CLOUD-BASED DESIGN AND MANUFACTURING: A NETWORK PERSPECTIVE

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CLOUD-BASED DESIGN AND MANUFACTURING: A NETWORK PERSPECTIVE

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DEDICATION

To my father, Weiyuan Wu, and mother, Hong Chen

for all their patience, perseverance, and sacrifice,

but most of all, for their unending love for me

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celebrated new years and mid-autumn days with their family. During these years, what I felt most distressed with is that I lost my grandfather and grandmother, and did not have a chance to take care of them before they passed away. In addition, I would like to thank my wife, Xiaoyi, for her patience, support, and faith in me. The days and nights away from my family while attending classes, taking qualifying exams, conducting research, and writing papers and this dissertation were truly difficult. Without having known and married my wife as well as the support of all these wonderful people, this piece of work would not have been completed within four years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CBD/CBM/ CBDM	Cloud-based design/Cloud-based manufacturing/ Cloud-based design and manufacturing
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
DES	Discrete event simulation
DMCloud	Design and manufacturing cloud
FEA	Finite element analysis
HaaS	Hardware-as-a-Service
IaaS	Infrastructure-as-a-Service
IoT	Internet of Things
PaaS	Platform-as-a-Service
PNs	Petri nets
RFQs	Request for quotations
RFID	Radio-frequency identification
RMS	Reconfigurable manufacturing systems
SPNs	Stochastic petri nets
SaaS	Software-as-a-Service
SOA	Service-oriented architecture
SNA	Social network analysis

SUMMARY

The motivation of this research is the need for reducing time and cost associated with maintaining information and communication technology (ICT) infrastructures for design and manufacturing in digitally networked environments, enhancing design communication and collaboration in distributed and collaborative design processes, and adapting to rapidly changing market demands. The objective of this dissertation is to propose a new design and manufacturing paradigm, namely, Cloud-Based Design and Manufacturing (CBDM), by systematically defining its holistic vision and key characteristics, discussing its anticipated benefits, and addressing the modeling and analysis of design collaboration and manufacturing supply chain networks for CBDM.

In this dissertation, the following challenges pertaining to CBDM are addressed: (1) the systematic development of a conceptual framework that defines the computing architecture, information and communication flow, the design and manufacturing process, the programming model, data storage, and the business model of an idealized CBDM system; (2) the development of a new approach for visualizing distributed and collaborative design processes, and measuring tie strengths in a complex and large design team, detecting design communities with common design interests or activities in cloud-based design (CBD) settings from a social network perspective; and (3) the development of a new approach that helps identify potential manufacturing bottlenecks that determine manufacturing scalability in cloud-based manufacturing (CBM) settings from a manufacturing network perspective.

Specifically, to address the first challenge, a detailed requirement checklist that defines future CBDM systems is presented. Key characteristics of CBDM are also identified. To further clarify the key characteristics, CBDM is systematically compared to other still relevant yet more traditional collaborative design and distributed manufacturing systems from a number of perspectives. In particular, CBDM is distinguished from earlier web- and agent-based approaches from the perspectives of computing architecture, design communication, sourcing process, information and communication, programming model, data storage, and business model. Moreover, a hypothetical future design and manufacturing scenario in a CBDM setting based on both currently existing and emerging new cloud-based service offerings is presented. To address the second challenge, a generic social network analysis (SNA)-based approach is presented to enhance design communication and collaboration in a CBD setting. Tie strengths are measured using Adamic and Adar index. Based on the Adamic and Adar index scores, implicit design networks are formally mapped into explicit social networks. Using quantitative measures in SNA, the associated social networks are captured and measured at both actor and systems levels, and design communities with common design activities within the network are detected. To address the third challenge, the problem formation for modeling and analyzing the material flow in CBM systems is presented. A stochastic petri nets (SPNs) model is developed to detect manufacturing bottlenecks and plan manufacturing scalability in CBM settings.

The contributions of this dissertation are categorized in three research domains: (1) proposing the first definition, a holistic vision, and an example of application scenario for CBDM, (2) modeling and analyzing information flow for improving cloud-based design collaboration, and (3) validating manufacturing scalability in cloud-based manufacturing.

CHAPTER 1

INTRODUCTION

1.1 Motivation and Objective

Owing to globalization, modern design and manufacturing activities are performed in an increasingly geographically distributed environment in which small- and medium-sized enterprises (SMEs) and large-scale enterprises have formed complex and decentralized design collaboration and manufacturing supply chain networks. To perform collaborative design and manufacturing more effectively and efficiently in the distributed and collaborative environment, both SMEs and large-scale enterprises have been faced with large capital expenditures on developing, operating, and maintaining reliable, interoperable, and scalable ICT systems.

Nowadays, the emergence of cloud computing represents a radical change in the way ICT systems are developed, delivered, managed, and maintained. The ICT sector at large has significantly benefitted from cloud computing through on-demand self-services, ubiquitous network access, rapid elasticity, pay-per-use, and location-independent resource pooling. Similar to the ICT industry, product design and manufacturing industries are also undergoing a seismic paradigm shift from traditional web- and agent-based design and manufacturing to cloud-based design and manufacturing by moving more core business functions onto cloud platforms [1, 2].

In the aerospace industry, Boeing has outsourced some of its important computationally expensive applications such as job scheduling to cloud computing service providers such as Amazon and Microsoft. Boeing is also implementing a private cloud system using OpenStack, the open source cloud platform, to allow data to be shared across several business lines [3]. In addition, in the automotive industry, automakers (e.g., BMW, Volkswagen, Mercedes-Benz, Volvo, and General Motors) have also adopted cloud computing technology to support vehicle-to-vehicle and vehicle-to-infrastructure communications. The cloud-assisted autonomous driving system [4] developed by BMW enables a vehicle to have ubiquitous access to data between nearby vehicles and data between vehicles and road infrastructure to sense threats and hazards, avoid or mitigate vehicle crashes, and plan efficient and optimal paths. Consequently, we envision that cloud computing has the potential to transform the way in which enterprises in product design and manufacturing maintain their ICT systems.

Moreover, over the past decade, collaborative software or groupware has been developed and integrated into ICT systems to help facilitate product development teams communicating, coordinating, and collaborating over geographical distances. Traditional communication and collaborative management tools include e-mail, faxing, voice mail, text chat, wikis, web publishing, and videoconferencing. With the advance of Web 2.0, social media has provided a highly interactive social collaboration platform through which users can create, discuss, exchange, and modify user-generated content [5]. Social collaboration platforms have enabled enterprises to collect and analyze massive amounts of social collaboration data and to integrate these data into distributed and collaborative digital product development processes.

For example, Microsoft has developed integrated cloud-based social collaboration services such as profiles, blogs, wikis, bookmarking, tagging, activities, communities, shared files, instant messaging, audio and video chat, and online meetings for enterprises to maximize the value of social collaboration in business environments [6]. General Electric (GE) announced that it has partnered with Local Motors to develop an online social collaboration platform, called FirstBuild, to source collaborative design ideas from a community of engineers, scientists, fabricators, designers and enthusiasts [7]. FirstBuild is intended to help refine existing GE products, identify market needs, design and prototype the next generation GE products. Consequently, it is anticipated that an increasing number of SMEs and large-scale enterprises in design and manufacturing will have the need to develop similar collaborative collaboration platforms or utilize existing ones as a service.

Therefore, the motivation of this research is the need for reducing time and cost associated with maintaining information and communication technology (ICT) infrastructure for design and manufacturing in digitally networked environments, enhancing design communication and collaboration in distributed and collaborative design processes, and adapting to rapidly changing market demands.

The objective of this dissertation is to systematically define a holistic vision for Cloud-Based Design and Manufacturing (CBDM), including its key characteristics and anticipated benefits, and to address two specific research issues related to CBDM including the modeling and analysis of design collaboration and manufacturing supply chain networks.

1.2 Cloud-Based Design and Manufacturing

Cloud-Based Design and Manufacturing (CBDM) refers to a service-oriented product development model in which service consumers are able to configure products or services as well as reconfigure manufacturing systems through Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Hardware-as-a-Service (HaaS), and Software-as-a-Service (SaaS) in response to rapidly changing customer needs [1].

In the IaaS model, cloud service providers offer on-demand access to computing resources such as virtual machines and cloud storage. In the PaaS model, cloud service providers deliver computing platforms such as social collaboration platforms, programming and execution environments for cloud computing. In the HaaS model, cloud service providers and consumers are enabled to rent and lease manufacturing equipment such as milling machines and 3D printers. In the SaaS model, cloud service consumers are enabled to run computationally expensive application software such as AutoCAD remotely without installing and running the software on their local computers.

Moreover, CBDM services can be categorized into four major deployment models: the public cloud, private cloud, hybrid cloud, and community cloud. In the public cloud, CBDM services are offered to the general public and delivered over the Internet. In the private cloud, CBDM services are delivered solely for a design and manufacturing enterprise. A CBDM system is hosted and managed internally or by a third-party vendor. The hybrid cloud is a composition of private and public clouds, offering the benefits of both private and public deployment models. In the community cloud, CBDM services are provided to multiple organizations from a certain community with similar business goals.

