping of the final product [37].

### 3.2.2. *Key research implementations*

The ManuCloud Project, funded under the European Commission's Seventh Framework Program for Research (FP7), is perhaps the research project most relevant to CM today [39]. According to Meier et al. [29], the ManuCloud project is meant to enable creation of integrated manufacturing networks spanning multiple enterprises which are facilitated by service oriented information technologies. According to the authors, "[The ManuCloud architecture] provides users with the ability to utilize the manufacturing capabilities of configurable, virtualized production networks, based on cloud-enabled, federated factories, supported by a set of software-as-a-service applications". This architecture is reproduced in Fig. 5.

The ManuCloud project architecture is very similar to the strategic vision of CM as presented in this report, and represents a major advancement toward the realization of CM.

## 3.3. *Low-hanging fruit: cloud-computing in manufacturing*

Xu [6] presents that the implementation of cloud computing in manufacturing can take two (2) forms. The first form is that which is discussed in the strategic vision section – that is, the mimicking of the cloud computing environment in manufacturing. The second form deals simply with the incorporation of cloud computing technologies into the manufacturing industry.

The implementation of cloud-computing technologies in the manufacturing industry can be termed the "low hanging fruit", as this requires little investment as compared to CM. In fact, cloud computing adoption has already begun to take place in significant numbers. Symonds [23] presents that the use of cloud-based enterprise resource planning (ERP) software, provided in a Software-as-a-service (Saas) format, allows users to utilize the latest software yet avoid the cost and hassle of maintaining the resource. Symonds presents that Saas is facilitated by the use of multi-tenant architectures which allow use of the resource by numerous companies, yet allow company specific attributes to be accommodated.

Katzel [24] presents that the manufacturing sector in defined by computing needs which vary significantly with the product life-cycle phase. Cloud-computing, as stated by Katzel, can be thought of as a utility service which can be accessed on-demand without owning the enabling technologies. According to Katzel, cloud-computing can aid manufacturing and engineering by providing data storage, software services, and computational power.

Edstrom [25] presents that typical server usage lingers at roughly 8–15% of total capacity. The need to oversize computing resources based upon peak usage rates, in addition to the cost of maintaining these technologies, makes a usage based pay on-demand system truly beneficial and cost effective.

Schultz [27] presents that despite its clear benefits, data storage in the cloud has been slow to gain popularity because of concerns over data security, meeting regulatory compliance requirements, and cloud performance.

## 3.4. *Automation, industrial control systems, machine-to-machine cooperation*

Automation and control technologies will enable inter- and intra-factory cooperation in CM environments, facilitating the ability to automatically execute manufacturing tasking generated by the cloud. As parts and assemblies are rarely manufactured by one piece of equipment, coordination and cooperation among machines and processing equipment will be required both within single factories and among multiple cooperative factories. Automation and control system technologies are crucial to the ability to efficiently route jobs through the required processing steps to completion.

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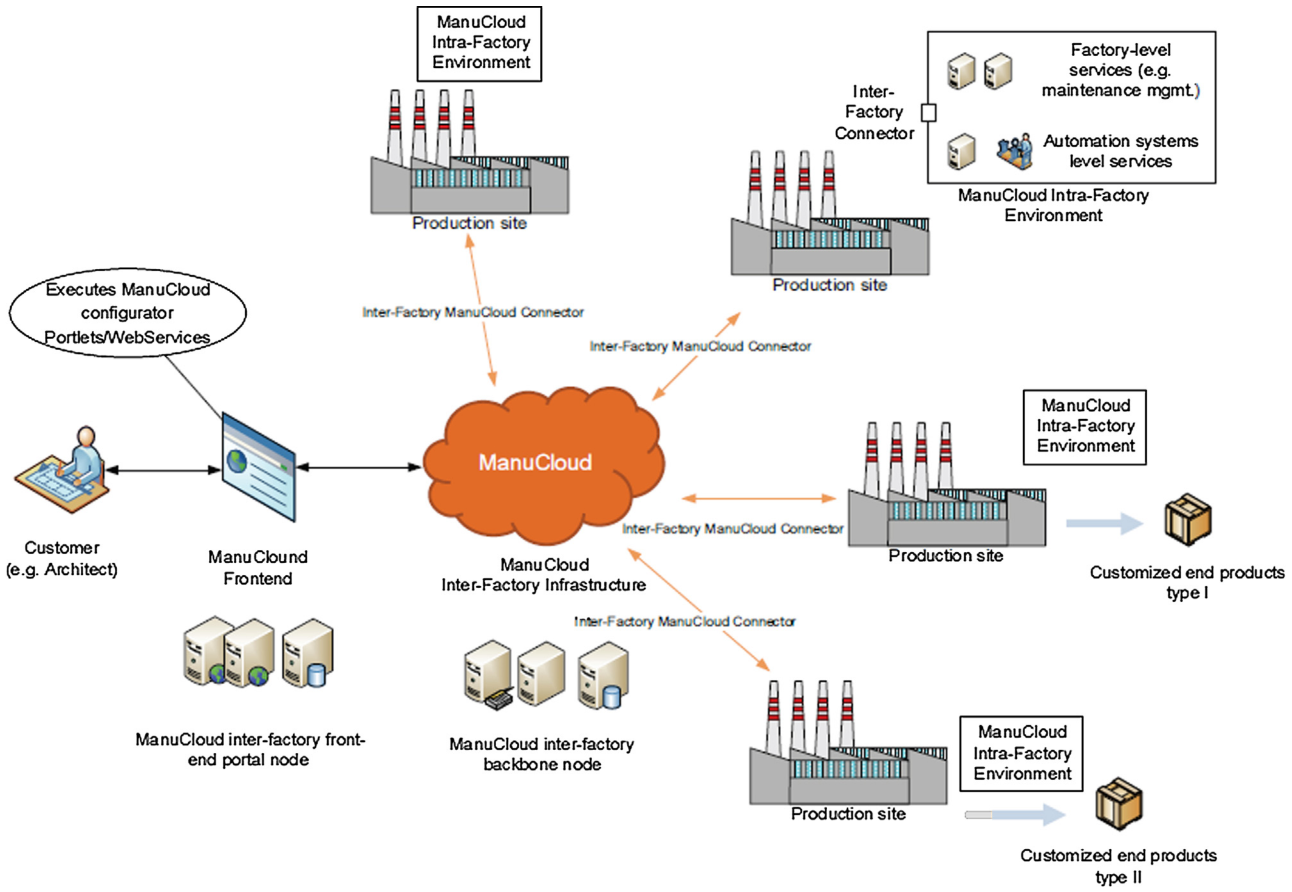

