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Enhancing the Product Realization Process With Cloud-Based Design and Manufacturing Systems

The rise of cloud computing is radically changing the way enterprises manage their information technology 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 (CAD) 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. [DOI: 10.1115/1.4025257]

Keywords: cloud computing, cloud-based design, cloud-based manufacturing, design and manufacturing cloud, collaborative design, distributed manufacturing, product development

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 to enhance product design and manufacturing from the perspective of information and resource sharing [1]. As manufacturing enterprises become increasingly concerned with meeting the dynamic requirements of a global marketplace, capturing, and sharing product-related information and knowledge along with reusing design and manufacturing resources in globally distributed settings has become a key challenge.

In recent years, the information technology (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*, and (5) *location-independent resource pooling* [2]. One particular benefit is that cloud computing allows for faster and more flexible development and implementation of IT solutions compared to traditional infrastructure and service models. Cloud computing is widely accepted in the IT field. However, it has just emerged on the horizon of other application domains such as computer-aided design and manufacturing. Consequently, new research investigating the potential of cloud computing technology for the field of product design and manufacturing is needed. In particular, a comprehensive definition of CBDM is needed, along with theoretical frameworks and prototypes that can guide 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]. Examples of research issues not yet fully understood include (1) mathematical models of product design search [13], (2) social networking perspective for product design [3,14], (3) user innovation, customer co-creation, and user experience (UX) design [15,16], and (4) the power of crowdsourcing for 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 exchange information securely to enhance effectiveness and efficiency of team collaboration. Another example is Fujitsu's 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 to address the following questions:

- What is cloud-based design and manufacturing, and how is it different from previous paradigm shifts?
- What new opportunities may be enabled through CBDM?
- What are potential obstacles in implementing CBDM and potential strategies for overcoming them?

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

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The remainder of this paper is organized as follows. In Sec. 2, we briefly present our vision of CBDM. In Sec. 3, we discuss how CBDM may impact the future development of (1) collaborative design, (2) knowledge-based systems, and (3) distributed manufacturing (see Fig. 1). In Sec. 4, we shift the focus to selected research issues related to CBDM and its potential application fields. Specifically, we address (1) the management of CBDM complexity; (2) future design search engines; (3) cloud-based human-computer interaction, and (4) human-to-human collaboration through the cloud. Section 5 presents the development of our prototype system. Section 6 concludes the paper.

2 Cloud-Based Design and Manufacturing

2.1 Existing Definitions of Cloud Computing. In preparation of providing a definition for CBDM, we first provide an overview of existing definitions for the paradigm 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 [21].”
- “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 [23].”
- “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 [24].”
- “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 [25].”

2.2 The Evolution of Cloud Computing. In Sec. 2.1, a number of widely used definitions of cloud computing were 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 during the 1960s [26]. 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 derives from pre-existing and well established concepts such as utility computing, grid computing, virtualization, service oriented architecture, and software-as-a-service [27,92]. 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 [26]. Another milestone is that Ian Foster and Carl Kesselman [27] 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 [28]. Since cloud and grid computing share a similar vision, Foster et al. identified the main differences between grid computing and cloud computing. The greatest difference is that cloud computing addresses Internet-scale computing problems by utilizing a large pool of computing and storage resources, whereas grid computing is aimed at large-scale computing problems by harnessing a network of resource-sharing commodity computers and dedicating resources to a single computing problem [23,29].

Compared to grid computing, we envision that cloud computing would be the most promising underlying concept that can be borrowed by 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 [27]. 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 by Tao et al. [30]. The architecture, core enabling technologies, typical characteristics for cloud manufacturing, and the relationships between cloud computing and cloud manufacturing have been described by Xu [31]. Xu [31] 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

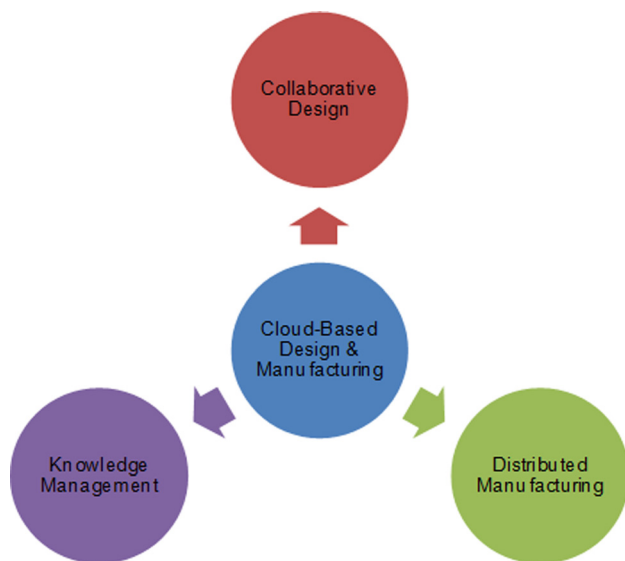


Fig. 1 Research opportunities related to CBDM

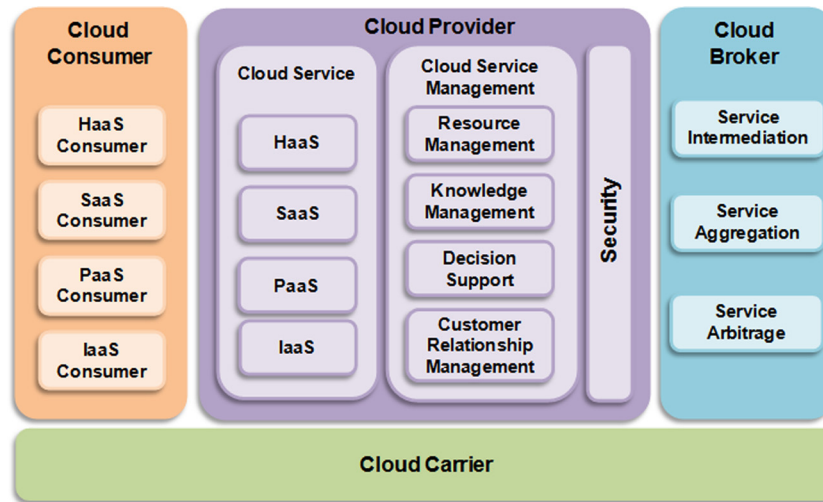


Fig. 2 CBDM conceptual reference model adapted from Ref. [21]

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 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 can foster knowledge and resource sharing and rapid product development with reduced cost through a social networking and negotiation platform between service providers and consumers. A design and manufacturing cloud (DMCloud) is a type of collaborative and distributed system consisting of a collection of interconnected physical and virtualized service pools of design and manufacturing resources (e.g., CAD/CAM tools, computer-aided manufacturing and finite element analysis (FEA) models, assembly lines, and CNC machine tools) as well as intelligent search capabilities for design and manufacturing solutions.