The key characteristics of CBDM include ubiquitous access to distributed large datasets, high-performance computing and computing scalability, on-demand self-services, cloud-based social collaboration, rapid manufacturing scalability, and pay-per-use. Based on these key characteristics, a future CBDM system should provide the following functional features: a cloud-based social collaboration platform, a cloud-based distributed file system, an open-source programming framework for cloud computing, a multi-tenancy architecture, a ubiquitous sensor network, an intelligent semantic search engine, and a real-time quoting engine. CBDM differs from traditional distributed and collaborative design and manufacturing from a number of perspectives, including computing architectures, design communication and collaboration, sourcing processes, ICT infrastructures, programming models, data and file systems, and business models. These differences will be articulated in Chapter 3.

1.3 Initial Challenge in Cloud-Based Design and Manufacturing

The initial challenge in CBDM is to systematically develop a conceptual framework that defines the computing architecture, information and communication, the design and manufacturing process, the programming model, data storage, and the business model of a future CBDM system [2, 8]. Although a few definitions pertaining to CBDM have recently been proposed, none of them has yet been commonly accepted. Moreover, some prototype systems have been developed and are being tested in industry; however, whether or not these prototypes are truly CBDM systems remains an open question. Therefore, the specific research issue pertaining to CBDM in general is to answer the following question: Can cloud-based design and manufacturing (CBDM) be considered a new, emerging paradigm in design innovation and digital manufacturing, or is it just old wine in new bottles?

To answer this question, the existing definitions of CBDM need to be compared, common key characteristics identified, and a requirements checklist that any idealized CBDM system should satisfy defined. In addition, CBDM needs to be systematically compared to other still relevant yet more traditional collaborative design and distributed manufacturing systems. Specifically, the newly derived requirements checklist could serve as a benchmark for developing future CBDM systems. To compare CBDM with relevant design and manufacturing approaches such as web- and agent-based design and manufacturing, a conceptual framework of CBDM is presented from the perspectives of computing architecture, design communication, sourcing process, information and communication, programming model, data storage, and business model. Further, this chapter presents an idealized CBDM example scenario in a hypothetical CBDM setting. The example scenario helps clarify the conceptual framework of CBDM and demonstrates the unique value of CBDM.

Moreover, to fully grasp the breadth, depth, and opportunities of CBDM as an emerging paradigm for distributed and collaborative product development, CBDM is further divided into its two counterparts: cloud-based design (CBD) and cloud-based manufacturing (CBM), which are addressed separately. The challenges in CBD and CBM are presented in Sections 1.3.1 and 1.3.2, respectively.

1.3.1 Challenge in Cloud-Based Design

Cloud-Based Design (CBD) refers to a networked design model that leverages cloud computing, service-oriented architecture (SOA), Web 2.0 (e.g., social network sites), and semantic web technologies to support cloud-based engineering design services in distributed and collaborative environments [5].

While a true CBD system does not yet exist, some companies already develop and provide select critical components for CBD systems. For instance, as shown in Figure 1-1, Autodesk offers a cloud-based computer-aided engineering software portfolio, including Autodesk 360 [9], AutoCAD 360 [10], Autodesk PLM 360 [11], Mockup 360 [12], SIM 360 [13], and so on. For example, AutoCAD 360 allows design engineers to view, edit, and share AutoCAD digital files using mobile devices such as smartphones or tablets. SIM 360 allows users to run mechanical simulations (e.g., computational fluid dynamics, finite element analysis, and structural dynamics) anywhere, anytime in the cloud on a pay-per-use basis.

Figure 1-1 Autodesk cloud-based product portfolio [13]

One of the most important benefits of the aforementioned cloud-based CAE tools is that they allow for computing capacity scalability through the creation of a virtual machine that acts like a real computer with an operating system, also referred to as virtualization. Cloud-based CAE software executed on virtual machines is separated from hardware. Virtualization enables enterprises to separate engineering software packages, computing resources, and data storage from physical computing hardware, thereby supporting time and resource sharing.

In addition to these cloud-based CAE tools, cloud-based social innovation platforms are also developed in the broader context of social product development [14] to enhance innovation and collaboration in CBD settings. For instance, 100kgrarages.com [15], a social network site for connecting consumers with small and medium-sized design companies or individual design engineers, allows a service consumer to search for capable and qualified design service providers in a virtual community by providing consumers with each alternative service provider’s profile page. Each profile page includes information such as specialties and sample designs of a service provider. In addition, 3DSwYm [16] (see Figure 1-2), developed by Dassault Systemes, integrates social media tools such as newsfeeds, wikis, forum, and chat room. 3DSwYm is designed to support design ideation, knowledge sharing, and collective innovation.

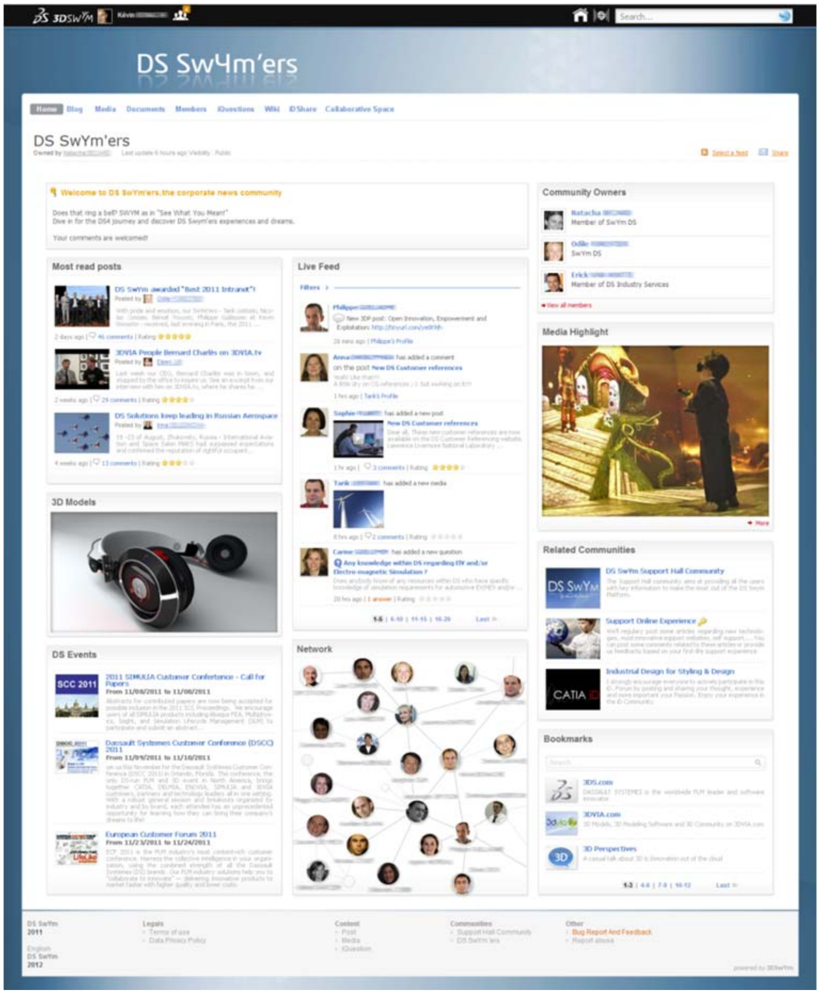


Figure 1-2 Social innovation platform SwYm developed by Dassault Systemes [16]

As engineering design processes are becoming increasingly distributed and collaborative in CBD settings, it is challenging to improve design communication and collaboration while complex design activities are being conducted [17]. Figure 1-3 illustrates a typical CBD setting in which engineers conduct product planning, conceptual design, embodiment design, detail design, prototyping, and manufacturing for the development of a mechanical excavator.

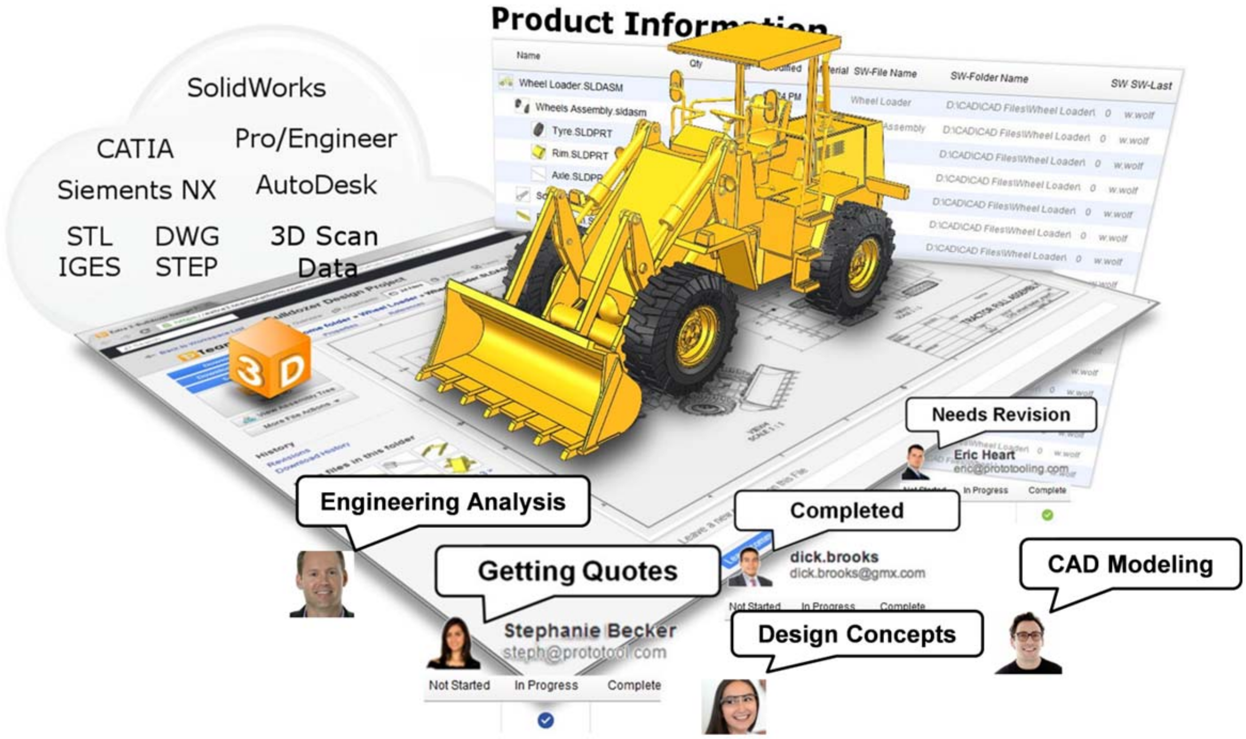


Figure 1-3 Distributed and collaborative design environment [18]

