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TOWARDS A CLOUD-BASED DESIGN AND MANUFACTURING PARADIGM: LOOKING BACKWARD, LOOKING FORWARD

Dazhong Wu
The G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332

J. Lane Thames
School of Electrical and Computer Engineering
Georgia Institute of Technology
Savannah, Georgia, 31407

David W. Rosen
The G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332

Dirk Schaefer*
The G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia, 30332

ABSTRACT

The rise of cloud computing is radically changing the way enterprises manage their information technology (IT) assets. Considering the benefits of cloud computing to the information technology sector, we present a review of current research initiatives and applications of the cloud computing paradigm related to product design and manufacturing. In particular, we focus on exploring the potential of utilizing cloud computing for selected aspects of collaborative design, distributed manufacturing, collective innovation, data mining, semantic web technology, and virtualization. In addition, we propose to expand the paradigm of cloud computing to the field of computer-aided design and manufacturing and propose a new concept of cloud-based design and manufacturing (CBDM). Specifically, we (1) propose a comprehensive definition of CBDM; (2) discuss its key characteristics; (3) relate current research in design and manufacture to CBDM; and (4) identify key research issues and future trends.

1 INTRODUCTION

Researchers and practitioners from industry continuously strive for new efforts to remain competitive in the area of product design and manufacturing. Many of these efforts have focused on addressing new ways of product design and manufacturing from the perspective of information and resource sharing [1]. As the manufacturing enterprises become increasingly concerned with meeting the dynamic requirements of a global marketplace, capturing and sharing product-related information and knowledge, and reusing design and manufacturing resources in globally distributed settings has become a key challenge.

In recent years, the IT sector at large has significantly benefitted from cloud computing through (1) *on-demand self-services*, (2) *ubiquitous network access*, (3) *rapid elasticity*, (4) *pay-per-use*, (5) *location-independent resource pooling* [2]. Of particular interest is that cloud computing allows for more affordable and flexible IT solutions compared to traditional infrastructure and service models. While cloud computing is already widely accepted in the IT field, it has just emerged on the horizon of other application fields such as computer-aided design and manufacturing. Little work has been reported on investigating the potential of cloud computing in the field of product design and manufacturing. In particular, a comprehensive definition of cloud-based design and manufacturing (CBDM) is needed, along with the theoretical framework guiding the design of CBDM systems.

As indicated by Ulrich [3], some of the major paradigms that guide current research in product design and manufacturing are consumer utility addressing design decisions related to key performance characteristics [4-5], design structure matrix focusing on the decomposition and integration of design problems [6-7], product architecture dealing with product platform and variety [8], decision making for modeling multiple trade-offs [5, 9, 10], and statistical and optimization methods for engineering design [11-12]. Some of the key research issues are not yet fully addressed such as (1) mathematical models of product design search [13], (2) social networking perspective in product design [3, 14], (3) user

*Corresponding Author, Email: dirk.schaefer@me.gatech.edu

innovation, customer co-creation and user experience (UX) design [15-16], and (4) the power of crowdsourcing in product innovation [17-18].

Although research related to CBDM is in its infancy, a few companies are conducting pilot studies of applying cloud computing to product design and manufacturing. For example, Autodesk claims that they are able to provide their customers with greater access to design and engineering documents anywhere and anytime [19]. Some of their featured services include: (1) Cloud rendering, providing customers with powerful rendering capabilities so as to have better visualization of 3D models; and (2) Software-as-a-service, helping designers to exchange information securely so as to enhance effectiveness and efficiency of team collaboration. Another example is Fujitsu, announcing its engineering cloud, which makes it possible to efficiently consolidate applications and high-volume data formats. Their engineering cloud is a good practice of platform-as-a-service, providing a high-speed thin client environment, server consolidation, and license consolidation, which dramatically reduces manufacturing costs and development time by leveraging the knowledge base in the cloud [20].

Accordingly, our goal in this paper is that trying to answer the following questions:

- What is cloud-based design and manufacturing, how is it different from previous paradigm shifts?
- What new opportunities are either enabled by or potentially drivers of CBDM?
- What are the obstacles to the success of CBDM, and potential strategies for solution?

In order to answer the above questions, we present an overview of the scientific basis for CBDM and its related fields as well as identify a number of related research issues and potential future directions for research.

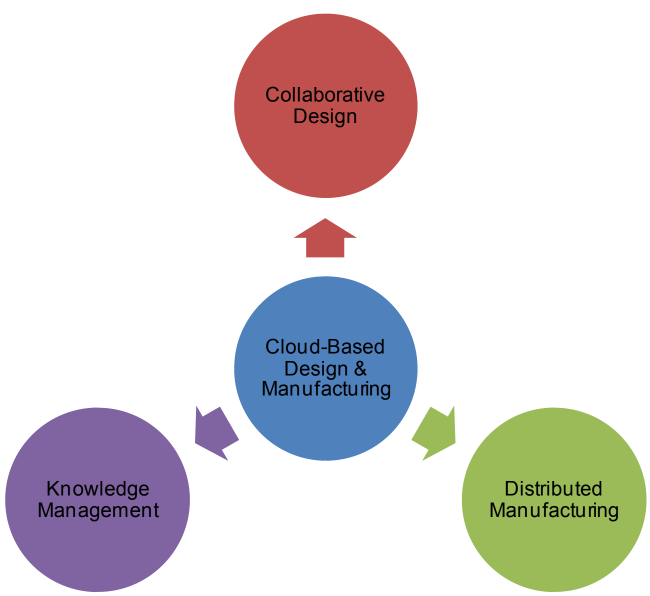

Figure 1 Research opportunities related to CBDM

The remainder of this paper is organized as follows. In the next section, we briefly present our vision of what CBDM may look like in the near future. Section 3 discusses future opportunities related to CBDM, with a focus on (1) collaborative design, (2) knowledge-based systems, and (3) distributed manufacturing (see Figure 1). In Section 4, we discuss some selected research issues and potential strategies for solution, including (1) management of CBDM complexity; (2) design search engine; (3) cloud-enabled human-computer interaction, and (4) human-human collaboration. Section 5 concludes the paper.