**Fig. 5.** ManuCloud architecture, from [29].

Stouffer et al. [12] discuss typical ICSs utilized in both process based and discrete-based manufacturing environments, including Supervisory Control and Data Acquisition (SCADA), Distributed Control Systems (DCSs), and Programmable Logic Controllers (PLCs). SCADA is a type of control system used to control manufacturing enterprises which are distributed over a large area, and is typically utilized in the gas and utilities industries. DCSs are used to control industrial process variables around a set target, and are common in process intensive industries. Finally, PLCs are computer based logic devices that control equipment and processes, and are often employed as part of a DCS system.

Programmable Automation Controllers (PACs) as described in [14] are a relatively new form of ICS which focus on emerging issues that limit ICS effectiveness, such as network connectivity, device interoperability, and enterprise data integration. According to [14], PACs feature modular designs, open (non-proprietary) architectures, and the ability to monitor multiple signal types such as analog, digital, and serial.

One of the most advanced control systems demonstrated in industry is the Siemens Totally Integrated Automation (TIA) system, which offers a wide range of control technologies in both SCADA and DCS environments [15]. The TIA system is based upon an open system architecture, which promotes modularity and interoperability with existing assets.

Much work has recently been done to establish open standards promoting technology connectivity and machine-to-machine communications. Developments in open architecture standards and communication protocols will serve to facilitate automation through promotion of "plug and play" technologies which can be offered from a wide variety of sources. The MTConnect Institute [19] has developed open (non-proprietary) and royalty free communication standards based upon the Extensible Markup Language (XML). These standards allow for machine-to-machine communications and promote interoperability between existing technologies. Similarly, the OPC Foundation [14] offers seven open communication specifications that also promote connectivity and interoperability.

Research regarding machine-to-machine communication is also common in the academic realm. CyberOPC is a dedicated protocol developed for communication with CNC machines over public networks [18]. The use of STEP-NC is discussed as a communication language between the shop floor and the plant scheduling level in [11,50–52]. Additionally, Hao et al. [13] discuss the enabling nature of Web Services (machine-to-machine communication over the World Wide Web) for the development of distributed manufacturing management frameworks.

### *3.5. Service composition*

The intrinsic value of a product is created by the combination of numerous materials, processes, and tasks performed by the manufacturer – value is added successively through planned manufacturing operations [45–49]. In order to optimize product value, CM environments will need to effectively and efficiently combine manufacturing services. This task becomes increasingly difficult in multiple-factory production environments.

Xu [6] discusses the creation of CM services, which are virtualized manufacturing resources made available to consumers through the cloud. The formation of CM services is enabled by the ability to identify, virtualize, and package both tangible and intangible resources. Xu presents numerous methodologies for identifying distributed resources, including such technologies as RFID,

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wireless sensor networks, and Global Positioning System (GPS), among others. The method of resource virtualization depends upon the form of resource being virtualized; computational and knowledge resources would be virtualized in a similar manner to that used in cloud computing technologies, and hardware resources would be converted into virtual machines using agent based technologies for distributed control and communication. Packaging resources and making them available as cloud based services, according to Xu, would be accomplished through description languages. One example of a CM service is STEP Resource Locator (STRL), which uses an URL, Action, and Query to identify a machine and task it with some requested service instructions.

Guo et al. [45] present an example about "online purchasing automobiles parts (OPAP)" to illustrate the concept of service composition in the context of CM. In order to enhance the quality of services composition, they investigate the issue of correlation-aware composite service [49] in virtual enterprises. Specifically, a correlation-aware composite service description model is proposed using OWL-S. A case study is conducted which validates the proposed model by comparing the quality of service of correlation-aware web services composition in virtual enterprises.

Tao et al. [46] formulate service composition optimal selection (SCOS) with multiple objectives and constraints, and propose a parallel intelligent algorithm called Full Connection based Parallel Adaptive Chaos Optimization with Reflex Migration (FC-PACO-RM). The performance of the proposed algorithm is validated by comparing with three serial algorithms and seven commonly used parallel methods. Tao et al. [47] focus on combinable relationship-based composite service network (CoRCS-Net). They introduce the concept of combinable strength and variation of combinable strength and investigate their distribution in CoRCS-Net. Tao et al. [20] present that the CM environment is in-part enabled by the creation of Manufacturing Cloud Services (MCSs). MCSs are cloud services that are formed when manufacturing resources are virtualized and encapsulated. These authors explain that MCSs can be categorized and combined into related manufacturing clouds, from which consumers can select particular MCSs to form their required production facility.

Zhang et al. [5] define Resource Service Composition (RSC) as the integration of existing resources to form composite services which can be used to address complex manufacturing tasks. According to these authors, the RSC has a four stage lifecycle (design, deployment, execution, and post-processing) which can be affected by numerous variables. The RSC lifecycle is initiated and maintained through a tri-modular system which executes the RSC, monitors for factors affecting lifecycle, and adjusts the RSC based upon system changes.

In research that stems from the ManuCloud project, Rauschecker et al. [30] describe the importance of Manufacturing Service Descriptions (MSDs) and Manufacturing Service Description Languages (MSDLs) in the virtual marketplace. According to these authors, MSDs describe available services and their limits, which the user community can then assemble into virtualized value chains.