In addition, the essential characteristics of CBDM [32], including on-demand self-service, ubiquitous network access, rapid scalability, resource pooling, and virtualization, are articulated in more detail as follows:

- (1) *On-demand self-service*: A customer or any other individual participating in the DMCloud 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 [33,34]. In order to easily reach such a communication capability, broad, and global network access is required. The DMCloud can provide such access to the network where DMCloud consumers reside through multiple tools, e.g., mobile phones and personal digital assistants. CBDM allows various stakeholders (e.g., customers, designers, and 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 DMCloud system allows these 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 DMCloud provider's design and manufacturing resources are pooled to serve service 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 FEA program packages). The CBDM model enables convenient and on-demand network access to such a shared pool of configurable manufacturing resources [35]. The real time sensor inputs, capturing the status and availability of manufacturing resources, ensures effective, and efficient DMCloud resource allocation.
- (5) *Virtualization*: The DMCloud provides a virtual environment through the simulation of the software and/or hardware upon which other software runs [21]. 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 (see Fig. 2) is proposed in addition to the CBDM definition. Mirroring the NIST cloud computing conceptual reference model [21], our CBDM conceptual reference model defines a set of actors, activities, and functions involved in the DMCloud. Four major actors are defined in the CBDM reference model: (1) cloud consumer, (2) cloud provider, (3) cloud broker, and (4) cloud carrier [21]. Table 1 lists the four major actors and their corresponding definitions. The interaction and communication among the actors in the DMCloud is shown in Fig. 2. A DMCloud consumer may request cloud services, i.e., *cloud software-as-a-service (SaaS)*, *cloud platform-as-a-service (PaaS)*, *cloud infrastructure-as-a-service (IaaS)*, and *cloud hardware-as-a-service (HaaS)*, from a service provider directly or via a cloud broker. A cloud provider provides DMCloud services through DMCloud service management, including resource management, knowledge management, decision support, and customer relationship management. A DMCloud provider must also manage security, ranging from physical security to virtual security. A cloud broker manages

Table 1 Actors in the CBDM conceptual reference model adapted from Ref. [21]

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

DMCloud 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 DMCloud services available to a DMCloud service consumer. As shown in Fig. 3, a knowledge management system (KMS) is the core of the DMCloud, which creates knowledge repositories based on its data and knowledge bases. Further, the KMS can foster knowledge and resource sharing among service providers and consumers through an intelligent search engine, and a series of negotiation mechanisms. For example, the intelligent search engine should help to identify who the key service providers and consumers are, which service providers know what, which service providers know which providers/consumers, and more importantly what resources and information they have. Since both DMCloud service providers and consumers try to find an optimal solution, (i.e., minimal cost and lead time, and higher service quality), a negotiation platform together with a series of negotiation mechanisms are needed to support negotiation processes in the DMCloud.

2.4.1 Software-as-a-Service (SaaS). SaaS delivers software applications, e.g., CAD/CAM, FEA tools, and enterprise resource planning software, to DMCloud consumers. The DMCloud consumers are able to install and run engineering and enterprise software through a web-based or thin client interface without purchasing full software licenses. The cloud services offered by Dassault Systems and Autodesk are examples among engineering analysis applications and allow remote execution of 3D software and high performance discrete computing environments [19,36]. The consumers of SaaS can be designers, engineers and managers, who need access to software applications.

2.4.2 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].

2.4.3 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.

2.4.4 Hardware-as-a-Service (HaaS). HaaS delivers hardware sharing services, e.g., machine tools, hard tooling, and manufacturing processes, to service consumers through the DMCloud. The DMCloud consumers are able to rent and release hardware from providers without purchasing them. Cubify.com is a good example, which allows service consumers to produce parts through any mobile device using their online 3D printing service without purchasing 3D printers [37]. The consumers of HaaS could be either engineers or end users, who may utilize manufacturing hardware.

3 Potential CBDM Application Fields

In this section, we explore 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.

3.1 Benefits of CBDM. The CBDM concept originated from rich cross-fertilizations between cloud computing, collaborative engineering design, distributed manufacturing, collective innovation, data mining, semantic web, virtualization, and knowledge-based systems. Consequently, based on the definition of CBDM, its essential characteristics and reference model, the following aspects make CBDM unique:

- An integrated technical and social networking platform, thereby enabling effective human-human collaboration within cross-functional, multidisciplinary, and geographically distributed work environments.
- 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.
- An ability to dynamically adapt the amount of computing resources and hardware needed, thereby satisfying the demand that is either predictable or unexpected.
- 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 CBDM and Collaborative Design. With the faster and higher demands of new and improved designs, companies are participating more often in global design chains and collaborations in order to gain competitive advantages [1,38]. Research in

Table 2 Major Activities in the CBDM conceptual reference model adapted from Ref. [21]

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 DMCloud.
PaaS	Uses the design and manufacturing platform in the DMCloud, as well as interacts and communicates with other users.	Provides and manages the DMCloud platform, as well as develops tools for consumers.
IaaS	Uses computing resources, internet services in the DMCloud.	Provides and manages computing resources, internet services in the DMCloud.