2 CLOUD-BASED DESIGN AND MANUFACTURING

2.1 Existing Definitions of Cloud Computing

In order to define CBDM and identify its key characteristics, we first review some of the existing definitions of cloud computing:

- "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 [25]."
- "Cloud computing refers to both the applications delivered as services over the internet and the hardware and systems software in the datacenters that provide those services. The services themselves have long been referred to as Software as a Service (SaaS)…. The datacenter hardware and software is what we will call a Cloud [22]. "
- "Clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms, and/or services). These resources can be dynamically reconfigured to adjust to a variable load (scale), allowing also for an optimum resource utilization. This pool of resources is typically exploited by a pay-per-use model in which guarantees are offered by the infrastructure provider by means of customized SLAs [21]."
- "A cloud is a type of parallel and distributed system consisting of a collection of interconnected and virtualized computers that are dynamically provisioned and presented as one or more unified computing resources based on service-level agreements established through negotiation between the service provider and consumers [26]."
- "Cloud computing is both a UX and a business model. It is an emerging style of computing in which applications, data and IT resources are provided to users as services delivered over the network. It enables self-service, economies of scale and flexible sourcing options…an infrastructure management methodology - a way of managing large numbers of highly virtualized resources, which can reside in multiple locations…[27]."

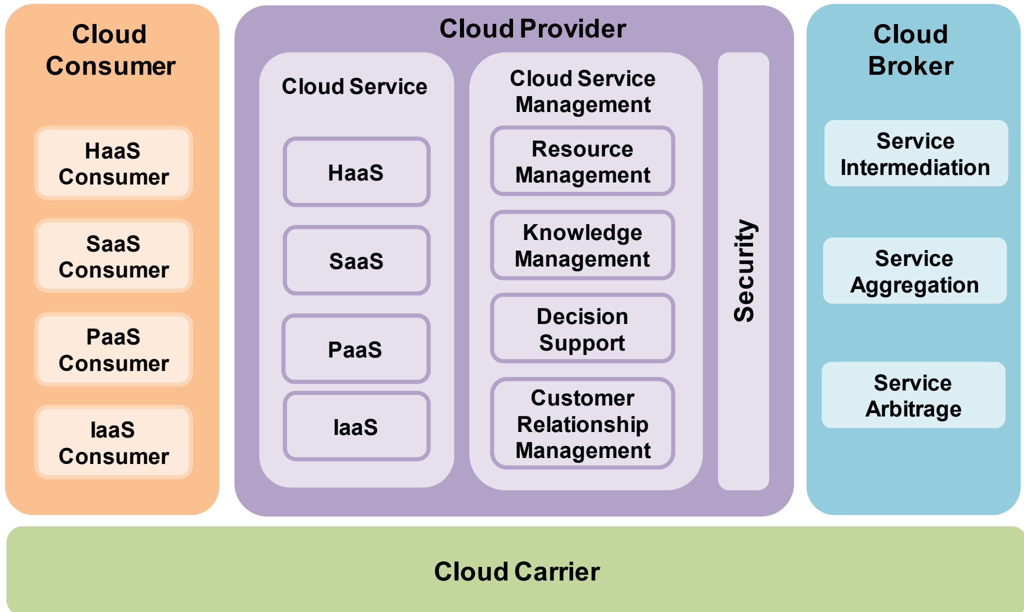

Figure 2 CBDM Conceptual Reference Model Adapted from [25]