### 3.6. *Manufacturing resources*

One implication of CM is the ability to dynamically adapt the amount of resources needed in order to satisfy the demand that is either predictable or unexpected [26]. The manufacturing cloud service can offer rapid scalability in some situations at certain levels, such as manufacturing cells, general purpose machine tools, and standardized machine components. In the situations where dedicated tools and equipment are required, the manufacturing cloud service can only offer a limited capability to quickly provide such resources. However, given that the cloud is a huge shared service pool of design and manufacturing resources, it is possible for cloud service consumers to find some dedicated tools and equipment for some specific products available in the manufacturing cloud that can satisfy their requirements. In order to facilitate rapid scalability, formal representation of manufacturing resources is crucial [43,44].

Cai et al. [55] propose a Semantic Web-based approach to discover distributed manufacturing resources for cross-enterprise multi-disciplinary collaboration. The constructed ontology enables knowledge discovery by incorporating graph search and semantic reasoning. Cai et al. [56] present a prototype semantic web system called ManuHub that facilitates efficient, accurate and automatic retrieval of the required manufacturing services derived from the semantic matchmaking of manufacturing service capabilities. Zhang et al. [57] present an ontology-based service oriented peer-to-peer architecture support effective and efficient manufacturing service discovery. A reputation based trust model for decision making is used to quantify the reputation of peers. Dong et al. [61] present an approach which utilizes service-oriented architecture, search agents, and the resource semantic model, to address web-based resource discovery. Tao et al. [58] define a resource service match and search framework and key technologies associated with it. The resource services are classified into four categories including word, sentence, number and entity information. Furthermore, the associated matching algorithms are proposed. Yin et al. [59] discuss resource registration, expression and encapsulation using XML in a manufacturing grid system in order to share distributed manufacturing resources. Shi et al. [60] present a manufacturing resource hierarchy model, consisting of a manufacturing resource layer, a resource expressing layer, and a resource interface layer, in order to aggregate and share manufacturing resources.

### 3.7. *Flexibility and agility*

The manufacturing environment is dynamic and ever-changing. CM will create an even more dynamic environment with the combination of multiple factories into production networks. In order to survive in such environments, CM systems must possess flexibility and agility which will help ensure schedule, cost, and quality compliance. Many authors have presented definitions of agility and flexibility in manufacturing. Hao et al. [13] state that advanced manufacturing systems are geared toward agility – that is, they are adaptive to changing market conditions and variable customer requirements. Panchal and Schaefer [16] define agility as the ability to successfully and quickly adapt to changes in the operating environment, both expected and unexpected. These authors further state that agility in the manufacturing realm often deals with the ability to quickly adapt a manufacturing resource to produce a different component or assembly.

Flexibility in CM will be facilitated almost exclusively by the ability to adjust the manufacturing process plan to accommodate changes in the manufacturing environment or to accommodate changing market conditions. That is, CM environments should allow for variation in the marketplace and changes in the manufacturing environment [13]. The ability to seek out alternate processes when the main process plan is interrupted, or when the market demands change should be the goal of any CM flexibility functionality.

Zhang et al. [5], as stated in Section 3.2, discuss how the lifecycle of RSCs can be affected by numerous factors. These authors argue that based upon the possible RSC interruptions, five (5) forms of RSC flexibility are required for maximum system adaptability: task, flow, resource service, QoS, and correlation. These flexibility categories are summarized in Table 1.

These authors promote the management of RSC through the adoption of a Flexibility Management Architecture, which is composed of three functional modules. The Function module

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**Table 1**
RSC flexibility types.

| Flexibility type | Implication |
|---|---|
| Task flexibility | RSCs can be constructed to adapt to many different tasks |
| Flow flexibility | Many RSC paths can be used to reach the required final condition |
| Resource service flexibility | Single resource services can complete many different tasks |
| Quality of service (QoS) flexibility | RSC can maintain a certain QoS, which is flexible |
| Correlation flexibility | RSC can adapt to changes in correlations among resources |

Created from [5].

constructs the RSC, optimizes it, and begins the execution phase. During RSC execution, the Monitoring module monitors those variables which affect the RSC lifecycle, and transmits information regarding abnormal changes to the Coordination module. The Coordination module then invokes corresponding adjustments to the RSC to ensure continued operations.

LaSelle [22] presents that mass customization is the new marketplace challenge, one which would be well served by a supply chain that can produce unique products of varying complexity on demand. LaSelle states that CM meets this goal by allowing manufacturing to keep pace with the ever-changing customer information. In short, CM allows the consumer direct access to the manufacturing industry through the internet, and as such industry can react to changing demand in real time. One challenge to increased system flexibility is the ability of automated machinery to adapt to new tasks while maintaining acceptable quality of service levels. LaSelle presents that robotic machinery programs often need repetitive adjustment before an acceptable result is obtained, a luxury which cannot be afforded in a world of mass customization. One solution proposed is the collection of task specific knowledge that, as a collective whole, enables autonomous process control without the need for machinery to "practice" tasks.

### 3.8. Business models

At the end of the day, for CM to be implemented on a wide spread basis it must have a feasible and value-generating business model. All parties (users, application providers, and PRPs) must benefit from the venture and must receive additional value on top of the value received in traditional manufacturing relationships.

In a broad sense, CM business models will need to support collaboration and cooperation to an unprecedented extent, as the mere survival of CM value chains will be reliant upon efficient and effective group action. Social psychology has offered numerous theories surrounding cooperation and collective decision making, all of which will help develop effective business models. Two of the most relevant social psychology theories for future CM environments are equity theory and game theory. Equity theory [9] deals with why individuals participate in groups and how they react when outcomes are disproportionately distributed. Equity theory is composed of 4 propositions as shown in Fig. 6.