In the conceptual, embodiment, and detail design phases, design engineers need to understand product specifications, customize their designs based on the existing product architecture, and perform preliminary engineering analysis using CAE application software. Since the original mechanical excavator design involves thousands of parts, each design engineer only designs select components of the entire design. To design the mechanical excavator in such a distributed and collaborative setting, design engineers must update product information and engineering changes of 3D CAD models and 2D drawings, discuss engineering analysis results, revise detail designs based on these engineering analysis results, and make decisions for multiple tradeoffs with their coworkers effectively and efficiently. Therefore, the specific research issue pertaining to CBD is to develop a new approach that analyzes information flow in distributed and collaborative design processes, measures information sharing behaviors in a complex and large design team, detects design communities with common interests or activities from a social network perspective as shown in Figure 1-2.

In addition to the challenge related to CBD, the challenge pertaining to CBM will be presented in the next section.

1.3.2 Challenge in Cloud-Based Manufacturing

Cloud-Based Manufacturing (CBM) refers to a networked manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable, and scalable production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource allocation in response to variable-demand customer generated tasking [19, 20].

Table 1-1 Cloud-based manufacturing-related definitions

Reference	**Definition**
[21]	"Cloud manufacturing is a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g., application service providers, agile manufacturing, networked manufacturing, manufacturing grids) and enterprise information technologies under the support of cloud computing, the Internet of Things (IoT), virtualization and service-oriented technologies, and advanced computing technologies."
[22]	"Cloud manufacturing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable and scalable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction."

Table 1-1 presents another two definitions related to CBM. As stated in Section 1.3.1, in the context of CBD, computing capacity scalability can be achieved through virtualization. In the context of CBM, rapid manufacturing scalability is accomplished through cloud-based sourcing processes. Manufacturing capacity is a metric that indicates how many objects such as parts or products can be produced per day by a manufacturing system. Manufacturing capacity needs to be adjusted in response to fluctuations in market demand. Capacity scalability refers to the adjustability of manufacturing capacity to adapt throughputs to changing market demand. For example, as market demand increases and exceeds the designed manufacturing capacity, manufacturing capacity needs to be increased to fulfil more orders and make more profits. On the other hand, as market demand decreases and is less than the designed manufacturing capacity, manufacturing capacity needs to decrease to reduce maintenance costs or avoid waste of resources. Addressing the capacity scalability problem is essentially to determine when, where, and by how much the capacity of a manufacturing system should be scaled.

In traditional manufacturing systems, if market demand grows, the cost of capacity expansion is justified by the economy of scale of the expanded capacity and the reduction of the shortage cost. Typically, manufacturing capacity expansion can be achieved in two ways: by scaling the capacity of an individual manufacturing resource and by adding manufacturing resources to existing in-house manufacturing systems. However, in case of unexpected and rapidly changing market demand, the expanded manufacturing capacity may later on actually become excess capacity if market demand weakens. Thus, capacity utilization will slacken. Because the capacity utilization rate is a key indicator of how efficient a manufacturing system is, the lower capacity utilization – the increasing amount of excess capacity – the less efficient a manufacturing system is.

CBM has the potential to achieve both capacity expansion and reduction in small- and medium-volume production cost effectively through the HaaS model. For instance, in the context of CBM, manufacturing companies may opt to crowdsource part of their manufacturing tasks that are beyond the existing in-house manufacturing capacity to third-party CBM service providers by renting their manufacturing equipment instead of purchasing more machines. To rapidly scale up and down manufacturing capacity in CBM, it is challenging to design a manufacturing network that allows for rapid and cost-effective manufacturing scalability. Therefore, the specific research issue pertaining to CBM is to develop a new approach that helps identify potential manufacturing bottlenecks that determine manufacturing scalability prior to the implementation and deployment of CBM systems.

Based on the challenges pertaining to CBDM, specific research questions and hypotheses are formulated in Section 1.4.

1.4 Research Questions and Hypotheses

The research roadmap of this dissertation is outlined in Figure 1-4. Research Question 1 relates to a systematic conceptual framework for developing an idealized CBDM system. It will be answered definitively by systematically developing the definition, characteristics, requirements, reference model, computing architecture, operational process, programming model, and business model of a future CBDM system. Research Question 2 relates to supporting design communication and collaboration in the context of CBD. Hypothesis 2, which corresponds to Research Question 2, is that a SNA-based approach can be used to support design communication and collaboration. It will be tested by means of two illustrative examples in a CBD setting. Research Question 3 relates to planning manufacturing scalability in the context of

CBM. Hypothesis 3, which corresponds to Research Question 3, is that discrete-event simulation can be used to simulate manufacturing operations and identify manufacturing bottlenecks that determines manufacturing capacity. Hypothesis 3 is tested using a hypothetic manufacturing supply chain example in a CBM setting.

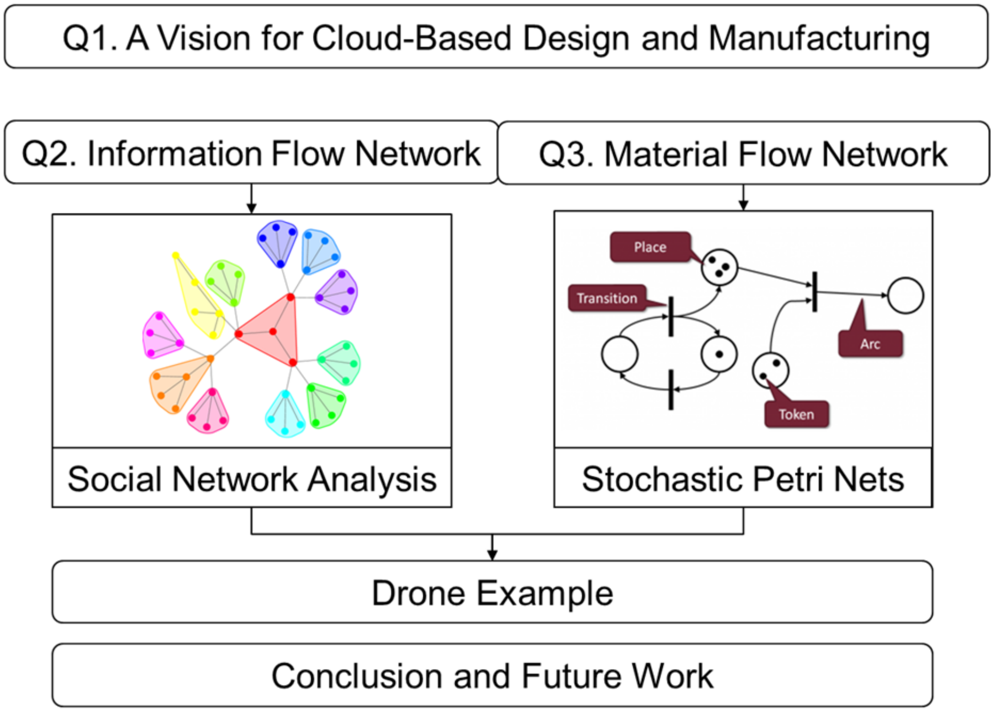


Figure 1-4 Research roadmap

1.4.1 *Research Question 1*

To develop a systematic conceptual framework for CBDM, Research Question 1 is formulated as follows:

<u>Research Question 1.a</u>:

- *What are the definition, characteristics, requirements, reference model, computing architecture, operational process, programming model, and business model of a Cloud-Based Design and Manufacturing (CBDM) system?*

Research Question 1.b:

- *How is a CBDM system different from a traditional collaborative design and distributed manufacturing system such as a web- and agent-based design and manufacturing system?*

Research Question 1.c:

- *What could an idealized CBDM scenario be?*

The research questions above are answered definitively in Chapters 3 and 4.

1.4.2 Research Question 2

To improve design communication and collaboration in CBD settings, it is important to capture and analyze information flow in engineering design processes. In general, there are two ways of analyzing information flow: (1) analyzing relationships between product modules that share design variables; (2) analyzing the sharing of information between individuals or design teams at different design phases (e.g., concept, embodiment, or detail design) as shown in Figure 1-5. This dissertation focuses on the second approach due to the inherent social nature of engineering design processes.