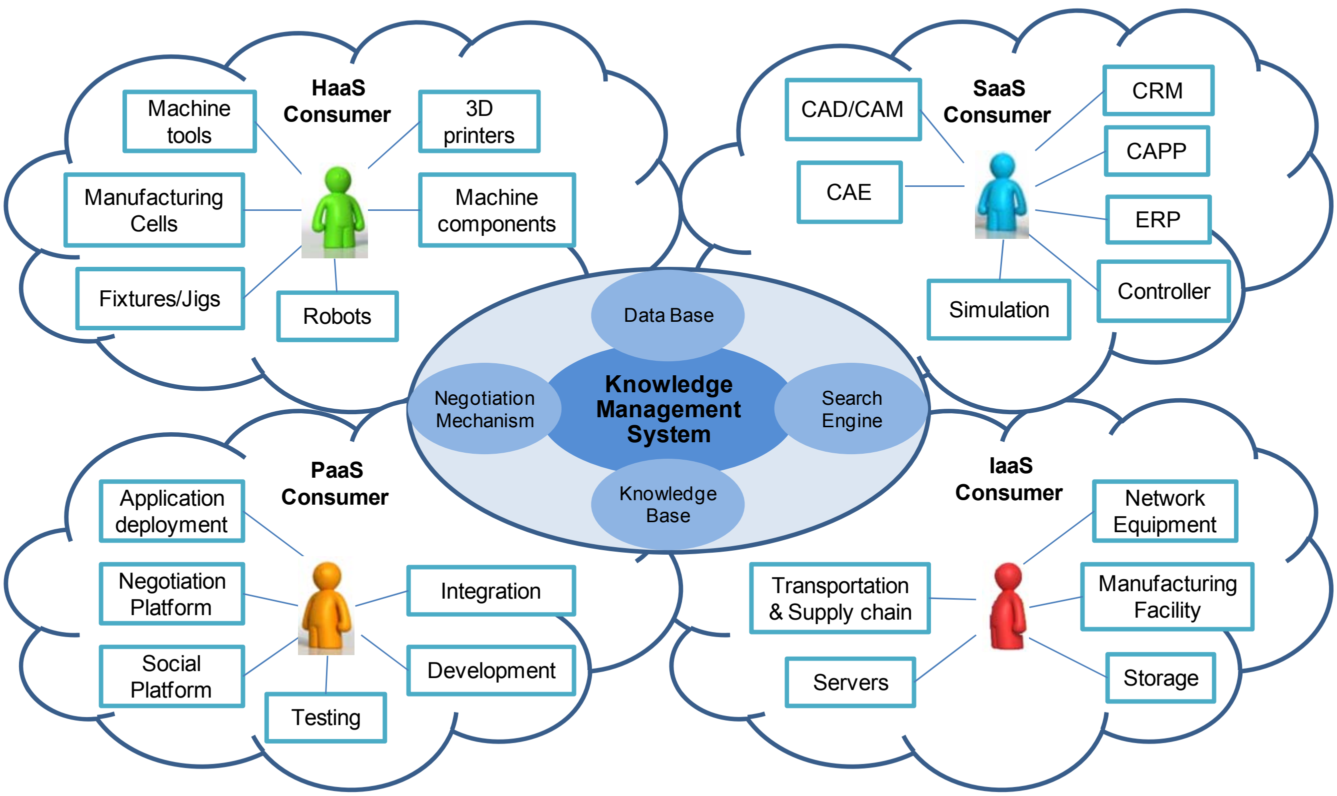

Figure 3 CBDM Example Services

Table 1 Actors in the CBDM Conceptual Reference Model Adapted from [25]

Actor	*Definition*
CBDM consumer	An entity that utilizes services offered by the cloud.
CBDM provider	An entity that provides services in the cloud.
CBDM broker	An entity that manages the use, performance, and delivery of cloud services, and negotiates relationships between cloud providers and cloud consumers.
CBDM carrier	The intermediary that provides connectivity and transport of cloud services from cloud providers to cloud consumers.

Table 2 Major Activities in the CBDM Conceptual Reference Model Adapted from [25]

Delivery Models	*Consumer Activities*	*Provider Activities*
HaaS	Uses hardware and associated manufacturing process for manufacturing and production operations.	Provides and maintains hardware, as well as supports manufacturing processes.
SaaS	Uses engineering software packages for design, manufacturing, and analysis.	Installs, manages, maintains, as well as supports engineering software applications in the cloud.
PaaS	Uses the cloud platform in the cloud, as well as interacts and communicates with other users.	Provides and manages the cloud platform, as well as develops tools for consumers.
IaaS	Uses computing resources, internet services in the cloud.	Provides and manages computing resources, internet services in the cloud.

2.2 The Evolution of Cloud Computing

In the previous section, a number of well known definitions of cloud computing are presented. Here we put these ideas in a historical perspective in order to understand the origin of cloud computing, where it comes from, and its evolution.

While the term cloud computing was only coined in 2007, the concept behind cloud computing, delivering computing resources through a global network, was rooted in 1960s [87]. The term "Cloud" is often used as a metaphor for the Internet, and refers to both hardware and software that deliver applications as services over the Internet [22]. When looking backward, one realizes that cloud computing is based on a set of pre-existing and well researched concepts such as utility computing, grid computing, virtualization, service oriented architecture, and software-as-a-service [90]. One milestone is utility computing, proposed by John McCarthy in 1966. The idea of utility computing is that "computation may someday be organized as a public utility." Due to a wide range of computing related services and networked organizations, utility computing facilitates integration of IT infrastructure and services within and across virtual companies [88]. Another milestone is that Ian Foster and Carl Kesselman proposed the concept of grid computing in 1999. A computational grid refers to a hardware and software infrastructure that provides dependable, consistent, pervasive, and inexpensive access to high-end computational capabilities [89]. Since cloud and grid computing share a similar vision, Foster et al. identified the main differences between grid computing and cloud computing [91]. The greatest difference is that cloud computing addresses Internet-scale computing problems, utilizing a large pool of computing and storing resources, whereby grid computing is aimed at large-scale computing problems by harnessing a network of resource-sharing commodity computers, dedicating resources to a single computing problem [21, 91].

Compared to grid computing, we envision that cloud computing would be the most promising underlying concept that can be borrowed in the fields of design and manufacturing due to the advantages of greater flexibility, ubiquitous availability of high capacity networks, low cost computers and storage devices as well as service-oriented architecture. Thus, before exploring CBDM in more detail, it is worthwhile to take a close look at what make cloud computing unique and how it is being leveraged in design and manufacturing fields.

Cloud computing can be seen as an innovation from different perspectives. From a technical perspective, it is an advancement of computing history that evolved from calculating machines with binary digit systems, to mainframe computers with floating-point arithmetic, to personal computers with graphical user interfaces and mobility, to the Internet that offers computing resources via distributed and decentralized client-server architectures, and eventually to utility, grid, and cloud computing [90]. From a business perspective, it is a breakthrough which is changing the mode of IT deployment and potentially creating new business models.

In order to leverage cloud computing in existing manufacturing business models and enterprise information systems, cloud manufacturing, based on cloud computing and service-oriented technologies, is proposed [23]. The architecture, core enabling technologies, typical characteristics for cloud manufacturing, and the difference and relationship between cloud computing and cloud manufacturing has been discussed. Xu [24] discusses the potential of cloud computing that can transform the traditional manufacturing business models by creating intelligent factory networks. Two types of cloud computing adoptions in the manufacturing sector have been suggested, direct adoption of cloud computing technology in the IT area and cloud manufacturing where distributed resources are encapsulated into cloud services and managed in a centralized manner.