Equity theory is important to the development of CM business models because it enforces the need for just and fair reward sharing among CM collaborators. Inequitable relationships will result in stressed relationships, which may impede the ability and willingness of collaborators to work together.

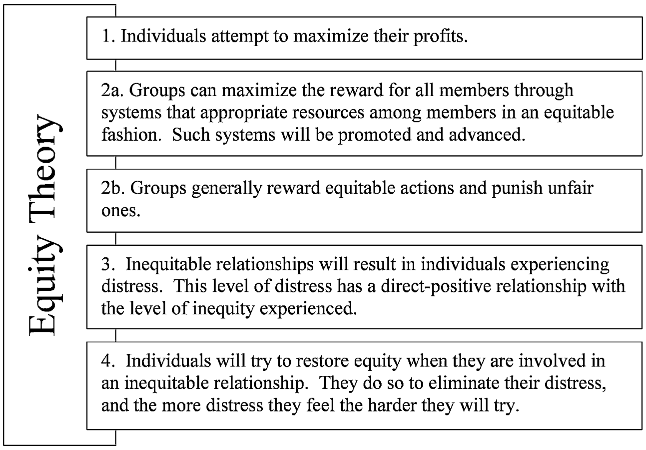
Game theory [10] deals with how rational individuals make decisions in mutually interdependent roles. Game theory can be non-cooperative, in which individuals can act together but are not bound by formal agreements, or it can be cooperative, where formal cooperation agreements are utilized. Game theory will help recognition of the motivations in cooperative environments and will help create environments which foster teamwork.

In many ways, the CM environment will utilize relationships that resemble those of joint ventures or collaborations. Parker [21] explains that joint ventures involve the formation of a legal entity separate from the parties coordinating the venture, while collaborative relationships involve 2 or more parties working together under contractually enforced terms. The purpose of both joint ventures and collaborations is to share information and expertise in order for all parties involved to do something they otherwise could not.

Parker states that intellectual property considerations occur throughout a four (4) stage life cycle (pre-contractual, formation, duration, and termination) of collaborative relationships. Throughout the entire collaborative relationship, the most important issues center around the use and control of background and foreground rights. Background rights, according to Parker, are those that each company holds prior to the relationship and intends to contribute to the venture. Foreground rights are those generated through the action of both parties throughout the length of the venture [21].

Similar background and foreground rights will exist in the CM environment. For example, a CM network may include numerous plating houses, each with existing plating process specifications that they will want to protect as IP (background rights). At the same time, the CM environment may create the need for these plating houses to collaborate to develop an improved plating process, which would be the equivalent of foreground rights resulting from a joint venture. Through proper negotiations between CM parties, both background IP interests can be protected and agreements can be made as to the use of foreground rights.

Wagner et al. [17] offer research regarding value management in collaborative environments. These authors offer a number of hypotheses regarding the link between value creation and appropriation, and how these concepts affect the attitudes and behaviors of participating parties. The work of these authors builds upon the equity theory. Using data from 186 manufacturing companies, Wagner et al. showed support for all but one of their eleven hypotheses. Table 2 summarizes their findings.



1. Individuals attempt to maximize their profits.

2a. Groups can maximize the reward for all members through systems that appropriate resources among members in an equitable fashion. Such systems will be promoted and advanced.

2b. Groups generally reward equitable actions and punish unfair ones.

3. Inequitable relationships will result in individuals experiencing distress. This level of distress has a direct-positive relationship with the level of inequity experienced.

4. Individuals will try to restore equity when they are involved in an inequitable relationship. They do so to eliminate their distress, and the more distress they feel the harder they will try.

**Fig. 6.** The 4 propositions of equity theory.
Adapted from [9].

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**Table 2**
Hypotheses offered by [17] regarding value creation and appropriation, and their relationships to the attitudes and behaviors of collaborating parties.

| Hypothesis designation | Hypothesis statement | Hypothesis supported by research? |
|---|---|---|
| $H_1$ | Relational satisfaction has a positive impact on relational trust | Yes |
| $H_{2a}$ | Relational satisfaction has a positive impact on the company's future collaboration intent | No |
| $H_{2b}$ | Relational trust has a positive impact on the company's future collaboration intent | Yes |
| $H_{3a}$ | Relational trust has a positive impact on value creation | Yes |
| $H_{3b}$ | Relational trust has a positive impact on value appropriation | Yes |
| $H_4$ | Relational satisfaction has a negative impact on value appropriation | Yes |
| $H_{5a}$ | Value creation has a positive impact on value appropriation | Yes |
| $H_{5b}$ | Value appropriation has a positive impact on the focal partner's level of project satisfaction | Yes |
| $H_{5c}$ | Given $H_{5a}$ and $H_{5b}$, value creation has a negative direct impact on the focal partner's level of project satisfaction | Yes |
| $H_6$ | Information exchange positively moderates the direct link between value creation and project satisfaction | Yes |
| $H_7$ | Project satisfaction has a positive impact on future collaboration intentions | Yes |

Wagner et al. conclude their research with three (3) main conclusions:

- Satisfaction is most higly driven by value appropriation.
- Collaborators compare their awards with those of others.
- The open and frequent exchange of information can ease tensions between competitors.

### 3.9. Implementation architectures, models and frameworks

Architectures, models, and frameworks for implementation of CM have been presented by numerous authors. These proposed structures vary in their complexity, maturity, and level of demonstrated potential, yet many have similar characteristics. Development of feasible implementation structures should be a key area of interest for academia and industry alike as they will help demonstrate the possible capabilities of a CM environment [33].