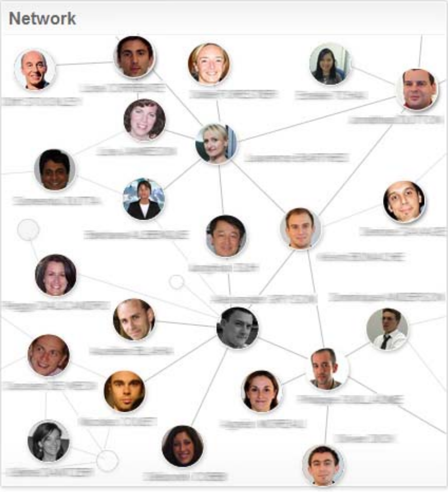


Figure 1-5 Information sharing between individuals or design teams [16]

While a few qualitative studies suggest how human and organizational systems could be restructured to bring about improved productivity and better communication, few of them investigate how information flow among entities can be formally modeled and analyzed in a quantitative way. Thus, this dissertation addresses the modeling and analysis of information flow and collaboration patterns through social network analysis (SNA). While social network analysis has recently been used to study inter-firm relationships of interconnected buyers and suppliers in supply chain management, few studies apply SNA in the context of engineering design. This is largely because (1) there is a lack of clarification with respect to metrics for measuring whether or not connections/ties between individuals or design teams exist; (2) there is no formal framework of developing a SNA approach for understanding information flow in engineering design; and (3) it is still difficult to conduct large-scale real-world industrial case studies.

To address the first two issues as a first step towards supporting design communication and collaboration in CBD settings, Research Question 2 and its hypothesis are formulated as follows:

Research Question 2.a:

- *What indices can be used to measure tie strengths between engineers in CBD?*

Hypothesis 2.a:

- *The Adamic and Adar index can be used to measure tie strengths in engineering design.*

Research Question 2.b:

- *How can communication and collaboration be improved?*

Hypothesis 2.b:

- *Measures and community detection methods in social network analysis can be used to improve communication and collaboration.*

The Hypotheses above are validated using two illustrative examples in Chapter 5.

1.4.3 Research Question 3

In the context of CBM, one of the key research issues is to manage the complexity of the material flow of manufacturing processes. For instance, if the material flow is badly managed, it may take more time for materials, parts, and assemblies to move from one service provider to another. Concurrent and synchronized material flow helps reduce manufacturing lead time, and thus ensure rapid scalability.

In this dissertation, concurrency refers to a property of manufacturing systems in which several manufacturing processes are executing simultaneously. Synchronization refers to the adjustment of manufacturing paces so that multiple manufacturing processes can be finished simultaneously. To cope with the complexity of concurrent systems, it is crucial to provide methods that allow for modeling, analyzing, and testing of the major components of system designs prior to implementation and deployment.

Therefore, Research Question 3 and its hypothesis are as follows:

Research Question 3:

- *How should the manufacturing scalability of a CBM system be planned prior to the implementation and deployment of a CBM system?*

Hypothesis 3:

- *Discrete-event simulation can be used to formally model and simulate the manufacturing network of a CBM system and to plan manufacturing scalability by identifying manufacturing bottlenecks.*

The Hypothesis 3 above is validated using a delivery drone example in Chapter 6.

1.5 Assumptions

In this dissertation, it is assumed that HaaS is more suitable for small- and medium-volume production, approximately 1 to 50 units per day (i.e., 300 to 15,000 units per year). In small- and medium-volume production, although market demand growth is relatively small, it is crucial to scale up manufacturing capacity to adapt to the relatively small market demand growth because the relative growth rate may be very high. Consequently, satisfying the small demand growth can still significantly increase the return on investment (ROI) for manufacturers in small- and medium-volume production. In traditional manufacturing settings, manufacturers purchase more manufacturing resources such as milling machines, lathes, or 3D printers to satisfy market demand growth. However, if market demand decreases, these added manufacturing resources may well become underutilized or idle. Moreover, the acquired manufacturing resources may not even be reused for producing future product variants or completely new products. Considering the costs of ownership, operations, and maintenance, manufacturers in small- and medium-volume production can benefit more from HaaS by temporarily renting manufacturing resources or sourcing manufacturing tasks to third-party service providers without purchasing and owning manufacturing equipment than those in large-volume production. Moreover, small- and medium-volume production is fairly common in industry, including the personalization industry, the rapid prototyping industry, the maintenance and repair industry, the medical device industry, the industrial electronics industry, and so on.

In contrast, in large-volume production (approximately more than 15,000 units per year), including mass customization and mass production, the relative growth rate in market demand is generally small in comparison to large production volumes. Manufacturers in large-volume production may not significantly increase their ROI by satisfying relatively small market demand growth. As a result, manufacturers in large-volume production may not benefit as much from CBDM through the HaaS model. However, it does not mean that manufacturers in large-volume production cannot benefit from CBDM at all. Note that CBDM delivers design and manufacturing services through four major service models: IaaS, PaaS, HaaS, and SaaS. Although manufacturers in large-volume production probably do not benefit as much from implementing HaaS, they can still benefit from implementing IaaS, PaaS, and SaaS. For instance, as stated previously, manufacturers in the aerospace and automotive industries such as Boeing, BMW, and GE benefit from CBDM by implementing IaaS, PaaS, and SaaS.

It is also assumed that a CBDM service consumer can almost always find qualified service providers whose manufacturing capacity is not fully utilized using cloud-based global sourcing platforms as stated before. This assumption seems strong; however, considering the entire life cycle of a manufacturing system, the time when a manufacturing system utilized at maximum capacity is usually short, although a manufacturing system is optimally designed. Moreover, even if a manufacturing service provider is operating at full capacity, in order to make more profits or receive larger orders, this service provider may still prioritize manufacturing tasks and reallocate their manufacturing capacity to accommodate more profitable business opportunities.

In addition, it is assumed that the most prevalent pay-per-use pricing model, which is based on constant price per service unit, is generally a desirable characteristic of CBDM. In addition to the pay-per-use pricing model, another common pricing model is subscription in which users subscribe based on constant price per service unit and a longer period of time. More flexible pricing models are also available, including assured volume of service units plus per-unit price rate, per-unit rate with a ceiling, and so on [23]. Although the pay-per-use pricing model is widely implemented [24], it is certainly not always the most desirable pricing model. For instance, in the SaaS model, it may be more cost-effective to utilize CAD and CAE application software in a pay-per-use fashion without an up-front investment or long-term commitment in situations where the software is occasionally utilized. However, pay-per-use can lead to unexpected high expenses in situations where the software will be constantly utilized for a long period of time. Similarly, in the HaaS model, it may be more cost-effective to rent manufacturing equipment in situations where manufacturing capacity needs to be temporarily scaled up to adapt to relatively small market demand increase. However, it can lead to unexpected high expenses in situations where sustainable and large market demand growth occurs. Consequently, as pricing models have become increasingly complex, there is no single comprehensive model that can be applied to all circumstances.

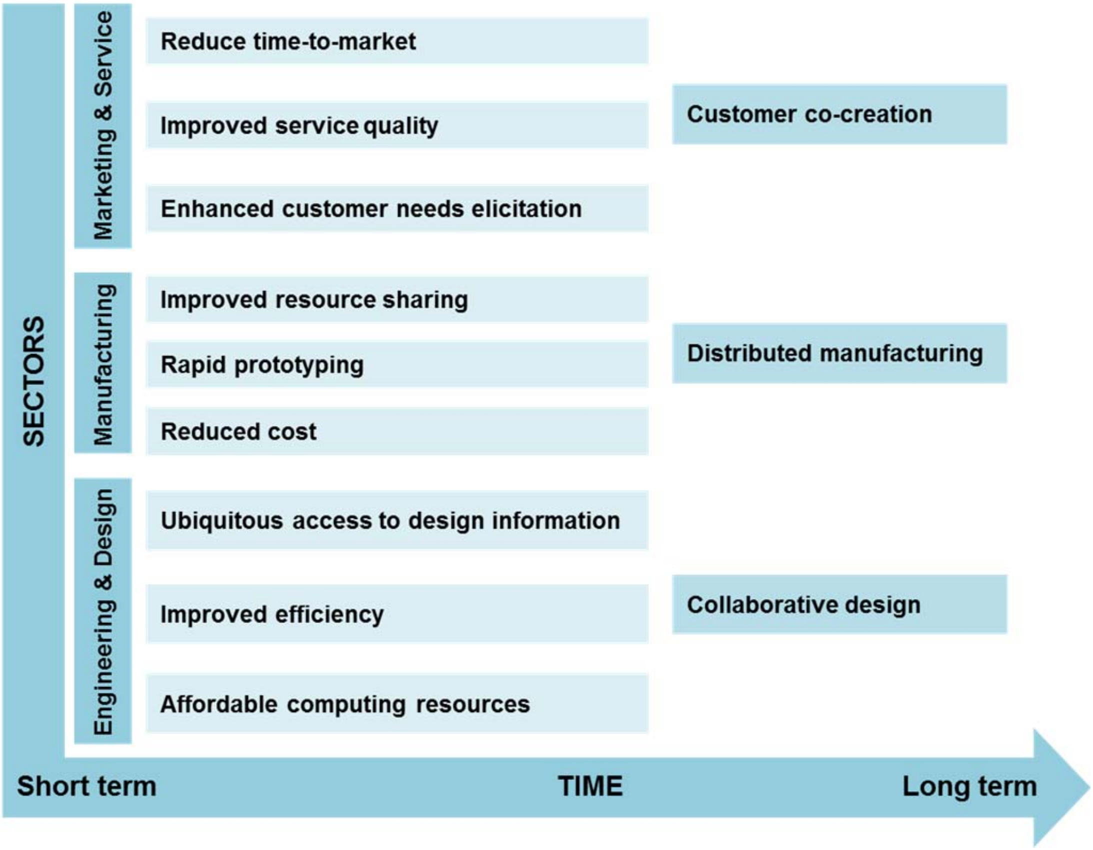


Figure 1-6 Potential impacts of CBDM across sectors [20]

1.6 Potential Impacts of Cloud-Based Design and Manufacturing

As to the magnitude of expected impact of CBDM, we envision that CBDM will have significant impacts on three key sectors, including marketing and service, engineering design, and manufacturing, as illustrated in Figure 1-6.