2.3 Defining Cloud-Based Design and Manufacturing (CBDM)

Based on the concept of cloud computing, we propose a definition of CBDM as follows:

Cloud-Based Design and Manufacturing refers to a product realization model that enables collective open innovation and rapid product development with minimum costs through a social networking and negotiation platform between service providers and consumers. It is a type of parallel and distributed system consisting of a collection of inter-connected physical and virtualized service pools of design and manufacturing resources (e.g., parts, assemblies, CAD/CAM tools) as well as intelligent search capabilities for design and manufacturing solutions.

In addition, the essential characteristics of CBDM, including on-demand self-service, ubiquitous network access, rapid scalability, resource pooling, and virtualization are emphasized as prerequisites to enable CBDM as follows:

1. *On-demand self-service*: A customer or any other individual participating in the cloud can provide and release engineering resources, such as design software, manufacturing hardware, as needed on demand. It provides a platform and intuitive, user-friendly interfaces that allow users (e.g., designers) to interact with other users (e.g., manufacturers) on the self-service basis.
2. *Ubiquitous network access*: There is an increasing need for a so-called customer co-creation paradigm, which enables designers to proactively interact with customers, as well as customers to share different thoughts and insights with designers [28-29]. In order to easily reach such a communication media, it requires a capability of broad and global network access. The design and manufacturing cloud (DMCloud) can provide such access to the network where cloud consumers reside through multiple tools, e.g., mobile phones and personal digital assistants. CBDM allows various stakeholders (e.g., customers, designers, managers) to participate actively throughout the entire product realization process.
3. *Rapid scalability*: The DMCloud allows enterprises to quickly scale up and down, where manufacturing cells, general purpose machine tools, machine components (e.g., standardized parts and assembly), material handling units, as well as personnel (e.g., designers, managers, and manufacturers) can be added, removed, and modified as needed to respond quickly to changing requirements. It helps to better handle transient demand and dynamic capacity planning under emergency situations incurred by unpredictable customer needs and reliability issues. For example, the cloud system allows the cloud service consumers to quickly search for and fully utilize resources, such as idle and/or redundant machines and hard tools, in another organization to scale up their manufacturing capacity.
4. *Resource pooling*: The cloud provider's design and manufacturing resources are pooled to serve cloud consumers in a pay-per-use fashion. Resources include engineering hardware (e.g., fixtures, molds, and material handling equipments) and software (e.g., computer-aided design and Finite Element Analysis (FEA) program packages). The CBDM model enables convenient and on demand network access to such a shared pool of configurable manufacturing resources [30]. The real time sensor inputs, capturing the status and availability of manufacturing resources, ensures effective and efficient cloud resource allocation.
5. *Virtualization*: The DMCloud provides a virtual environment through the simulation of the software and/or hardware upon which other software runs [25]. It enables enterprises to separate engineering software packages, computing and data storage resources from physical hardware, as well as to support time and resource sharing.

2.4 CBDM Reference Model

To illustrate what a DMCloud may look like, a CBDM high-level conceptual reference model is proposed in addition to the CBDM definition (see Figure 2). Mirroring with the NIST cloud computing conceptual reference model [25], the CBDM conceptual reference model defines a set of actors, activities, and functions involved in the DMCloud. For example, four major actors are defined in the CBDM reference model: (1) cloud consumer, (2) cloud provider, (3) cloud broker, and (4) cloud carrier [25]. Table 1 lists the four major actors and their corresponding definitions. The interaction and communication among the actors in the cloud is shown in Figure 2. A cloud consumer may request cloud services, i.e., *cloud hardware-as-a-service (HaaS)*, *cloud software-as-a-service (SaaS)*, *Cloud platform-as-a-service (PaaS)*, *Cloud infrastructure-as-a-service (IaaS)*, from a cloud provider directly or via a cloud broker. A cloud provider provides cloud services through cloud service management, including resource management, knowledge management, decision support, and customer relationship management. A cloud provider must also manage security, ranging from physical security to virtual security. A cloud broker manages cloud services through service intermediation, service aggregation and service arbitrage. Four types of DMCloud services and their corresponding activities are presented in Table 2. Figure 3 presents some example CBDM cloud services available to a cloud consumer.

Hardware-as-a-service (HaaS)

HaaS delivers hardware sharing services, e.g., machine tools, hard tooling, and manufacturing processes, to cloud consumers through the DMCloud. Cloud consumers are able to rent and release hardware provided by a third party without purchasing them. The Cubify.com 3D online printing service is a good example, which allows cloud consumers to produce parts through any mobile device using their online 3D printing service without purchasing 3D printers [31]. The consumers of HaaS could be either engineers or end users, who may utilize manufacturing hardware.

Software-as-a-service (SaaS)

SaaS delivers software applications, e.g., CAD/CAM, FEA tools, and Enterprise Resource Planning (ERP) software to cloud consumers. Cloud consumers are able to install and run engineering and enterprise software through a thin client interface without purchasing full software licenses. The cloud service offered by Dassault Systems and Autodesk are by far the best known examples among engineering analysis applications, allowing remotely running 3D software and high performance discrete computing environments [19, 32]. The consumers of SaaS can be designers, engineers and managers, who need access to software applications.

Platform-as-a-service (PaaS)

PaaS provides an environment and a set of tools (e.g., an interactive virtual social platform, a negotiation platform, and a search engine for design and manufacturing solutions) to consumers and application developers to assist them in integrating and delivering the required functionality. A good example is Fujitsu, providing a high-speed thin client environment, server consolidation, and license consolidation, which dramatically reduces manufacturing costs and development times by leveraging a knowledge base in the cloud [20].

Infrastructure-as-a-service (IaaS)

IaaS provides consumers with fundamental computing resources, e.g., high performance servers and storage space. These services are offered on a pay-as-you-go basis, eliminating downtime for IT maintenance as well as reducing costs dramatically. The consumers of IaaS could be engineers and managers, who need access to these computing resources.