Xu [6] proposes a four (4) layer CM framework consisting of a manufacturing resource layer, a virtual service layer, a global service layer, and an application layer. See Fig. 7. According to Xu, the Manufacturing Resource Layer contains the physical manufacturing resources and capabilities of the shop floor, which are ultimately provided to the customer in Software-as-a-service (Saas) and Infrastructure-as-a-service (Iaas) delivery models. The Virtual Service Layer identifies, virtualizes, and packages the resources as CM services, which are then managed using the Global Service Layer (GSL). The GSL, depending upon the task demanded, can operate in both partial and complete services modes. In the partial service mode, the GSL does not handle all CM related activities – rather, the resource providers take some control of the process flow and the GSL helps administratively manage the CM activities. The complete service mode, however, coordinates and manages the entire CM activity. Most importantly, the GSL is a cloud platform and provides services using the Platform-as-a-service (Paas) model. Finally, Xu discusses the Application Layer, which provides the user-resource exchange portal. Through the Application layer, the user can construct manufacturing applications from the virtualized manufacturing resources.

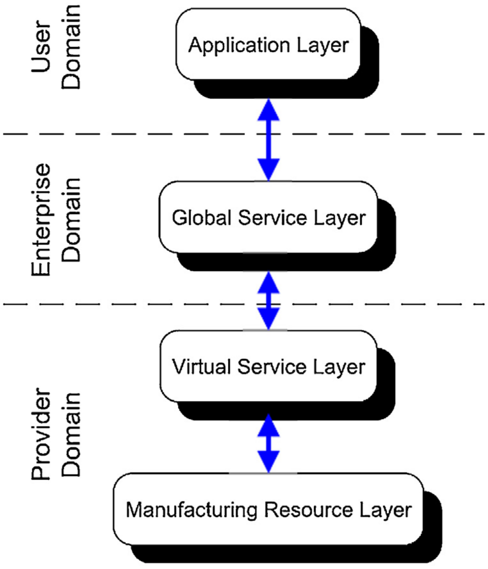

**Fig. 7.** CM layered framework, from [6].

Wu et al. [7] propose a Cloud Based Design and Manufacture (CBDM) model composed of a cloud consumer, cloud provider, cloud broker, and cloud carriers. The cloud consumers serve the obvious role of utilizing the cloud's services, while the providers have the equally obvious role of providing services in the cloud. The cloud broker is an intermediate party between the consumers and providers, and manages the use, performance, and delivery of services. Finally, the cloud carriers enable the exchange of services between providers and consumers through the provisioning of transport networks. See Fig. 8.

As can be seen in Fig. 8, Wu et al. specify that there are four cloud service types, including Hardware-as-a-service (Haas), Software-as-a-service (Saas), Platform-as-a-service (Paas), and Infrastructure-as-a-service (Iaas). The particulars of these service types are shown below in Table 3.

Schaefer et al. [8] propose a Distributed Infrastructure with Centralized Interfacing System (DICIS) as a CBDM structuring architecture. The DICIS is composed of three asset groups (human, communication, and manufacturing process) bounded by a centralized interface and a distributed infrastructure. See Fig. 9.

As can be seen in Fig. 9, the three asset groups are combined together in the distributed infrastructure, and the centralized interface enables the system to function as a whole. Human assets include consumers, producers, and managers. The communication assets proposed include a communication network (internet), network security, and 2 interfaces for communicating with the human and manufacturing process asset groups. Finally, the manufacturing process asset group is composed of hardware and software resources used in the CBDM environment.

Tao et al. [20] propose a four stage CM model where manufacturing resources are controlled through the internet via intelligent monitoring systems. These resources are virtualized and encapsulated into Manufacturing Cloud Services (MCSs). These MCSs, in contrast to the actual physical resources they represent, can be accessed and invoked in the cloud. After creation of many different MCSs based upon the manufacturing resources available, the MCSs are categorized and organized into manufacturing clouds of similar services. For example, milling services may be represented by

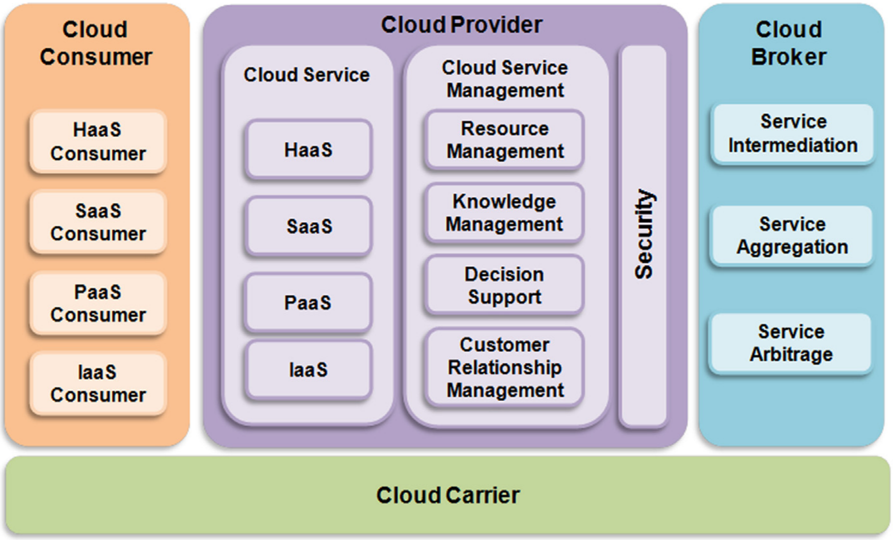

**Fig. 8.** CBDM model, from [7].

**Table 3**
Services types described by [7].

| Service type | Description |
|---|---|
| Haas | Providers can rent hardware to consumers through the CBDM environment. |
| Saas | Consumers can utilize software using thin client interfaces without purchasing licenses. |
| Paas | Consumers can access tools necessary for product development process within the CBDM environment. |
| Iaas | Consumers can access computing resources for exploitation without purchasing or maintaining them. |

multiple MCSs which are then organized into one manufacturing cloud. Users can then search the manufacturing clouds for services and combine MCSs to fit their needs. See Fig. 10.

As can be seen in Fig. 10, the CM environment is enabled by consumers, providers, and operators. In addition to the CM model shown in Fig. 10, Tao et al. propose a ten layer architecture for CM implementation, which is shown in Fig. 11.