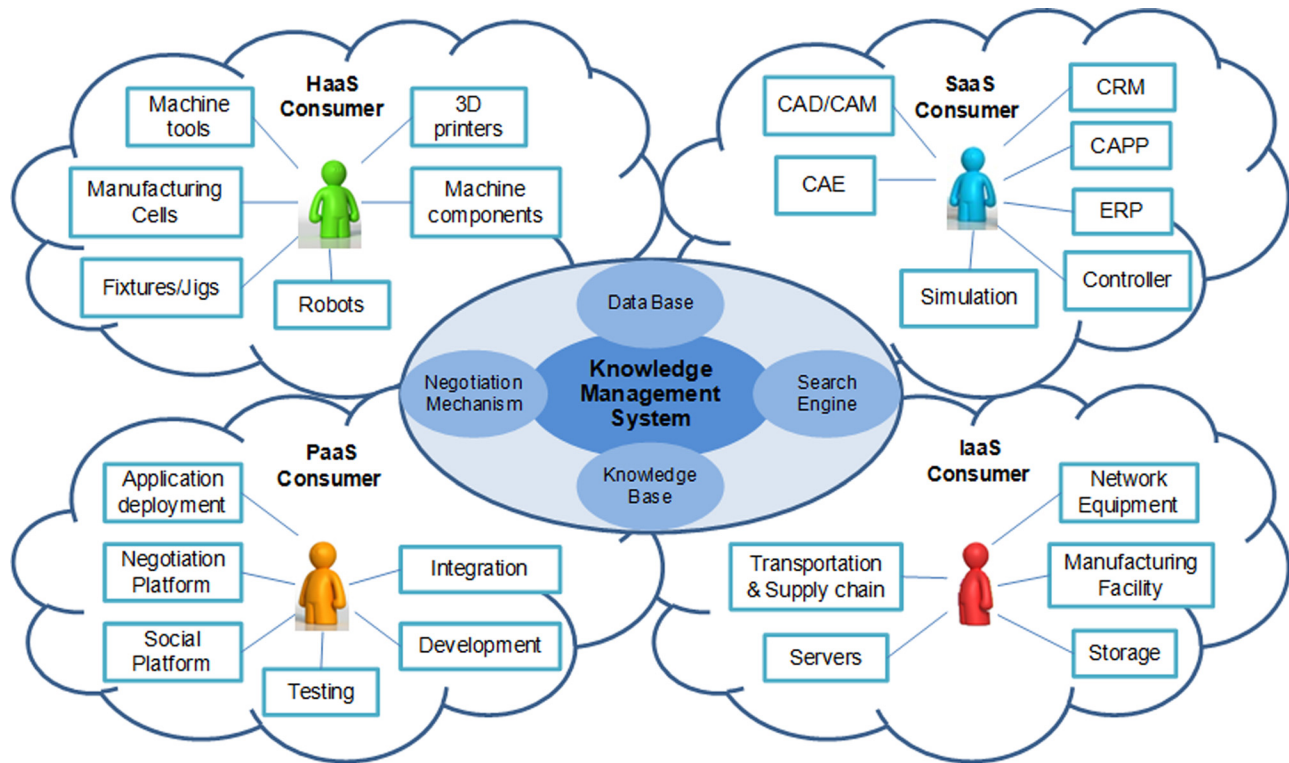


Fig. 3 CBDM example services

collaborative design is focused on helping designers generate creative ideas and collaborate more efficiently and effectively by sharing design and manufacturing resources through formal and informal interactions [39,40]. So far, the most important research avenues in collaborative design are web-based design and agent-based design [94]. 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 [41]. 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 [41]. However, two research issues have not yet been fully addressed:

- An approach that enables various stakeholders (such as customers and designers) to participate in various design phases in collaborative design.
- An approach that can help generating creative design ideas and reduce time-to-market by leveraging collective intelligence and openness.

Therefore, with the benefits 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 changed recently, 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 application programming interface (APIs) allowing them to develop more customized products. The value of customer co-design through the DMCloud is attributed to the increased preference fit, reduced design effort,

and unique UX, i.e., I designed it myself [42]. Local motors is pioneering this new customer co-design paradigm in the design and manufacturing field, allowing customers to 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 [33,34].

3.2.2 Collective Innovation. According to the Microsoft discrete manufacturing cloud computing survey [43], which polled most leading IT and business decision-makers, attention is increasingly paid to innovative business capabilities uniquely delivered through the DMCloud, 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 to solve the problems of organizational innovation. Slawsby and Rivera [44] 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 [45] and open innovation [46] 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 [45]. Open Innovation refers to the use of inflow and outflow of knowledge across organizational boundaries to accelerate innovation [46].

As one of the open innovation models, crowdsourcing is based on an idea competition, in which a design problem is outsourced to the general public or a large targeted group [17]. Take the fully autonomous vehicle design competition funded by Defense Advanced Research Projects Agency (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, a new process of product ideation is required 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 CBDM and 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 DMCloud is a huge shared service pool of design and manufacturing resources, it is possible for 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 [47,48]. AM allows the DMCloud providers to be able to rapidly scale up and down manufacturing capacity 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 [49]. For indirect approaches where dedicated tools are required, AM fabricates those tools, which has been called “rapid tooling” [50]. 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 [51].

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 [52]. Hao et al. [53] propose an internet enabled framework based on web services and agents for cooperative manufacturing management in the level of interenterprise, intra-enterprise, and shop floor. Frayret et al. [54] present a strategic framework for designing and operating agile networked manufacturing systems which enables collaborative planning, control, and management of manufacturing activities.

3.4 CBDM and Knowledge Management Systems. A KMS refers to a system for creating knowledge repositories, for improving knowledge access, for sharing as well as communicating information through collaboration, for enhancing the knowledge environment, and for managing knowledge as an asset for an organization [55]. A KMS offers integrated services to DMCloud serv-

ice providers and consumers for creating, sharing, and reusing design and manufacturing knowledge in the DMCloud. Two selected perspectives associated with CBDM are presented in Secs. 3.4.1 and 3.4.2: (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 DMCloud. 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 [56]. Hamburg [57] applies data mining and augmented fuzzy methods to support product development. Agard and Kusiak [58] apply data mining algorithms for the design of product families, emphasizing on the analysis of functional requirements. Romanowski and Nagi [59] 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 and Yih [60] present a data mining based production control approach for the testing and rework cell in a dynamic computer integrated manufacturing system. Rokach and Maimon [61] present a new feature set decomposition methodology that is capable of dealing with the data characteristics associated with quality improvement. Hui and Jha [62] investigate the application of data mining to extract knowledge from the customer service database for decision support and machine fault diagnosis. Wang [63] discusses the nature and implications of data mining techniques in manufacturing and product design, emphasizing its definitions, techniques, and procedures. Harding et al. [56] present a comprehensive overview of the applications of data mining in manufacturing engineering.