3 POTENTIAL CBDM APPLICATION FIELDS

So far we have presented the concept of cloud computing and its origin, based on which CBDM is proposed as a new concept. In the following, we elaborate further on the impact CBDM may have on the advancement of selected aspects of design and manufacturing, including (1) collaborative design, (2) distributed manufacturing, and (3) knowledge management systems, respectively. The literature on any of them is very broad and we will not attempt to survey all of it here.

3.1 The Advantages of CBDM

As has been shown in the definition, the CBDM concept has resulted from rich cross fertilizations between cloud computing, collaborative engineering design, distributed manufacturing, collective innovation, data mining, semantic web, virtualization, and knowledge-based systems. The motivation for introducing CBDM is based on the belief that CBDM can lead to important advances in new ways of thinking about product design and manufacturing.

Consequently, based on the definition of CBDM, its essential characteristics and reference model, the following aspects make CBDM unique:

1. An integrated technical and social networking platform, thereby enabling effective human-human collaboration in the cross-functional, multi-disciplinary and geographically distributed work environment.
2. A ubiquitous computing environment that may provide unique human-computer interaction, real time data and more accurate customer needs information, thereby enabling a new way of managing customer relationship and product innovation.
3. An ability to dynamically adapt the amount of computing resources and hardware needed, thereby satisfying the demand that is either predictable or unexpected.
4. The capability of intelligent search for design and manufacturing solutions enabled by semantic web technology and social network analysis, thereby promoting information and knowledge reuse and cost reduction.

3.2 Collaborative Design

With the faster and higher demands of new and improved designs, companies need to participate in global design chains and collaborate with each other to gain competitive advantages [1, 92]. Research in collaborative design is focused on helping designers generate creative ideas and collaborate more efficiently and effectively by sharing design and manufacturing resources and services through formal and informal interactions [33-34]. So far, the most important research works in collaborative design are web-based design and agent-based design. In web-based design, a collaborative design system developed with the web would primarily provide: (1) access to catalogue and design information on components and sub-assemblies; (2) communication among multidisciplinary design team members in multimedia formats; and (3) authenticated access to design tools, services and documents [93]. In agent-based design, an agent approach allows developers to focus on objects rather than functions, thereby providing applications that are modular, decentralized and changeable [93]. However, two research issues are not fully address yet:

1. An approach that enables various stakeholders (such as customers and designers) to participate in various design phases in collaborative design.

2. An approach that can help generating creative design ideas and reduce time-to-market by leveraging collective intelligence and openness.

Therefore, with the advantages of CBDM stated before, collaborative design is one of CBDM's primary application areas.

3.2.1 Customer Co-Design

Traditionally, the collaborative design process was expensive and time consuming because most of the computer tools used for product design were generally stand-alone applications. While this has changes in the recent past, the CBDM concept may lead to further improvements of the original customer co-design model in order to improve individualization in product design. For example, customer co-design has been applied by organizations such as Google who developed a core product platform and provided users with APIs allowing them to develop more customized products. The value of customer co-design through the cloud are attributed to the increased preference fit, reduced design effort, and unique UX, i.e., I designed it myself [35]. Local Motors is pioneering this new customer co-design paradigm in the design and manufacturing field, allowing customers participate in making their unique cars, which the manufacturer can then produce to order. Thus, the design cloud enables various stakeholders (such as customers and designers) to participate actively throughout the entire product realization process, including product planning, concept development, embodiment design, detail design, testing and refinement, and production planning [28-29].

3.2.2 Collective Innovation

According to the Microsoft discrete manufacturing cloud computing survey [36], which polled most leading IT and business decision-makers, attentions are increasingly paid to innovative business capabilities uniquely delivered through the cloud, e.g., new ways to generate creative ideas. Collective innovation builds upon the concepts of collective intelligence and openness. It provides systematic strategies for CBDM regarding how individuals can be connected together solve the problems of organizational innovation. Slawsby & Rivera [37] discuss the concept of collective innovation, and suggest that organizations should harness the power of collective intelligence to develop new ideas, to prioritize them, and then to allocate resources to those ideas. Collective innovation is also related to many of the recent concepts such as user innovation [38] and open innovation [39] which have proven to be able to increase the innovation rate at many global enterprises. User innovation refers to the innovation carried out by the customers and end-users in a product development process [38]. Open Innovation refers to the use of inflow and outflow of knowledge across organizational boundaries to accelerate innovation [39].

As one of open innovation models, crowdsourcing is based on an idea competition, in which a design problem is outsourced to a general public or a large targeted group [17]. Take the fully autonomous vehicle design competition funded by DARPA as an example. The purpose of this project is to create the first fully autonomous ground vehicle capable of completing an off-road course within a limited time. In order to achieve effective design through crowdsourcing, it requires a new process of product ideation by leveraging the power of the crowd. The design cloud enables companies to quickly share and collect design ideas submitted from lead users and designers around the world. Hence, one of the implications of CBDM would be the ability to generate creative design ideas and reduce time-to-market by leveraging collective intelligence and openness.

3.3 Distributed Manufacturing

One implication of CBDM is the ability to dynamically adapt the amount of resources needed in order to satisfy the demand that is either predictable or unexpected. 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. 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. However, when those resources are not available, it takes time and money to duplicate them. This limitation is against the rapid scalability attribute of the CBDM concept.