In similar fashion to other architectures presented, that proposed in [20] consists of manufacturing resources and abilities at the lowest level. These resources are then virtualized and managed in a cloud environment, and then made available to consumers through an application layer. The seven functional layers of the architecture are facilitated by the three layers of knowledge, cloud security, and a network such as the internet. Tao et al. also state

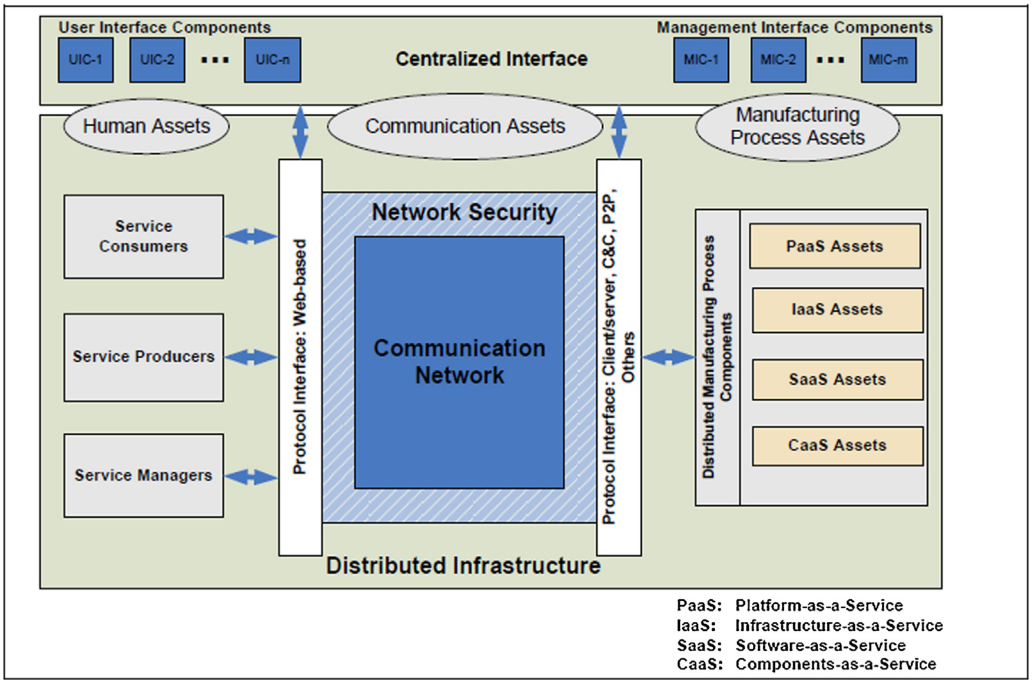

**Fig. 9.** DICIS, from [8].

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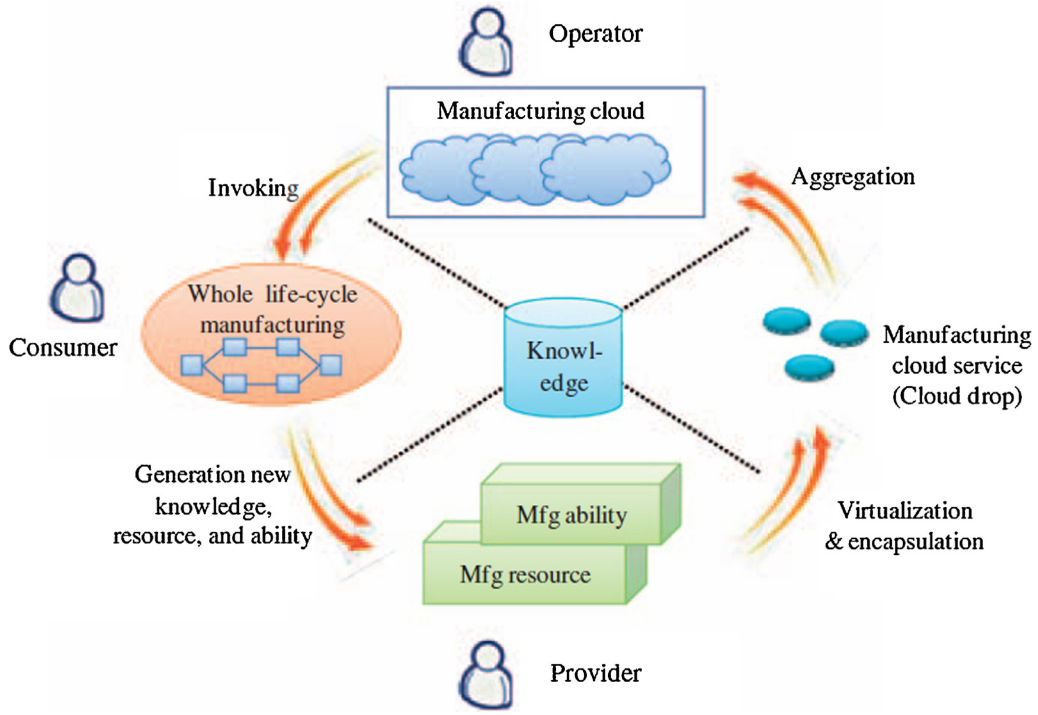