Since introduced in 1980s by Pearl [64], Bayesian networks (BNs) have become increasingly popular to represent and discover knowledge. McNaught and Chan [65] 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 and Shi [66] 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-based methods [67].

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 [68–70]. 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 [71]. 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 [72]. Zhang et al. [73] 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. [74] 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 and Harding [75] 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. [76] present an information-sharing framework for assembly design based on ontology, which can explicitly represent semantics. Cho et al. [77] propose meta-concepts for ontology developers to consistently identify domain concepts of parts libraries and to systematically structure them. Lin et al. [68] propose a manufacturing system engineering ontology to enhance the semantic interoperability and reuse of knowledge resources. Li and Ramani [78,79,80] propose to use shallow natural language processing and domain-specific design ontology for design information retrieval. Fiorentini et al. [81] analyze the requirements for the development of structured knowledge representation models for manufacturing products using ontology. Lim et al. [82,83] propose a methodology for building a semantically annotated multifaceted ontology for product family modeling. Gruber [84] 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 the semantic web can enable the DMCloud to represent design and manufacturing data explicitly, and therefore it helps designers and engineers share and reuse these data effectively and efficiently.

4 An Overview of Selected Research Issues

4.1 Modeling CBDM Systems.

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 multidisciplinary distributed development teams [86]. In order to design such a system, it is imperative to specify and integrate DMCloud components into a DMCloud system that meets requirements, to allocate the requirements to the system's components, and to analyze the flow of material and information.

4.1.2 Previous Work. Cloudonomics is a new discipline founded by Weinman [85] seeking to provide a rigorous approach to cloud benefit quantification based on calculus, statistics, system dynamics, economics, and computational complexity theory [86]. Weinman [87] 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 formalism is based

on set theory, metric spaces, measure theory, graph theory, function spaces, and 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. [88] present the resource service transaction issue of cloud manufacturing and propose 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. [89] discuss the resource optimization problem in multimedia clouds 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 processes 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 Sec. 4.1.2, four research questions related to managing system complexity are:

- (1) *How can the DMCloud system be modeled in order to capture its requirements, structure, functions, and behaviors?*
- (2) *How to model the DMCloud system at the system level in order to understand complex collaboration patterns?*
- (3) *What metrics should we use to measure such social and technological networks?*
- (4) *How to detect communities/clusters and key actors in the DMCloud network?*

4.2 Design Search Engine

4.2.1 Research Issue. Contemporary product design and manufacturing is a knowledge-intensive process undertaken by distributed and multidisciplinary organizations. Due to the vast amount of data and information available in the DMCloud, engineers are facing a significant challenge to 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 [67]. 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:

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

4.3 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 DMCloud, effective methods of human-computer interaction (HCI) are required which can improve UX by providing easy access to 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 DMCloud, in particular, coordination, communication, and cooperation, through key characteristics of CBDM such as ubiquitous network access [80].

4.3.2 Previous Work. Previous efforts aimed at exploring various key components of experience and addressing functionality and usability of individual products [82]. Specifically, research focused on three perspectives including (1) interactive product's instrumental value, (2) emotion and affective computing, and (3) experience [90]. No consideration is given to rigorous formulation, and none of the current research fully addresses the design of UX.

4.3.3 Research Questions. Considering the challenge posed in Sec. 4.3.1 and limitation of previous work, three research questions arise:

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

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 types 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 [42,91,92]. Specifically, Franke et al. [42] formulated a lead user theory as a set of four interrelated tested hypotheses. On the other hand, Howe [93,94] and Brabham [95] 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 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:

- (1) *What type of customer co-design framework should CBDM adopt in order to respond to real time customers' feedback effectively and efficiently at different product development phases? And how to transfer design capability to users?*
- (2) *How to access the "sticky" user information in the DMCloud in order to transfer customer requirements to design parameters?*
- (3) *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?

- (4) *What tools should be designed in order to promote human-human collaboration? And how to design them?*

5 Development of a Prototype System

In this section, we describe various details of our prototype DMCloud, which was developed for the DARPA and their Manufacturing Experimentation and Outreach (MENTOR) project. The implementation of our prototype served as a DMCloud pilot study and represents our first attempt at building a real-world CBDM system. The objective of our prototype system and the MENTOR project is to deploy and integrate design and manufacturing resources such as CAD software and additive manufacturing equipment into 1000 high schools across the United States. The goal is to engage students from these participating high schools in a series of collaborative design and distributed manufacturing experiments. At present, the prototype facilitates CBDM by enabling users across clusters of schools to (1) learn modern CAD and analysis software tools to design novel devices; (2) practice collaborative design and distributed manufacturing; (3) utilize a distributed manufacturing infrastructure; and (4) understand collaborative design through technical and social networking systems.

5.1 Overview of DMCloud. The DMCloud can be public, private or hybrid. Our prototype developed at Georgia Tech for the MENTOR project is currently implemented as a private DMCloud, but it can be easily extended to be a public DMCloud. It builds upon an integrated collaborative design and distributed manufacturing infrastructure with tools such as CNC machine tools, AM machines (i.e., 3D printers), and engineering software through a partnership constituting a network of high schools dispersed across the United States. This enables students to learn and participate in product realization as a continuum of design, analysis, simulation, prototyping, and manufacturing activities. In this pilot DMCloud, SaaS provides students with access to web-based software applications over the Internet and hence eliminates the need to install and run software on their own computers. Engineering design, analysis, and simulation tools from Dassault Systems are integrated into the DMCloud. PaaS provides students a ubiquitous computing environment with a centralized interfacing server. Specifically, our DMCloud is constructed from existing technologies such as Sakai, Moodle, Drupal, Wiggio, Google Docs, etc., Sakai, for example, is an open-source, Java-based service-oriented software platform, providing a distributed collaboration and learning environment [96]. A set of tools is provided to help students learn basic design for manufacturing concepts, apply the concepts to their designs, and perform collaborative design and distributed manufacturing during the decision making process. For example, a basic knowledge base, built in our DMCloud, can help students select appropriate machines and materials based on the specifications of different machines and various material properties. IaaS provides students with a platform virtualization environment along with high performance computing servers and storage space. HaaS provides students with a heterogeneous hardware environment including 3D printers, milling machines, lathes, laser cutters, and other CNC machines.