One solution to this problem is to use manufacturing processes that do not require tools, such as additive manufacturing (AM) techniques. For instance, 3D printing, the fastest growing sector of additive manufacturing, utilizes "ink-jet" print-heads to dispense droplets of material to create parts in layers without tooling [67-68]. AM allows the cloud providers to be able to rapidly scale up and down manufacturing capacity in both directly and indirectly. Specifically, the direct approach is that 3D printing can be used to fabricate final production components and devices in order to achieve rapid scalability [69]. The indirect approach is that in the case where dedicated tools are required, AM fabricates those tools, which has been called "rapid tooling" [70]. Currently, AM is being used for production of customized or short-run, high-value products in order to avoid having to use tooling. In the future, AM should be used for an increasing number of applications, particularly as the technology and materials improve. For applications where direct AM is either not appropriate or not feasible, a rapid tooling approach may be suitable. Rapid tooling includes many different approaches including rapid patterns for casting (e.g., investment casting and sand casting), soft tooling (e.g., silicone moulds and epoxy moulds), and hard tooling (e.g., spray metal tooling, nickel electroformed tooling, and cast metal tooling). These techniques of rapid tooling offer the potential to address the issue of manufacturing scalability when dedicated hard tools are required [71].

Another implication of CBDM is the ability to coordinate distributed participants in the manufacturing cloud such that they can contribute to various capabilities necessary for manufacturing. One solution is to use cooperating intelligent entities to represent domain specific knowledge and make decisions through a negotiation mechanism [72]. Hao et al. [73] propose an internet enabled framework based on web services and agents for cooperative manufacturing management in the level of inter-enterprise, intra-enterprise, and shop floor. Frayret et al. [74] present a strategic framework for designing and operating agile networked manufacturing systems which enables collaborative planning, control, and management of manufacturing activities.

3.4 Knowledge Management Systems

A knowledge management system (KMS) refers to a system for creating knowledge repositories, improving knowledge access, and sharing as well as communicating information through collaboration, enhancing the knowledge environment and managing knowledge as an asset for an organization [40]. A KMS offers integrated services to cloud providers and consumers for creating, sharing, and reusing design and manufacturing knowledge in the DMCloud. Two selected perspectives associated with CBDM are presented in Section 3.2.1 and 3.2.2: (1) data mining and (2) semantic web.

3.4.1 Data Mining for CBDM and Intelligent Search

The vast amounts of product-related data in the DMCloud require intelligent and automated data analysis methodologies, which can provide decision support by discovering useful information and knowledge in the cloud. Data mining is an interdisciplinary field which discovers patterns from large data sets, involving artificial intelligence, machine learning, statistics, etc, and therefore becomes an extremely important technique for CBDM.

Traditionally, the primary applications of data mining include engineering design, manufacturing systems, job shop scheduling, fault diagnostics, quality assurance, and decision support systems [41]. Hamburg [42] applies data mining and augmented fuzzy methods to support product development. Agard & Kusiak [43] apply data mining algorithms for the design of product families, emphasizing on the analysis of functional requirements. Romanowski & Nagi [44] propose a data mining approach for generating parts and subassemblies using text mining, and extract design and configuration rules from the bills of material data using association mining. Kwak & Yih [45] present a data mining based production control approach for the testing and rework cell in a dynamic computer integrated manufacturing system. Rokach & Maimon [46] present a new feature set decomposition methodology that is capable of dealing with the data characteristics associated with quality improvement. Hui & Jha [47] investigate the application of data mining to extract knowledge from the customer service database for decision support and machine fault diagnosis. Wang [48] discusses the nature and implications of data mining techniques in manufacturing and product design, emphasizing on its definitions, techniques, and procedures. Harding et al. [41] present a comprehensive overview of the applications of data mining in manufacturing engineering.

Since introduced in 1980s by Pearl [49], Bayesian Networks (BNs) becomes increasingly popular to represent and discover knowledge. McNaught & Chan [50] discuss the potential application of BNs in manufacturing, with a focus on the development of an intelligent decision support system to aid fault diagnosis and correction during product system testing. Li & Shi [51] present a causal modeling approach to discover the causal relationships among the product quality and process variables in a rolling process by integrating manufacturing domain knowledge with the generic learning algorithm.

On the other hand, as more and more standard parts and assembly are used in products and various manufacturing processes become more and more mature, there is an increasing need for a search engine to help engineers search for design concepts, 3D models, and manufacturing processes at the conceptual design, embodiment design, and detail design phases, respectively. In addition, in order to better satisfy customer needs, innovation in product design needs to be supported by allowing designers to analyze and synthesize previous designs by finding designs that match a design concept they are pursuing. Today, you can easily find a 3D model in the Google 3D Warehouse, which is a collection of 3D models allowing people to find, share and store 3D models online. However, web search for product design and manufacturing processes is still in its infancy, and cannot satisfy the requirements of product design and manufacturing. We have a vision that the emerging DMCloud system has a potential for engineers to search for design and manufacturing solutions that match the design concept and corresponding manufacturing processes through shape or geometry based search methods rather than text-base methods [52].

Consequently, the success of applying data mining to CBDM plays a key role in discovering patterns from the DMCloud and helping cloud users quickly pinpoint designs and manufacturing processes that they are looking for.

3.4.2 Semantic Web Technology for CBDM

The increasing amount and growing complexity of product design requires methods and tools to represent product design and manufacturing related data in the DMCloud explicitly and formally [53-55]. The semantic web provides a common framework that allows data to be represented and reused across applications, enterprises, and community boundaries, which promotes common formats for data on the World Wide Web [56]. The purpose of the semantic web is enabling users to search and share information more easily by allowing the data from diverse sources to be processed directly by machines [57]. Zhang et al. [58] provide a state-of-the-art overview of research and development efforts in the area of internet/web enabled collaborative design and manufacturing solutions, and present a detailed case study on the implementation of web-based product information sharing and 3D visualization on the web. Dai et al. [59] present an interactive, three-dimensional, and web-based e-commerce system, through which consumers and partners can take part in product design and communicate their ideas with suppliers online.