With respect to marketing and services, in the short term, CBDM has the potential to accelerate product time-to-market, enhance quality of service (QoS), and improve the elicitation of customer needs and requirement analysis. In the long term, a CBDM system is an integral enabler for implementing customer co-creation, mass collaboration, and social product development. With respect to engineering design, in the short term, CBDM will allow designers to have ubiquitous access to massive amount of datasets related to design, streamline design processes, and improve performance in computationally expensive design tasks. In the long term, cloud-based social collaboration platforms will significantly improve collaborative design in geographically dispersed environments. With respect to manufacturing, in the short term, CBDM has the potential to improve manufacturing resource sharing, rapid prototyping, and reduce costs of ownership, operations, maintenance. In the long term, CBDM will significantly improve responsiveness to rapidly changing market demand and unexpected disturbances from internal and external manufacturing environments and enhance remote diagnosis, prognosis, and maintenance in distributed manufacturing.

1.7 Organization of This Dissertation

The logic flow and connectivity of the chapters in this dissertation are illustrated in Figure 1-7.

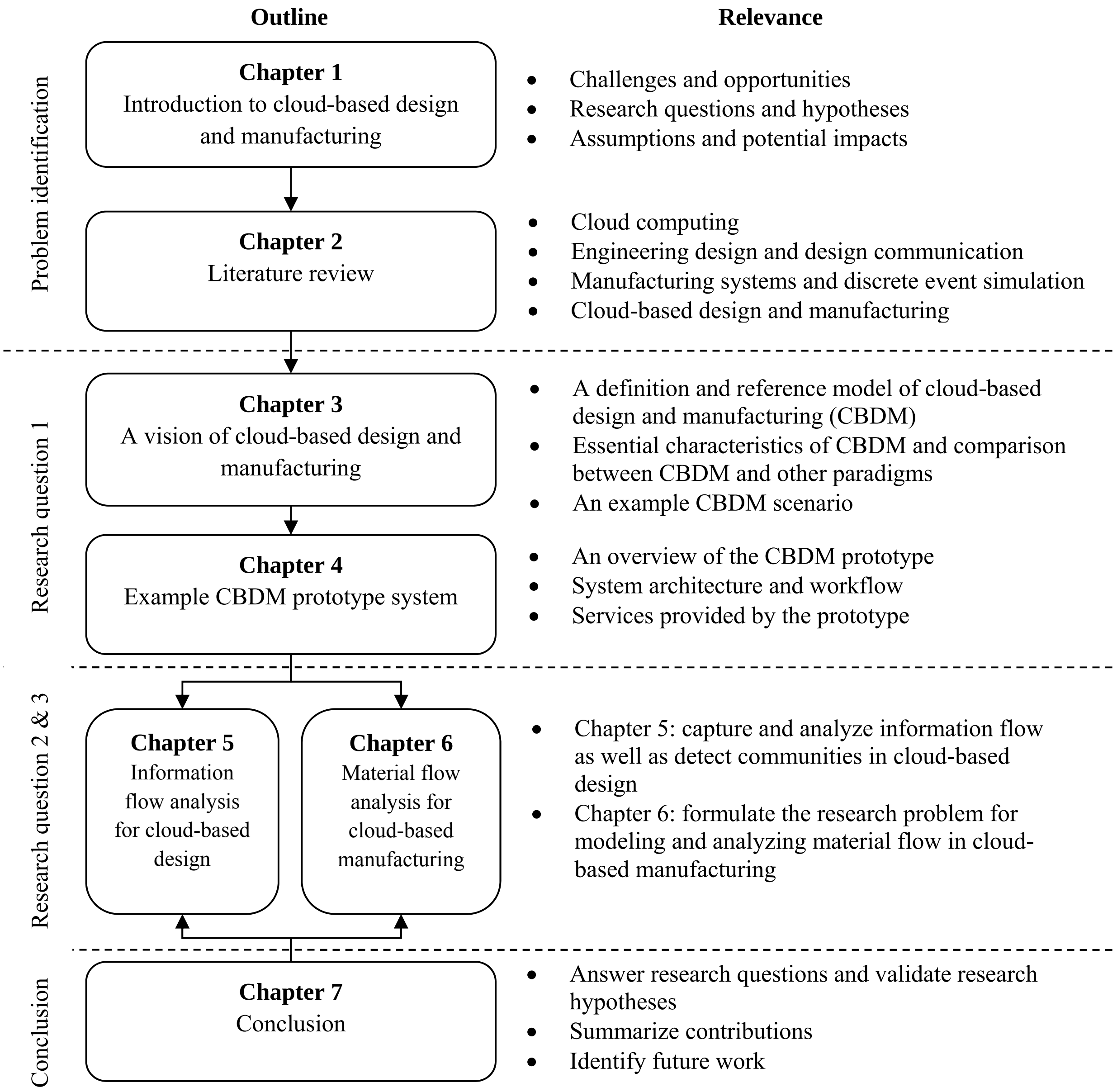


Figure 1-7 Outline of the dissertation

In Chapter 1, the background and motivation of the dissertation are presented. First, research challenges in CBDM as a whole as well as challenges specific to CBD and CBM are identified. Based on these challenges, three research questions and hypotheses are formulated.

In Chapter 2, research related to CBDM is reviewed. Because CBDM originates from cloud computing, existing definitions of cloud computing are first introduced. Afterwards, an overview of the scientific basis for CBDM and its related fields is presented, including collaborative design and design communication, distributed manufacturing and manufacturing scalability. In addition, the state-of-the-art with respect to research and development activities in both academia and industry is presented. Based on the literature review and surveys, existing research gaps in CBDM are identified.

In Chapter 3, a definition of CBDM, a reference model, and essential characteristics are presented. In particular, CBDM is distinguished from web- and agent-based approaches in terms of computing architecture, design communication, sourcing process, information and communication, programming model, data storage, and business model. In addition, a detailed requirements checklist for developing idealized CBDM systems is presented. In order to clarify the vision of CBDM, an idealized design and manufacturing scenario in a hypothetical CBDM setting based on currently existing and emerging or future cloud-based service offerings is also presented.

In Chapter 4, in order to conduct a pilot study of CBDM systems, a prototype system collectively developed by several research groups at Georgia Tech is discussed. This project was funded by Defense Advanced Research Projects Agency (DARPA). The objective of the prototype system and the MENTOR project was to deploy and integrate design and manufacturing resources such as computer-aided design (CAD) software and additive manufacturing equipment into a thousand high schools across the U.S. The major features of the prototype are presented.

In Chapter 5, in order to allow engineers to gather, process, and share product design-related information seamlessly using cloud-based services, a new approach to improve design communication and collaboration in CBD settings based on SNA is proposed. Two design projects that were conducted in a graduate level engineering design class are used as illustrative examples to validate the SNA framework. The results indicate that the SNA-based approach has the potential to improve design communication and collaboration by capturing and visualizing information flow as well as detecting community structures and key actors.

In Chapter 6, in order to plan manufacturing scalability in the context of CBM, a discrete event simulation-based approach is proposed. Stochastic petri nets (SPNs) are used to formally represent the structure of a CBM system and analyze the dynamic behaviors of the system (e.g., boundedness, safeness, reachability, and deadlock). A delivery drone example is used to validate the simulation-based approach. The results provide the insight to system designers about planning manufacturing scalability in CBM settings.

In Chapter 7, the research presented in this dissertation is summarized. The contributions of this research and potential directions for future research are highlighted.

1.8 Summary

This chapter presented a brief initial overview of CBDM. Specifically, the main challenge pertaining to CBDM as a whole and challenges specifically pertaining to CBD and CBM, respectively, were identified. Based on these challenges, three research questions and hypotheses were articulated. At the end of the chapter, the technical organization of this dissertation was outlined.

CHAPTER 2
LITERATURE REVIEW

Chapter 1 provided a brief overview of CBDM. In particular, Chapter 1 identified the challenges related to CBDM. Because CBDM evolves from traditional collaborative design and distributed manufacturing by leveraging new technologies such as cloud computing and social computing, Chapter 2 provides a systematic literature review of cloud computing, collaborative design, and distributed manufacturing. In addition, this chapter presents an overview of CBDM progress from both academia and industry for identifying research gaps.