5.2 System Architecture of DMCloud. As shown in Fig. 4, the proposed system architecture of our DMCloud can be captured by a five-layer conceptual model that defines the overall structure of the DMCloud, including (1) user, (2) centralized portal, (3) application, (4) service, and (5) resource layers. The representation of the system architecture is a mapping mechanism between product design and manufacturing processes, which links the product designs to the corresponding manufacturing processes (as shown by dotted red arrows). The centralized portal enables cloud-based human-computer interaction, facilitates effective data

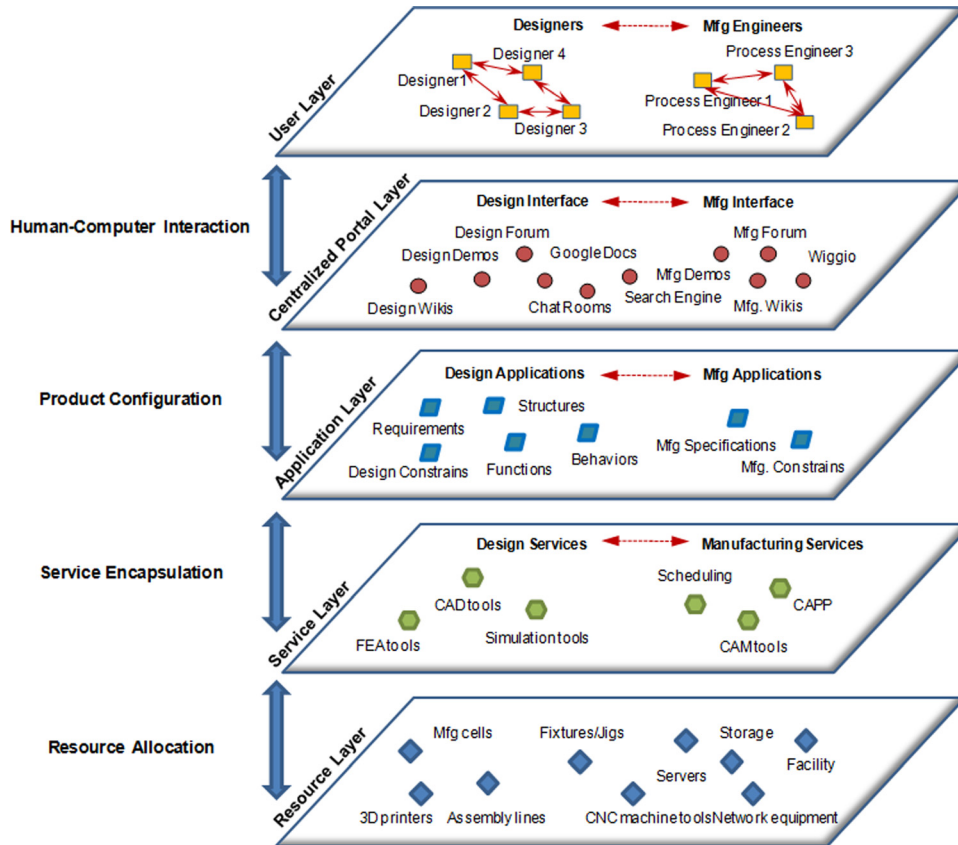


Fig. 4 System architecture of the DMCloud system

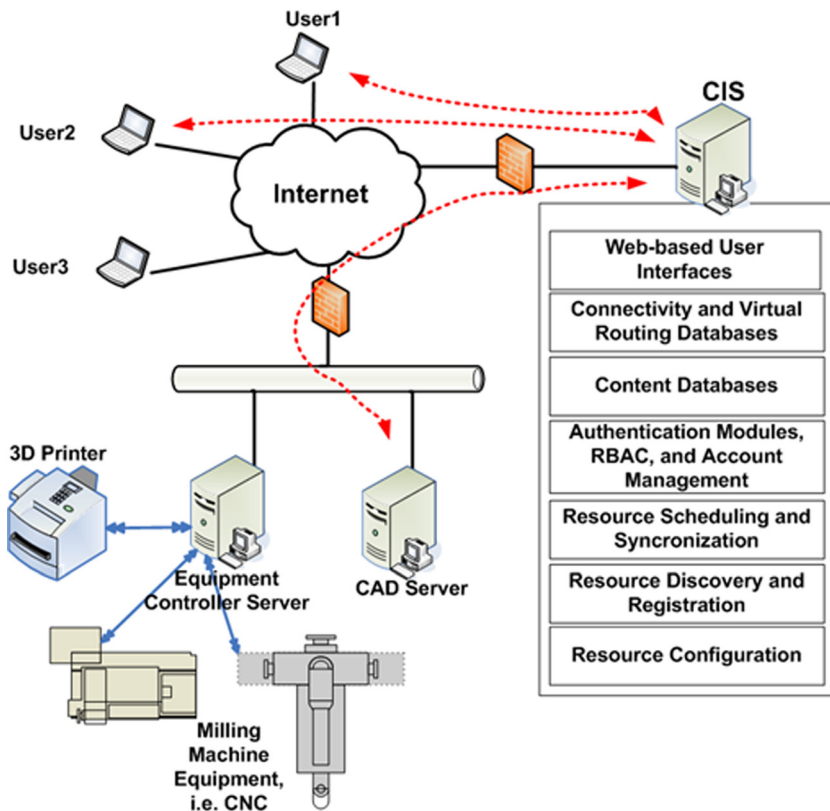


Fig. 5 Workflow of the DMCloud system [97]