Due to the fact that knowledge representation is one of the pillars of the semantic web, Lin & Harding [60] investigate ontology-based approaches for representing information semantics with a focus on how to support information autonomy that allows the individual team members to keep their own information models rather than requiring them to adopt standardized terminology. Kim et al. [61] present an information-sharing framework for assembly design based on ontology, which can explicitly represent semantics. Cho et al. [62] propose meta-concepts for ontology developers to consistently identify domain concepts of parts libraries and to systematically structure them. Lin et al. [53] propose a manufacturing system engineering ontology to enhance the semantic interoperability and reuse of knowledge resources. Li & Ramani [63] propose to use shallow natural language processing and domain-specific design ontology for design information retrieval. Fiorentini et al. [64] analyze the requirements for the development of structured knowledge representation models for manufacturing products using ontology. Lim et al. [65] propose a methodology for building a semantically annotated multi-faceted ontology for product family modeling. Gruber [66] argues that the role of semantic web includes: (1) capture; (2) store; (3) distribute; (4) communicate; and (5) create collective knowledge. He suggests that the social web and the semantic web should be combined in order to achieve truly collective intelligence. As a result, we believe that the development of semantic web can enable the DMCloud to represent design and manufacturing data explicitly, and therefore it helps designers and engineers share and reuse them effectively and efficiently.

We have discussed some major opportunities as stated above. In Section 4, we focus on a number of selected research issues associated with CBDM and potential strategies for addressing them.

4 SELECTED RESEARCH ISSUES AND STRATEGIES FOR SOLUTION

4.1 Management of CBDM System Complexity

4.1.1 Research Issue

A CBDM system is a large-scale, complex system, consisting of heterogeneous components such as hardware, software, data, people, and facilities. It becomes increasingly complex when these components are handled by multi-disciplinary distributed development teams. In order to design such a system, it is imperative to specify and integrate cloud components into the cloud system that satisfies its requirements and allocates the requirements to the system's components as well as the analysis of the flow of material and information.

4.1.2 Previous Work

Cloudonomics is a new discipline founded by Weinman [75], seeking to provide a rigorous approach to cloud benefit quantification based on calculus, statistics, system dynamics, economics, and computational complexity theory. Weinman [76] proposes an axiomatic cloud theory that can be used to rigorously develop cloud models, which may be the first step towards formal modeling of clouds. This formulism is based on set theory, metric spaces, measure theory, graph theory, function spaces, linear algebra, where a cloud is defined mathematically as a 6-tuple structure, satisfying five formal axioms: (1) common; (2) location-independent; (3) online; (4) utility; (5) on-demand. Cheng et al. [77] present the resource service transaction issue of cloud manufacturing and propose the comprehensive utility models that consider the revenue, time, and reliability for resource service provider, resource service demander, and resource service agent, respectively. Nan et al. [78] discuss the resource optimization problem in multimedia cloud to provide services with minimal response time or minimal resource cost. The datacenter is modeled as a node-weighted tree-like graph, and the queuing model is used to capture the relationship between the service response time and the allocated resources.

However, all of these models and theories address the modeling issue from the manufacturing operations perspective. Much remains to be done to model CBDM from design and manufacturing perspective, in particular, modeling design process and manufacturing performance (e.g., manufacturing cost, cycle time, machine utilization, and throughput).

4.1.3 Research Questions

Considering the limitations of current methods in Section 4.1.2, one research question related to managing system complexity is:

- *How can the CBDM system be modeled in order to capture its requirements, structure, functions, and behaviors?*

4.1.4 Potential Strategy: Model-Based System Engineering

One potential solution is modeling the CBDM system based on model-based system engineering methodology, which can systematically and formally capture the requirements, structure, behaviors, and constraints [79]. The system meta-model can also be integrated with the mathematical models to perform engineering analysis and simulation. By capitalizing on modeling and simulation, it helps to synthesize design and manufacturing alternatives, evaluate performance, select alternatives, and finally configure optimal design and manufacturing solutions. Consequently, modeling and analysis of the CBDM system enables managers and engineers to embrace CBDM paradigm shift with more confidence.

4.2 Design Search Engine

4.2.1 Research Issue

Contemporary product design and manufacturing is a knowledge-intensive process undertaken by distributed and multi-disciplinary organizations. Due to the vast amount of data and information available in the cloud, engineers are facing a significant challenge in quickly find what they are looking for such as material selection, conceptual designs, and manufacturing processes.

4.2.2 Previous Work

Currently, most search engines for design and manufacturing solutions are based on text keywords. Some advanced web-based search engines have been developed that support queries based on 3D sketches, 2D sketches, and 3D shapes [52]. However, none of them has the capability of searching for designs at the level of conceptual, embodiment, and detail designs, as well as manufacturing processes, allowing engineers to focus on product innovation rather than trivial 3D modeling.

4.2.3 Research Questions

Taking the drawbacks of current approaches into account, three key research questions need to be addressed are as follows:

- *What key attributes should be defined in order to measure the performance of a design search engine?*
- *What techniques could be used by a design search engine in order to help cloud users search for design and manufacturing solutions more effectively and efficiently?*
- *How can the negotiation process between service providers and consumers be modeled in order to select the optimal solution among the search engine results?*

4.2.4 Potential Strategy: Bayesian Networks and Joint Decision Making

One possible strategy for solution is to apply BNs to product design and manufacturing information retrieval. BNs can discover the casual relationships and have been proven to be a good model to manage uncertainty. Hence it can be used to match cloud users' queries to relevant designs and manufacturing processes in a database. In addition, the negotiation process between cloud providers and consumers can be described as a bilateral interaction process, which is essentially a process of joint decision making with partial information exchange [80].