**Fig. 10.** Cloud manufacturing abstract, from [20].

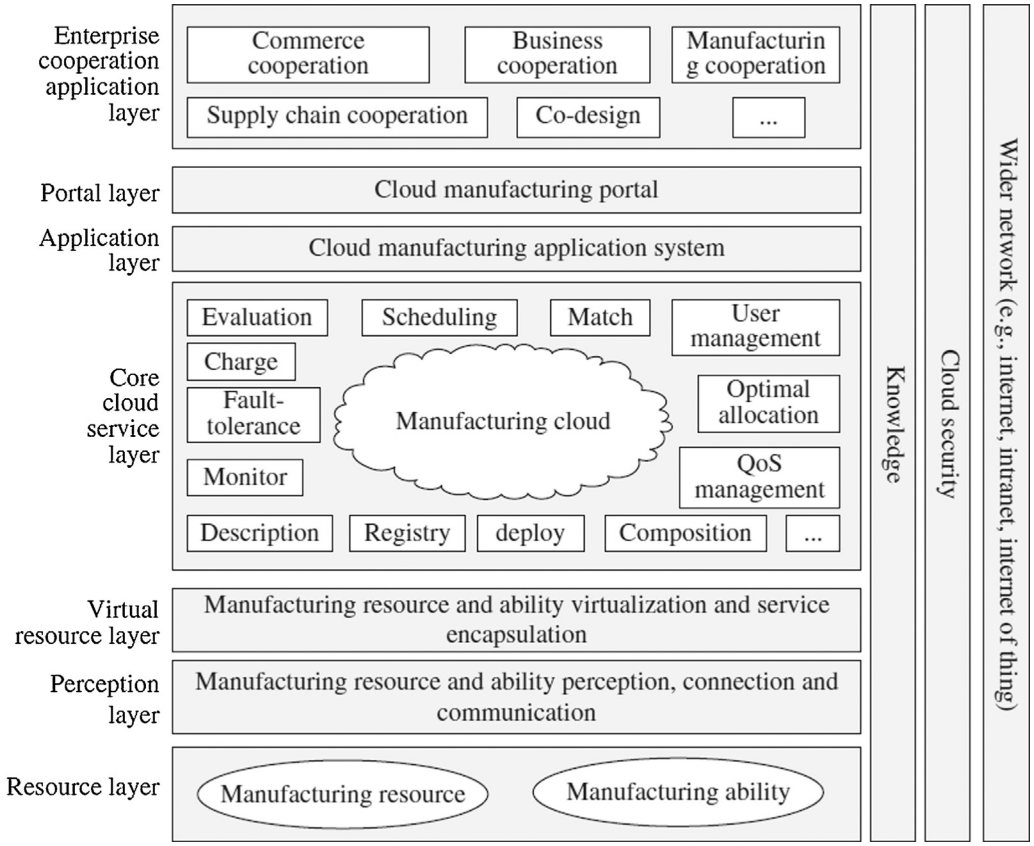

**Fig. 11.** Ten layer architecture, from [20].

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that CM platforms can be public, private, community, or hybrid environments.

## 4. Potential impact and future work

### 4.1. Potential impact

As illustrated in Fig. 12, we envision a possible impact of CM on three key sectors including engineering design, manufacturing, as well as marketing and service.

*Engineering design*: In the short term, the benefits of CM on engineering design are ubiquitous access to design information, improved efficiency, and affordable computing resources. In the long term, the impact area is collaborative design which is to support engineering design in geographically dispersed environments.

In the past two decades, the most important research works in collaborative design are web-based design and agent-based design. The architectures for web-based collaborative design can be classified into three categories: thin server and thick client, thin client and thick server, and peer-to-peer which are enabled technologies such as the Web, HTML, ActiveX, and CORBA. In agent-based design, the agent technology allows developers to focus on objects rather than functions, providing applications that are modular, decentralized and changeable. However, both web and agent-based approaches are lack of socio-technical network, mass collaboration, and inter-connected design knowledge pool capabilities which CM may have the potential to possess.

*Manufacturing*: In the short term, the benefits of CM on manufacturing are improved resource sharing, rapid prototyping, and reduced cost. In the long term, the impact area is distributed manufacturing.

Although much progress has been made with regard to distributed manufacturing, its current state does not yet fully support the needs of modern manufacturing enterprises. One of the critical issues still not fully addressed is scalability. However, CM has the potential to offer rapid scalability in some situations at certain levels, such as manufacturing cells, general purpose machine tools, and standardized machine components. For example, 3D printing technology does not require tooling, allowing the cloud service providers to rapidly scale up and down manufacturing capacity. In addition, the 3D printers connected in the cloud also help rapid tooling which makes rapid scalability possible for traditional manufacturing processes requiring tools.

*Marketing and service*: In the short term, the benefits of CM on marketing and service are reduced time-to-market, improved service, and enhanced user experience. In the long term, the impact area is customer co-creation.

In order for manufacturing enterprises to create value through collaboration, there is an increasing need to establish a new form of information, knowledge and resource sharing mechanism that emphasizes the generation and realization of various product stakeholders' value. CM has the potential to create new marketing channels for information and resource sharing which will transform the traditional product realization process into a value co-creation process. Specifically, the co-creation process enhanced by CM can engage customers, designers, manufacturing engineers, and production managers to communicate with each other through social media such as Facebook, Twitter, Blogs, and online forums.

### 4.2. Future work

#### 4.2.1. Automation and control

CM is still a poorly defined field of study and would benefit from detailed research in many areas. Much work is required to develop inter-factory industrial control systems which could facilitate a CM environment. Stouffer et al. provide evidence of room