2.1 Cloud Computing

In this section, an overview of existing definitions for cloud computing [25-27] is provided as a basis for conceiving the concept of CBDM. Several commonly used cloud computing definitions are provided as follows:

- "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" [28].
- "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" [29].
- "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." [30].

- "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" [31].
- "Cloud computing is both a user experience (UX) and a business model. It is an emerging style of computing in which applications, data and ICT 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…" [32].

In addition to these widely used definitions, cloud computing is further introduced from a historical perspective in order to understand its origin and 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. 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. 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 [33]. One milestone is utility computing, proposed by John McCarthy in 1966 [34].

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 the integration of ICT infrastructure and services within and across virtual companies [35, 36]. Another milestone is that Ian Foster and Carl Kesselman proposed the concept of grid computing in 1999 [37]. A computational grid refers to a hardware and software infrastructure that provides dependable, consistent, pervasive, and inexpensive access to high-end computational capabilities [38, 39]. Since cloud and grid computing share a similar vision, Foster et al. [40, 41] identified the main differences between grid computing and cloud computing. Their 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.

Compared to grid computing, it is envisioned 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 makes cloud computing unique and how it may be 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. From a business perspective, it is a breakthrough which is changing the mode of ICT deployment and potentially creating new business models.

2.2 Engineering Design

As stated in previous section, cloud computing is an innovative computing model that connects a large number of virtual machines or computers through a communication network such as the Internet. In light of the benefits of cloud computing in the field of ICT, cloud computing also bears the potential to enhance engineering design in distributed and collaborative settings. In CBD settings, engineering design becomes a social and technical process in which products are designed by teams of people in single or multiple companies through the cloud. In this section, traditional descriptive models for engineering design processes and conventional computer-aided design tools/systems are reviewed with a focus on the evolution of CAD tools/systems. As engineering design environments are increasingly becoming distributed and collaborative, major challenges lie in communication and collaboration. Therefore, approaches to support design communication and collaboration are also presented.

According to literature surveys, many researchers have proposed descriptive models that abstract engineering design processes. Among these models, one of the most widely known is perhaps the one proposed by Pahl and Beitz [42]. It presents a systematic engineering design approach including four core design phases: product planning and clarifying the task, conceptual design, embodiment design, and detail design. Similarly, Ulrich and Eppinger [43] introduce a more refined design process by incorporating prototype testing, refinement, and production ramp-up into the original Pahl and Beitz approach. Since these two well-accepted design approaches were first proposed and later on become common design practice in industry, many similar models based on a similarly linear sequence of design phases have been proposed. Interestingly, almost all of these models represent incremental variations or modifications of the before-mentioned two original based models [44, 45].

In addition to systematic design processes, engineering design also needs to be facilitated by computer-aided systems to assist designers in the creation, analysis, and optimization of a design. Design engineers have used computer-aided design (CAD) systems to design products since the 1960s. Table 2-1 briefly summarizes key milestones of the evolution of computer-aided design from centralized standalone systems, to distributed web-based systems, and finally to a potential new paradigm, often referred to as cloud-based design (CBD).

Table 2-1 Evolution of computer-aided design systems

Time	**Configuration**	**Characteristics**
1960s	Centralized	Standalone system; Operate on large and expensive computers; Generate 2D drawings with a light pen on a CRT monitor;
1970s	Centralized	Standalone system; Operate on affordable personal desktop computers; Perform 3D solid modeling;
1980s	Distributed	Thin server + strong client; Heavy-weighted client mechanism; Hard to be implemented on the Internet;
1990s	Distributed	Strong server + thin client; Light-weighted client mechanism; Adopt the application service provider (ASP) model Easy to be implemented on the Internet;
Beyond 2010s	Distributed	Cloud computing-based; Virtualization; Multi-tenancy; Social media; Ubiquitous access; Software-as-a-Service; Pay-per-use;

It is argued that the first CAD system, SKETCHPAD, was developed by Ivan Sutherland in the early 1960s. SKETCHPAD was a centralized standalone system which consisted of a large and at the time expensive computer with 306 kilobytes of core memory, an oscilloscope display screen, a light pen for input, and a pen plotter for output [46]. The first commercial applications of CAD systems were found in large enterprises, mainly in the automotive and aerospace industries. Back then, those were the only ones who could afford and justify the extremely high operation and maintenance costs of the early-day CAD systems. With the advancement of computer hardware and geometric modeling, CAD systems could be run on more affordable personal desktop computers and allowed for 3D solid modeling. With the advancement of the Internet and the client-server model, distributed CAD and the sharing of decentralized computing resources became possible. Later on, web-based CAD system based on the thin server-strong client architecture turned out to be hard to implement because of the heavy-weighted client mechanism; however, CAD systems based on the strong server-thin client architecture model are more effective and efficient in distributed and collaborative settings because of their light-weighted client mechanism [47-50]. One of the latest technological advancements related to computer-aided product development, often referred to as cloud-based design (CBD), started to emerge at the beginning of the 2010s. Because of the inherent characteristics of CBD systems as stated before based on cloud computing, virtualization [51-53], multi-tenancy [54-56], ubiquitous access, software-as-a-service, pay-per-use business model, and so on, it has the potential to become a game changer for the next generation distributed and collaborative design.

2.2.1 Communication and Collaboration in Engineering Design

As identified in Chapter 1, one of major challenges in engineering design is to enhance design communication and collaboration, especially in geographically dispersed settings. The major purposes of design communication include articulating an issue, asking for clarification, eliciting requirements, generating concepts or principles, reverse engineering, requesting information, comparing solutions, and making decisions [57-60]. Capturing the purposes of design communications can significantly improve the effectiveness and efficiency of design communication by ensuring that engineers know what expected inputs and outputs should be from a communication. With respect to the content or artefacts that are exchanged or shared among individuals or teams, almost all design communications revolve around artefacts including sketches, engineering drawings, computer-aided design files, simulation, finite element analysis files, physical product, calculation, assembly, prototype, and report. According to Hendersen [61], among these artefacts, sketches, engineering drawings, and finite element analysis files are perhaps the most fundamental components of engineering design communication in most design contexts. In order to effectively and efficiently support design communication, Gopsill et al. [60] have synthesized the requirements of effective design communication from the review of literature. Some of the most important requirements include: (1) to enable individuals to have ubiquitous access to design-related data, (2) to enable individuals to communicate via multiple channels such as virtual meetings and text messages, (3) to enable individuals to record changes to an artefact as a consequence of a communication, (4) to enable individuals to share text-based descriptions of an artefact, (5) to enable individuals to share electronic references to an artefact, (6) to enable individuals to solicit responses (e.g., surveys and polls) from one another. However, few studies investigate how to enhance communication and collaboration in engineering design in a quantitative way.

2.2.2 Social Network Analysis for Communication and Collaboration

Because social media increasingly play an important role in supporting communication and collaboration in a socio-technical environment, SNA provides both a visual and a mathematical analysis of communication and collaboration relationships between individuals [62, 63].

Haythornthwaite [64] introduced SNA as an explicit approach and set of associated techniques for the study of information exchange. Jensen and Neville [65] studied SNA using machine learning and data mining techniques and developed methods for constructing statistical models of network data. Kim and Srivastava [66] presented an overview of the impact of social influence in E-commerce and suggested key issues to focus on, including how to combine social influence data into user preferences, and how to exercise social influence in the context of customers' purchase decision making. Borgatti and Li [67] discussed the potential of SNA for supply chain management by applying network concepts to both hard (e.g., material and money flow) and soft (friendships and sharing-of-information) types of ties. Gloor et al. [68] introduced a novel set of SNA-based algorithms for mining the Web, blogs, and online forums to identify trends and find the people launching these new trends. Lin et al. [69] developed a social networking application, SmallBlue, which unlocks the valuable business intelligence of 'who knows what?', 'who knows whom?', and 'who knows what about whom?' within an organization. Their goal was to locate knowledgeable colleagues, communities, and knowledge networks in companies. Hassan [70] demonstrated how SNA theory supports the task of designing ICT-enabled business processes by providing social network metrics for evaluating alternative process designs. These metrics offer better information for process designers who are faced with making ICT investment tradeoffs, especially as the process design task is being undertaken. Braha and Bar-Yam [71] analyzed the statistical properties of real-world networks of people involved in product development activities and showed that complex product development networks exhibit the 'small-world' property, meaning that actors can be reached from every other by a small number of steps. Despite the literature as mentioned above has investigated product development from a social process perspective, little is known about the potential of social network analysis to investigate information flow and collaboration patterns in engineering design. Especially, the research gap is that few studies are conducted to identify potential metrics for measuring the existence of connections between participants in engineering design. Without formal measures for relationships between individuals in this context, the linkages in social networks are neither rigorous nor accurate.