4.3 Cloud-Enabled Human-Computer Interaction

4.3.1 Research Issue

As more and more computers and other mobile devices (e.g., mobile phones and personal digital assistants) get connected to the cloud, it necessitates an effective way of human-computer interaction (HCI) which can improve UX by providing easy accesses to the cloud services and promoting comprehension between humans and computers. With the advance of CBDM, HCI shows its increasing importance in accommodating complicated interactions between users and computers in the cloud, in particular, coordination, communication, and cooperation, through key characteristics of CBDM such as ubiquitous network access.

4.3.2 Previous Work

Previous efforts aimed at exploring various key components of experience and addressing functionality and usability of individual products. Specifically, classical research focuses on three perspectives including (1) interactive product's instrumental value, (2) emotion and affective computing, and (3) experience [81]. No consideration is given to the rigorous formulation, and none of the current research fully addresses the design of UX.

4.3.3 Research Questions

Considering the challenge posed in 4.3.1 and limitation of previous work, three research questions arise:

- *What attributes or dimensions should be defined for measuring UX in order to effectively capture UX in the context of CBDM?*
- *How to quantify those identified dimensions? And what is the relationship between them and a CBDM system?*
- *How to design the CBDM system in order to enable technical coordination, communication, and cooperation between humans and computers in the cloud?*

4.3.4 Potential Strategy: Activity-Based Affective Modeling

In the context of CBDM, UX can be formulated as a set of dynamic states, representing a series of activities and the dynamics of human-computer interaction in the cloud. Activity-based UX can capture various dimensions of UX of cloud consumers and the casual links of multiple activities [82]. In order to design a CBDM system that enables better coordination, communication, and cooperation between cloud consumers and computers, the Petri net formulism can be utilized to model the affective aspect of UX of cloud consumers.

4.4 Cloud-Enabled Human-Human Collaboration

4.4.1 Research Issue

Traditionally, it has been assumed that generating design ideas and implementing them was the exclusive task of design and manufacturing firms. In the context of CBDM, while customers, engineers, and other participants involved more and more in the design process, it necessitates a need for CBDM to change the traditional design process, starting with eliciting customer needs, and then transforming them to functional requirements, design parameters, and process variables. The major problem of this design process is that it takes place purely inside the company in series without incorporating customer feedbacks into the iterative design process in parallel.

In order to leverage the wisdom of customers and other participants, it is essential that CBDM be integrated with new ways of design processes that facilitate collaboration between internal designers, developers and external participants.

4.4.2 Previous Work

Previous research has shown that some of the most important and innovative products and processes tend to be developed by lead users, either user firms or individual end users [35, 83]. Specifically, Franke et al. [35] formulated a lead user theory as a set of four interrelated tested hypotheses. On the other hand, Howe (2008) [84] and Brabham [85] discussed the potential of crowdsourcing to help companies to leverage the creative wisdom of crowds. However, the factors determining collaboration in developing innovations between designers inside firms and customers outside firms and information asymmetry have not been properly addressed yet. In addition, while the web-based crowdsourcing has been developed for years, it has not been integrated with engineering tools and design evaluation systems but rather implemented as an online communication channel.

4.4.3 Research Questions

Relevant research questions emanating from the challenges brought forth in Section 4.4.2 are as follows:

- *What type of customer co-design framework should CBDM adopt in order to respond the real time customers' feedbacks effectively and efficiently at different product development phases? And how to transfer design capability to users?*
- *How to access the "sticky" user information in the cloud in order to transfer customer requirements to design parameters?*
- *What type of collaborating mechanisms should CBDM adopt in order to provide an effective interactive information channel between professionals inside a company and crowds outside it?*
- *What tools should be designed in order to promote human-human collaboration? And how to design them?*

4.4.4 Potential Strategy: Customer-Centered Co-Design, Swarm Intelligence and Social Networking Platform

1. Customer-Centered Co-Design:

Customer-centered co-design is a means of transferring customer needs into design parameters effectively and efficiently. In order to access the "sticky" user information, customer-centered co-design approach enables cloud providers to search for the design space and proactively work on the design alternatives. It helps cloud providers communicate interactively with cloud consumers at different stages of product realization process. In addition, product innovation can also be fostered through the voice of customers.

2. Swarm Intelligence:

Swarm intelligence is a population-based stochastic technique used in combinatorial optimization problems. The idea is that collective intelligence can arise from the interactions of relatively simple individuals [86]. Two key aspects of swarm intelligence are self-organization and stigmergy. Self-organization, a process where a collaboration pattern based on attraction and repulsion principles appears in an open system without a central authority, can describe the process in which crowds can be guided and managed without a centralized control. Stigmergy, a mechanism of spontaneous indirect coordination, can be the communication mechanism among a set of distributed agents in the cloud.

3. Social Networking Platform:

Most valuable information and insights perhaps are gained by interacting with customers in an interactive fashion. Hence, integrating social network effects in product design is becoming inevitable. In order for a cloud service provider to quickly recognize customer needs in a cost-effective fashion, a social network platform built in the DMCloud would be a promising solution. With the social networking platform, interactive information sharing among customers over the cloud becomes very convenient. Therefore, such a platform helps designers capture, analyze and manage customer information, and identify a product or service with largest potential market share.

5 CLOSING REMARKS

In this paper, the concept of cloud-based design and manufacturing (CBDM) was presented. We proposed a definition and provided a vision for CBDM. The paper provides a brief survey of related research and associated technologies with a focus on the opportunities enabled by CBDM such as exploring the potential of utilizing cloud computing for selected aspects of collaborative design, distributed manufacturing, collective innovation, data mining, semantic web technology, and virtualization. We also identified a number of key research issues that need to be further examined and potential strategies for solution. The concept of CBDM will be constantly evolving. Development of the theoretical framework for CBDM will become increasingly important as moving to the next generation of design and manufacturing.

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