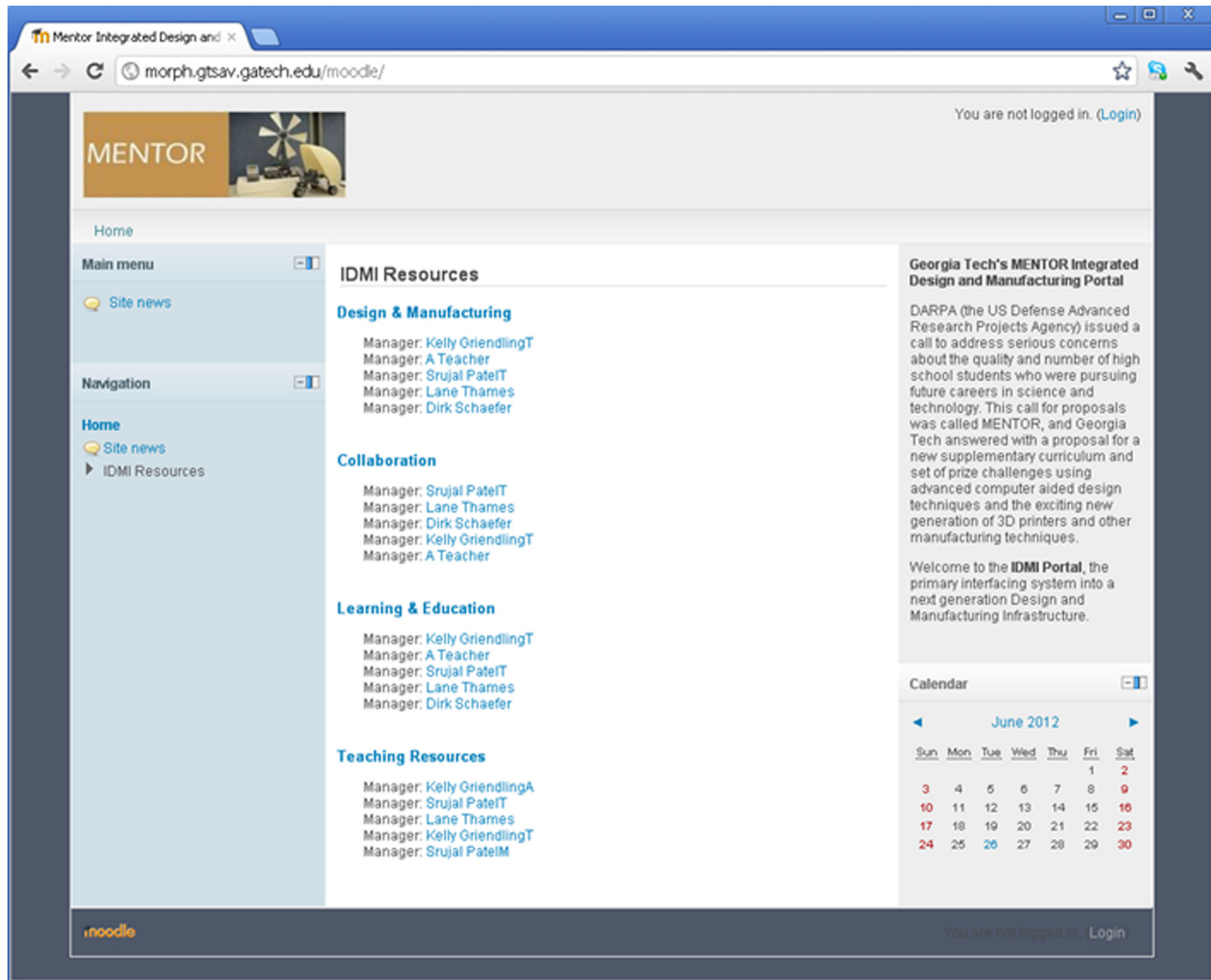


Fig. 6 Main menu of the DMCloud portal

collection, and provides seamless integration of resources and services into the overall DMCloud. A product configuration process transforms the data collected from the centralized portal layer to conceptual designs and high-level manufacturing specifications and constraints. Service encapsulation transforms conceptual designs to embodiment and detail designs as well as consolidates all services based on conceptual designs from the application layer. Resources are then allocated according to the detailed designs from the service layer. The detailed functions of each layer are illustrated as follows:

- (1) **User layer:** Encompasses key actors in the DMCloud, i.e., product designers and manufacturing engineers, who form the social network within and/or across service providers.
- (2) **Centralized portal layer:** The key function of this layer is to provide a centralized interface (i.e., product design and manufacturing process interfaces) to cloud providers and consumers, which facilitates communications among designers and manufacturing engineers as well as coordination between them. Specifically, the centralized portal provides forums, Wikis, chat rooms, and demos for better communication. It also provides social networking tools such as Wiggio as well as document sharing tools like Google Docs for sharing design and manufacturing information.
- (3) **Application layer:** The key function of this layer is to transform the information acquired via the centralized portal to product requirements, structures, functions,

behaviors, design constraints, as well as corresponding manufacturing specifications and constraints.

- (4) **Service layer:** The key function of this layer is to provide various engineering tools, such as CAD/CAM/CAE/CAPP, simulation, and scheduling tools. Service layer delivers detailed designs and manufacturing processes based on the information from the application layer. For example, a specific part of a product is associated with a routing in the process. A part can be decomposed to a set of design attributes (e.g., design features and constraints). Similarly, a process routing can be decomposed to several manufacturing attributes (e.g., cycle time and type of work center).
- (5) **Resource layer:** Encompasses all the product design and manufacturing process related resources available in the DMCloud such as fixtures/jigs, 3D printers, CNC machine tools, manufacturing cells, assembly lines, facility, servers, network equipment, etc.