As part of SNA, the aim of community detection is to (1) detect organizations or individuals with similar interests; and (2) create data structures to handle queries or path searches [72]. The modern science of graph theory has brought significant advances to our understanding of complex networked systems. One of the most relevant features of graph theory is community detection or clustering, i.e., the organization of vertices in clusters, with many edges joining vertices of the same cluster and with comparatively fewer edges joining vertices of different clusters [73]. Girvan and Newman [62] proposed an algorithm aiming at the identification of edges lying between communities and their successive removal, a procedure that after some iterations leads to the isolation of the communities. In this seminal work, the intercommunity edges are detected according to the values of a centrality metrics, the edge betweenness that expresses the importance of the role of the edges are transmitted across the graph following paths of minimal length. Identifying clusters of customers with similar interests in the network of purchase relationships between customers and products of online retailers, like Amazon, enables us to set up efficient recommendation systems [74], that better guide customers through the list of items of the retailer and help companies to improve their sales and profitability. Tyler et al. [75] developed a methodology for the automatic identification of communities of practice from email logs by using the betweenness centrality algorithm. This approach enables the identification of leadership roles within the communities. Clauset et al. [76] developed an algorithm for inferring community structure from network topology, which is applied to analyze a large network of co-purchasing data from Amazon.com. The research gap between CBD and SNA is that few studies investigate the measurement of tie strengths and validate the potential of SNA on understanding communication and collaboration in engineering design.

Table 2-2 Evolution of manufacturing systems

Time	**Systems**	**Configuration**	**Characteristics**
1900s	Assembly line	Centralized	Reduced labor costs; Increased production rate;
1960s	Toyota production systems	Centralized	Reduced waste of over production; Reduced waiting time; Reduced defective products; Continuous improvement;
1980s	Flexible manufacturing systems	Centralized	Reduced inventories; Improved productivity; Increased system reliability; Increased variety of parts; Improved machine utilization; Improved response to engineering changes;
1990s	Reconfigurable manufacturing systems	Centralized	Capacity scalability; Increased responsiveness to market changes; Reduced time required for product changeover; Reduced lead time for launching new manufacturing systems; Rapid integration of new technology;
2000s	Web-based and agent-based manufacturing systems	Distributed	Improved information sharing; Improved resource reuse; Improved computational performance; Remote monitoring and control;
Beyond 2010s	Cloud-based manufacturing systems	Distributed	Rapid capacity scalability; Reduced time-to-market; Reduced costs; Ubiquitous computing environment; Pooled manufacturing resources; Improved information sharing; Improved resource reuse; Improved machine utilization;

2.3 Manufacturing Systems

Similar to the evolution of computer-aided design systems described in the previous section, manufacturing systems have also undergone a number of major transitions due to changing market demands and emerging technologies [77, 78]. Table 2-2 shows a brief evolution of manufacturing paradigms from the assembly line, to Toyota production systems (TPSs), to flexible manufacturing systems (FMSs) [79-81], to reconfigurable manufacturing systems (RMSs) [82-86], to web- and agent-based manufacturing systems [87], and finally to a potential new paradigm, often referred to as cloud-based manufacturing [2].

For example, Ford installed the first assembly line, in which interchangeable parts can be added to a product in a sequential manner to produce finished products more efficiently and cost-effectively. In the 1960s, to reduce manufacturing costs, TPSs, also known as just-in-time production systems [88, 89], were devised. TPSs are characterized by a number of principles that assist in eliminating waste by reducing waiting time, inventory, and the number of defective products. In the 1980s, FMSs were developed to allow for manufacturing systems to adapt to functional changes. Specifically, the major advantage of an FMS is that it allows for variation in both parts and assemblies; however, its implementation is usually costly. According to Koren et al., "in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements, reconfigurable manufacturing systems (RMSs) are designed at the outset for rapid change in structure, as well as in hardware and software components" [82]. The key features of RMS include modularity, integrability, customization, convertibility, and diagnosability [84].

The previously stated manufacturing systems fall into the category of centralized manufacturing with significant changes in machine tools, manufacturing plant layouts, and business models. With the development of the Internet, distributed manufacturing systems have been increasingly adopted by industry; two major approaches for distributed manufacturing are web- and agent-based manufacturing systems. Web-based systems [90-93] use the client-server architecture with the Internet to provide a light-weight platform for geographically dispersed teams to access and share manufacturing-related information via a web browser [49, 94]. Likewise, with the increasing structural and functional complexity of web-based manufacturing systems, agent-based manufacturing systems aim at improving computational performance and communication using agents [95, 96]. Agent-based manufacturing systems [87, 97-99] consist of agents (e.g., manufacturing cells, machine tools, and robots) exhibiting autonomous and intelligent behavior such as searching, reasoning, and learning. For example, an agent is an independent problem-solver capable of making decisions by interacting with other agents and its environment [87].

2.3.1 Manufacturing Scalability

Among these aforementioned manufacturing systems, RMSs are characterized by cost-effective capacity scalability. Manufacturing scalability allows manufacturing enterprises to adapt to expected or unexpected demand changes through the structure modifications of existing manufacturing systems. According to Putnik et al. [100], scalability can be implemented through two principles as follows:

- “Several identical elements of the system architecture may be linked together to provide scaled performance or functionality.”
- “A single element of the system architecture may be scaled by upsizing and downsizing its characteristic parameters.”

Extensive surveys in the literature with a focus on manufacturing capacity expansion can be found in Manne [101], Freidenfelds [102], and Luss [102]. Manufacturing capacity scalability can be accomplished at the machine and system levels. From a machine aspect, Asl and Ulsoy [103] presented an approach based on feedback control theory for modeling capacity scalability in an RMS. From a system aspect, Deif and ElMaraghy proposed an approach based on an optimization technique to achieve optimal capacity scalability [104]. Wang and Koren presented a capacity planning methodology for RMSs that can incrementally scale manufacturing capacity using a Genetic Algorithm [105]. Gyulai et al. [106] introduced a novel approach for capacity management for assembly systems with dedicated and reconfigurable assembly lines. The proposed approach integrated the line assignment and capacity planning problems. Based on the cost model estimated by multivariate linear regression, the approach can be used to determine whether a certain product should be assembled on a dedicated or on a reconfigurable line, or it should be outsourced. Moreover, capacity planning was formulated as a mixed integer linear programming problem in which the objective is to minimize the total production cost. Because the identification of bottleneck machines is an integral part of capacity planning, Li et al. [107] presented a data-driven methodology to detect manufacturing bottlenecks in a production line that significantly reduce manufacturing capacity. The identification of the bottleneck locations can help manufacturers scale up manufacturing system capacity more cost effectively by scaling up manufacturing capacity of the bottleneck nodes (e.g., a machine, a manufacturing cell, or an assembly line) of a production line.

2.3.2 Discrete Event Simulation

Section 2.3.1 reviews approaches that address manufacturing capacity scalability using closed-form analytical formulations such as control theories and optimization techniques. In this section, simulation-based approaches [108-111] for addressing manufacturing capacity scalability are reviewed. An extensive literature review on simulation for manufacturing system design and operation can be found in Negahban and Smith [112]. According to this survey, discrete event simulation (DES) is one of the most commonly used techniques for analyzing and understanding the dynamics of complex stochastic systems such as manufacturing systems and supply chain networks.

Specifically, Hon and Xu [113] proposed a simulation-based method to address manufacturing capacity planning for a multi-stage multi-product manufacturing system. In this method, the bottleneck machines were detected by DES. As one type of DES, stochastic petri nets (SPNs) have been demonstrated as an effective approach in modeling and simulating manufacturing systems in which concurrency and communication are key characteristics [114-119]. Zurawski & Zhou [120] discussed fundamental concepts and properties of SPNs including reachability, boundedness and safeness, conservativeness, liveness, and reversibility. Li et al. [121] conducted a review on deadlock control of automated manufacturing systems based on SPNs with a focus on deadlock prevention and control strategy. As absence of deadlocks is critical in manufacturing systems, their occurrences often deteriorate the utilization of manufacturing resources and may lead to catastrophic results in safety-critical systems. To handle deadlock problems in resource allocation systems, three commonly-used mathematical tools include graph theory, automata, and SPN. Particularly, SPN are considered as a popular formalism because of their structural and behavioral analysis. Zhou et al. [122] presented a SPN-based approach to modeling, analysis, simulation, and scheduling of semiconductor manufacturing systems in which timed-PN are used for system simulation and performance evaluation. Labadi et al. [123] presented an approach for modeling and performance analysis of inventory systems based on SPN. They described the synchronization of discrete and batch token flows in discrete batch processes using SPN. Analytic performance evaluation techniques were developed for the model with illustrative applications to the inventory systems. Their results have shown that SPN is powerful for both modeling and performance evaluation of inventory systems. Kim et al. [124] proposed a formal selection framework of multiple navigation behaviors for a service robot. In the presented approach, modeling, analysis, and performance evaluation are conducted based on SPN. The proposed framework enabled a robot to select the most desirable navigation behavior in run time according to environmental conditions by using a probabilistic approach. In addition, SPN have several advantages over direct use of other modeling formalisms such as finite state automata or Markov processes. They conducted experiments on real guidance tasks with visitors by implementing the framework in a guide robot. The results have shown that the proposed strategy is useful for a robot's selection of an appropriate navigation behavior in a dynamic environment.

Moreover, DES is conventionally executed using historical data that are collected offline from manufacturing systems. As a computational expensive tool, high performance computing techniques such as cloud computing have further increased the use of DES in manufacturing system operations planning and scheduling in recent years [125]. It has been argued that simulation-as-a-service in the cloud will perhaps be a future trend [126-129].

2.4 Cloud-Based Design and Manufacturing Progress in Academia and Industry

After reviewing the literature in CBDM-related areas such as cloud computing, engineering design, and manufacturing systems, research progress in CBDM from both academia and industry is reviewed in this section.