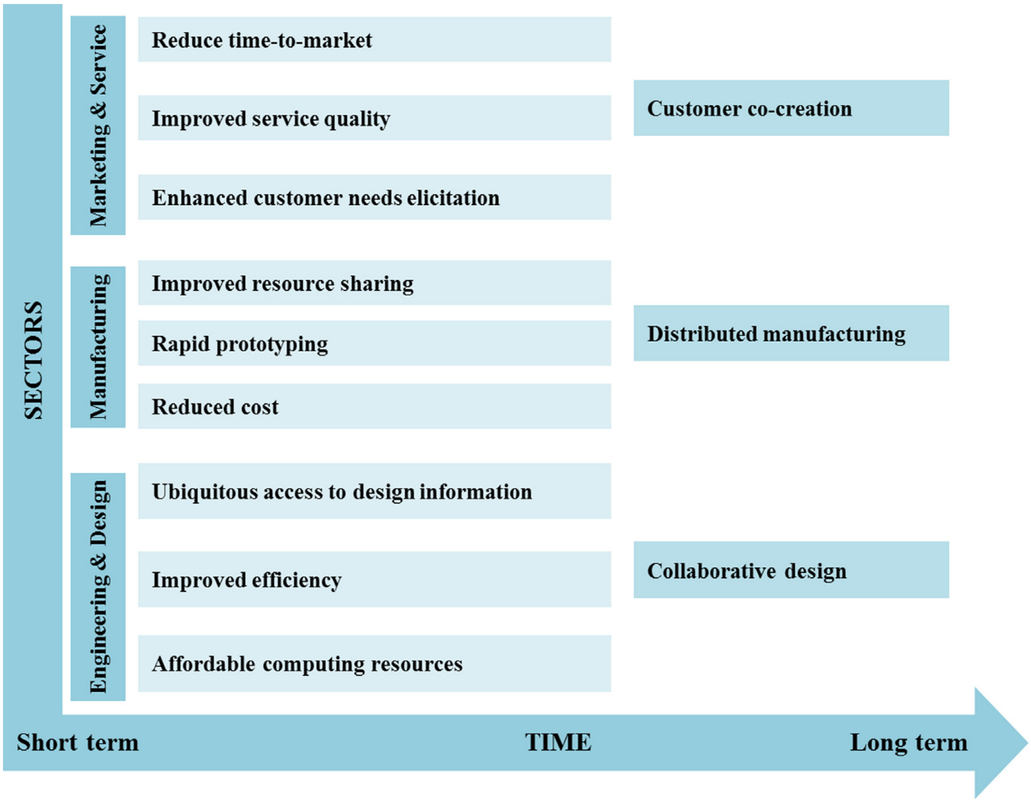

**Fig. 12.** The potential impact of cm across sectors [54].

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for improvement within the field of ICS [12]. These authors are discussing that DSC and PLC communications, which are typically used in a manufacturing industry, are normally executed in intra-factory environments. While these communications are usually more reliable and allow faster transmittal of data than do SCADA systems, they are typically not well suited for long distance communication environments. Therefore, enabling geographically distributed factories which can be controlled in an inter-factory style ICS will require control systems which have the characteristics of high speed, high reliability, and long distance range. Needed is a system fit for industrial process control with the range ability of a current SCADA system.

Additionally, CM systems can only be as flexible and robust as their controlling logic and control systems permit. Therefore, research in the area of artificial intelligence and its possible applications to the CM field will help ensure flexibility in manufacturing. The future trend should be to move away from automation towards integrated intelligence which not only allows automation of tasks but also allows for autonomy in tasking and task flexibility [64]. The ultimate goal should be to enable robust service compositions that are autonomously reconfigured with minimal human intervention. Moreover, flexibility will also be enabled by open communication standards as proposed by the MTConnect Institute. Ensuring shop floor connectivity will allow for efficient and effective machine-to-machine communication, providing coordination among value chain members during the manufacturing process. The development of open communication standards is an area of potential further research.

#### *4.2.2. Business model*

With limited examples of commercially viable implementations, it is still undetermined as to what applications are feasible for CM. Business model development should focus on a few main research questions:

- Who will benefit from this implementation of CM and how? Why would those involved in this business model choose a CM operating environment over a traditional manufacturing environment?
- How will equity be assured when value is delivered as a result of shared-interest, multiple-party work? How will value be maximized and distributed in accordance with value added?
- Should collaborators within the CM environment be bound by formal operating agreements, or should they be subject to a free market style environment? Does this vary based upon the situation, and why? Perhaps a hybrid environment would be best?
- How should IP be handled in collaborative environments? What about background and foreground rights?

#### *4.2.3. Information and resource sharing*

A huge amount of data and unstructured manufacturing-related information needs to be shared across upstream design and downstream manufacturing in CM. A primary technical barrier is that traditional manufacturing systems lack frameworks for seamless information and resource sharing mechanisms that facilitate communication and collaboration in distributed and collaborative settings. Specifically, a key component of such seamless information and resource sharing mechanism is a framework for capturing the implicit and complex collaboration structure, identifying key service provides and consumers. One of the key research questions in terms of information and resource sharing:

- How can we investigate the communication and interaction patterns between service providers and consumers in order to capture the implicit collaboration structure and key service providers and consumers in CM networks?

#### *4.2.4. Distributed system simulation*

Manufacturing system performance is often a central issue in the design, development, and configuration of systems. In order to validate the performance of CM, it is critical to conduct quantitative structure and behavior analyses for CM. Discrete-event modeling and simulation allows us to model behavioral properties such as reachability, boundedness, and liveness. In addition, other essential manufacturing performance metrics include cycle time, machine utilization, and throughput etc. So far little work has sought to evaluate the potential desirable performance such as time saving and improved machine utilization enabled by CM. Hence, the main research question in this area is:

- How can we capture material flows and evaluate performances of production processes for CM systems?

#### *4.2.5. Cost estimation*

With decision makers in manufacturing enterprises hesitating to move manufacturing business to the Cloud, it is critical to justify the perceived cost savings by estimating the cost quantitatively. Product costing is defined as a process of estimating the cost of final product at design stage. It turns out that the predominant percentage of manufacturing cost of a product is determined at the product design stage. Therefore, accurate estimating product cost at the early stage of product development processes is crucial for production mangers to make decisions. However, little research work has been conducted to estimate product cost in the context of CM. Therefore, it is very worthwhile to develop cost models to provide insights into cost drivers, value added, and non-value added manufacturing activities for CM. The research question is the following:

- How can we examine the potential cost savings from CM during early stages of product development?

As cloud manufacturing (CM) has been recognized as a promising paradigm for the next generation manufacturing systems, many research studies on CM have been conducted. This review aims to highlight the motivations and drivers of CM, propose a strategic vision, present current status of CM, and point out some of the key future directions.

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