5.3 Workflow and Services in the DMCloud. The overall workflow of our DMCloud is illustrated in Fig. 5. Our DMCloud consists of a centralized interfacing server (CIS) incorporated with the Moodle learning management system [96]. As shown in Fig. 5, geographically dispersed cloud users (i.e., students) can collaborate on a design project by utilizing our DMCloud services such as CAD design tools (e.g., CATIA), 3D printers, and CNC milling machines. For example, our DMCloud provides users

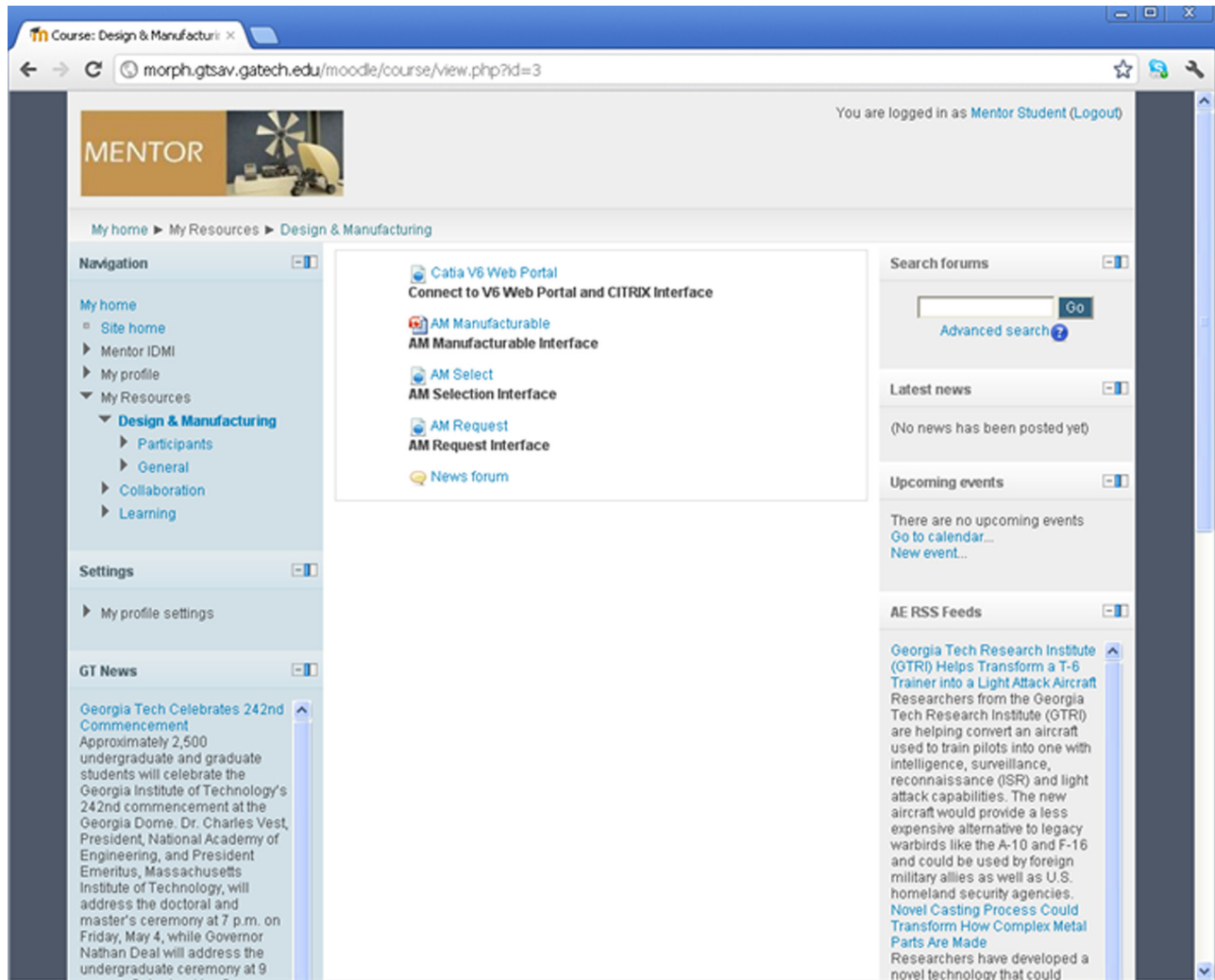


Fig. 7 Design and manufacturing module of the DMCloud portal

CATIA access to design 3D models through the online portal as shown in Figs. 6 and 7. When a part design is ready to fabricate, STL files will be generated and submitted to one of the idle 3D printers in the DMCloud for actual production. The CIS also provides applications for resource management (e.g., resource scheduling, resource configuration, and synchronization), and knowledge management (e.g., manufacturability analysis).

Some of the DMCloud services that are provided by our DMCloud include the following:

- (1) **Cloud-based design:** The commercial Dassault Systems suite of design and analysis tools such as CATIA and Simulia are integrated in the DMCloud, which enable commercial CAD systems and engineering analysis capabilities, as well as collaboration.
- (2) **Cloud-based manufacturing:** Several manufacturing services (see Fig. 7) were developed to aid in the transition from CAD models to fabrication with AM technology as follows:
 - (a) AM-Select: Allow students to interactively identify feasible AM systems and materials available within our DMCloud.
 - (b) AM-Advertise: Allow independent manufacturing subsystems to advertise service availability and associated service usage parameters.
 - (c) AM-Request: Allow service consumers to request AM services and other DMCloud resources from service providers.
 - (d) AM-Manufacturable: Enable manufacturability analysis such as whether a specific part is manufacturable on a specific machine (i.e., a 3D printer). If not, it will provide information about what properties of the part prevent manufacture.
 - (e) AM-DFAM: Provide design for additive manufacturing data and knowledge bases.
 - (f) AM-Teacher: Assist users with tutorials, service wizards, videos, and other learning content.
- (3) **Social networking tools:** As shown in Fig. 8, several social networking tools (e.g., chat rooms, forum, and Wiggio) are integrated in the DMCloud to facilitate collaboration among participants during the product realization process. For example, users can easily have real-time feedback from other participants through chat rooms. A design forum is utilized as another effective way for users to learn and share via collaboration. In addition, the Wiggio service allows users to host virtual meetings and video conference calls, to create to-do lists and assign tasks, and to upload and manage files in shared folders.

5.4 Discussion. Since an ideal CBDM system does not exist yet, our motivation for developing the DMCloud was to lay a foundation allowing us to investigate the research issues, such as those mentioned in Sec. 4, through design and manufacturing experiments in the real world. As a first step to understand the

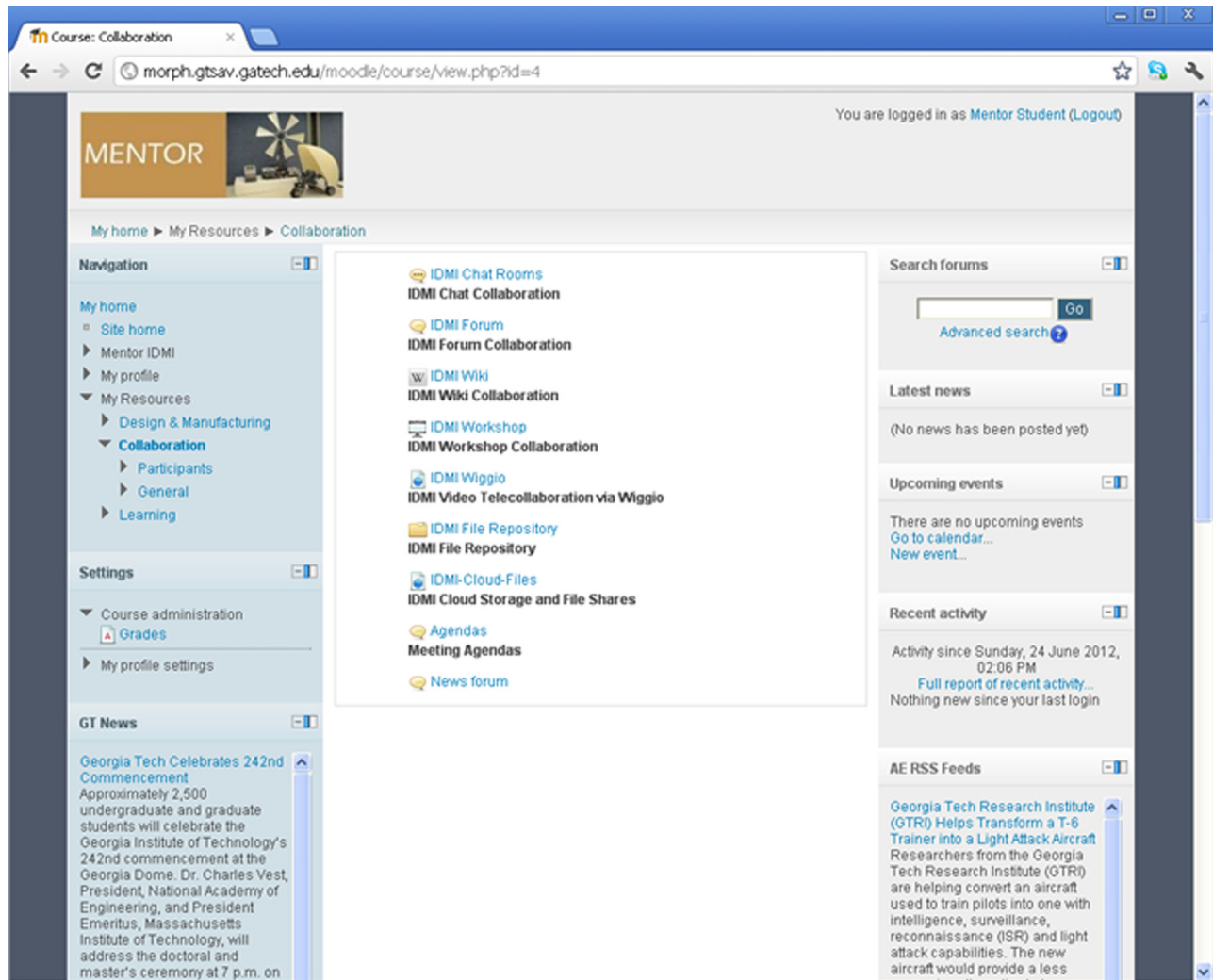


Fig. 8 Social networking tools in the DMCloud

fundamentals of CBDM, the primary value of our DMCloud is highlighted by the following standpoints:

- (1) In order to assist with product design and manufacturing information retrieval and search for optimal solutions, a large and comprehensive data and knowledge base as well as a resource pool are required for a design search engine to support queries and fulfill the negotiation process between service providers and consumers. As more resources and services become available, our DMCloud has a potential to pool design and manufacturing resources together to serve cloud consumers and providers, thereby ensuring effective and efficient information retrieval and resource allocation.
- (2) In order to provide effective cloud-based human-computer interactions, our DMCloud provides a centralized user interface that has a potential of aggregating and synthesizing the data acquired from various sensors and multiple information channels, thereby improving UX by providing easy access to cloud services. It also facilitates coordination, communication, and cooperation between humans and computing devices in the cloud.
- (3) Regarding cloud-based human-human collaboration, our DMCloud helps us observe how designers and other participants interact with each other, and what types of information are required for them to facilitate collaboration in order to make the product development process more effective and efficient. Our DMCloud also enables us to discover

knowledge embedded in the cloud and its social networks. It is essential to uncover the complex relationships of cloud actors and social networking aspect of CBDM systems. Specifically, some key information can be identified through our DMCloud including social network metrics and communities with similar interests.

6 Closing Remarks

The primary contribution of this paper is that it presented the concept of cloud-based design and manufacturing (CBDM) as well as a first step toward understanding the key characteristics and fundamentals of it. We presented a brief survey of related research and associated technologies with a focus on the potential CBDM application fields such as collaborative design, distributed manufacturing, and knowledge management systems. We also identified several key research issues that need to be further examined. A general CBDM system architecture was proposed and a prototype CBDM system was developed based on it, called DMCloud. We described an overview of our DMCloud, overall workflow, and current services it provides. This work is an initial step in the direction of gaining a better understanding of CBDM. Our future research will address modeling and analysis of CBDM systems, intelligent search engines for CBDM systems, and exploring cloud-based human-computer interaction as well as human-human collaboration mechanisms within CBDM systems.

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