To leverage cloud computing in existing manufacturing business models and enterprise information systems, cloud-based manufacturing (CBM), based on cloud computing and service-oriented technologies, was first proposed by Li et al. [130]. The architecture, core enabling technologies, typical characteristics for cloud manufacturing, and the relationships between cloud computing and cloud manufacturing have been described by Xu [22]. Xu 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 by Xu [22], including (1) direct adoption of cloud computing technology in the IT area and (2) cloud manufacturing where distributed resources are encapsulated into cloud services and managed in a centralized manner.

While research pertaining to CBDM is in its infancy, several companies are developing select prototype components for ideal CBDM systems. For example, General Electric (GE) and the Massachusetts Institute of Technology (MIT) are jointly developing a crowdsourcing platform to support the ongoing adaptive vehicle make portfolio of the Defense Advanced Research Projects Agency (DARPA). The new crowdsourcing platform is expected to enable a global community of experts to design and rapidly manufacture complex industrial systems such as aviation systems and medical devices by connecting data, design tools, and simulations in a distributed and collaborative setting. Another frequently quoted example is MFG.com [131], which connects service consumers that request design and manufacturing services to service providers. Consumers provide technical product specifications and select qualified service providers based on geographic locations, certifications, manufacturing capacity, or a combination of these factors. The above examples are intended to provide an impression of the types of CBDM services offered by some of the major players in this field. Some other example service providers who can offer services through the IaaS, PaaS, HaaS, and SaaS models are listed in Table 2-3. More example cloud-based services and their price schemes are detailed in Section 2.4.

Table 2-3 Service providers and their service offering

Provider		**Service**
IaaS	Google Drive [132], Dropbox [133]	Online storage, file syncing
	Amazon Elastic Compute Cloud [134]	Virtual machines
PaaS	Microsoft Windows Azure [135]	Developing and hosting web applications
	Amazon Relational Database Service [136]	Database query system for analysis of large datasets
	Salesforce.com [137], NetSuite [138]	Developing user interfaces and social network sites
HaaS	Ponoko [139], Shapeways [140]	Additive manufacturing
	MFG.com [131], Quickparts.com [141]	Supplier search engine, cloud-based e-Sourcing
SaaS	Autodesk 360 platform [9]	CAD file editing, mobile viewing, cloud rendering
	Dassault Systems [142]	3D modeling
	Sabalcore [143]	High performance computing for FEA/CFD

2.4.1 CBDM Progress in Academia

This section reviews current and recent research initiatives pertaining to CBDM. The first cloud manufacturing project was funded by China's National High-Tech Research and Development program and National Basic Research Program. The goal of the project was to "realize the general sharing of global manufacturing resources, reduce time-to-market, improve quality of service, as well as reduce manufacturing costs." The cloud manufacturing concept proposed by Li et al. [130] refers to a service-oriented, knowledge-based smart manufacturing system which encompasses the entire product development lifecycle from market analysis to design, manufacturing, production, testing, and maintenance. Meanwhile, the goal of the ManuCloud project (2010), launched by the European Commission's Seventh Framework Programme (EC FP7) with € 5 million ($6,700,000), is to "develop a service-oriented IT environment as basis for the next level of manufacturing networks by enabling production-related inter-enterprise integration down to shop floor level." Recently, the Engineering and Physical Science Research Council (EPSRC) in the United Kingdom funded a project, titled "Cloud Manufacturing – Towards a Resilient and Scalable High Value Manufacturing" with £2.4 million ($4,050,000). The objective of this research is to "develop a holistic framework and understand its role within global manufacturing networks through: seeking the appropriate products, sectors, scales and volumes; identifying the impacted lifecycle stages from design to manufacture, maintenance and re-cycling; understanding how new product design and manufacturing will be influenced by lifecycle data; and finally analyzing how future products will be influenced by cloud manufacturing enabling local on-demand supply of components and services."

Another successful project on CBDM conducted in the U.S. is part of the Manufacturing Experimentation and Outreach (MENTOR) program of DARPA [144]. The MENTOR effort is part of the Adaptive Vehicle Make (AVM) program portfolio. Several teams were awarded contracts for the MENTOR program, including Georgia Tech. The vision for the MENTOR program was to "develop an integrated, distributed design and manufacturing infrastructure that can support a progressive set of prize challenge competitions through integrated CAD, CAE, and CAM tools." The goal of this project, led by Georgia Tech [145], was to "engage students from these participating high schools in a series of collaborative design and distributed manufacturing experiments." The developed prototype system, Design and Manufacturing Cloud (DMCloud), builds upon an integrated distributed manufacturing infrastructure with tools such as CNC machine tools, additive manufacturing machines (i.e., 3D printers) through a network of high schools dispersed across the U.S. This prototype system enables students to learn and participate in product development as a continuum of design, analysis, simulation, prototyping, and manufacturing activities. In the DMCloud [146], IaaS provides students with a platform virtualization environment along with high-performance computing servers and storage space. PaaS provides students with a ubiquitous computing and development environment. Specifically, the DMCloud is constructed from existing technologies, including Sakai, Moodle, and Drupal. HaaS provides students with a heterogeneous hardware environment including 3D printers, milling machines, lathes, laser cutters, and other CNC machines. Providing students with access to web-based software applications over the Internet, SaaS eliminates the need to install and run software on their own computers. The software includes engineering design, analysis, and simulation tools from Dassault Systems. The DMCloud is currently implemented as a private DMCloud, but it can easily be extended to be a public or hybrid CBDM system. The prototype system, DMCloud, will be detailed in Chapter 4.

2.4.2 CBDM Progress in Industry

In addition to research projects being conducted in academia, several companies are developing and testing similar commercial systems, most notably in the consumer product industry with rapid prototyping manufacturing resources. These companies utilize cloud-based services as a technology enabling their ventures and connecting designers with manufacturing resources over the Internet. Quirky offers users with access to a complete product creation enterprise [147]. The business model of Quirky incorporates the originating designers into the wealth-sharing model and provides them with a portion of the profits that their products yield. The Economist also discusses Shapeways, a company offering 3D printing services over the Internet. In contrast to the vetting process used in the Quirky business model, Shapeways provides users immediate access to 3D printers to build any object that they want. Tables 2-4 to

2-7 list some of the example service providers, services they deliver, and price schemes in the IaaS, PaaS, HaaS, and SaaS arenas, respectively.

Table 2-4 Example providers in IaaS

Provider	Service	Price Scheme
Rackspace	Internet hosting	Starting at $17/month
Amazon Elastic Compute Cloud (EC2)	Virtual machines	$0.48/hour for 4 cores, 15GB memory
Google Compute Engine		$0.163/hour for 2 cores, 1.8 GB memory
Amazon Simple Storage Service (S3)	Online storage, file syncing	$0.055/GB/month over 5000 TB/month
Google Drive		Free for 25GB; $4.99/month for 100GB $9.99/month for 200GB $49.99/month for 1TB $99.99/month for 2TB
Dropbox		Free for 2GB $19.99/month for 100GB

Table 2-5 Example providers in PaaS

Provider	Service	Price Scheme
Google App Engine	Developing and hosting web applications	$9/app/month
Microsoft Windows Azure		Free for up to 60 minutes of CPU/day, 10 sites, 1GB storage, 20MB of MySQL (first 12 months) $0.02/hour, up to 240 minutes of CPU/day, 100 sites, 1GB storage, 20MB of MySQL (first 12 months)
Google BigQuery	Database query system for analysis of massively large datasets	$0.12/GB/month, limit: 2TB $0.035/GB, limit: 20,000 queries/day, 20TB of data processed/day $0.02/GB, limit: 20,000 queries/day
Amazon Relational Database Service (RDS)		$0.025/hour for Micro DB Instance $0.090/hour for Small DB Instance $0.180/hour for Medium DB Instance $0.365/hour for Large DB Instance $0.730/hour for Extra Large DB Instance
Salesforce	Workflow automation, sales teams, enterprise analytics, custom websites	$125/user/month for Enterprise $250/user/month for unlimited

Table 2-6 Example providers in HaaS

Provider	Service	Price Scheme
Shapeways	3D printing	Starting from \$0.75/cm3 for sandstone Starting from \$1.40/cm3 for strong plastic Starting from \$8.00/cm3 for stainless steel Starting from \$20.00/cm3 for sterling silver
Cubify.com		\$1299 for 140×140×140 mm, 16 colors, plastic \$2499-3999 for 275×265×240 mm, 18 colors, plastic

Table 2-7 Example providers in SaaS

Provider	Service	Price Scheme
Autodesk 360 platform	Storage, DWG editing, mobile viewing, rendering, design optimization, structure analysis	Free for 5GB storage
TeamPlatform	Sharing and viewing CAD files, synchronize CAD files, track changes, visual search, CAD Meta-Data search, 3D printing quoting, project management	Free for up to 10 workspaces, up to 5 guests, up to 5 shared pages and forms, 1GB \$25 for unlimited workspaces, guests, shared pages and forms, storage
CadFaster MyCadbox	View and share CAD models	Free for sharing 10 models; \$9.99/month for up to 100 models
Sabalcore	High-performance computing for FEA/CFD	\$0.20-\$0.29/core-hour for premium service \$0.20/core-hour for high-volume service
Penguin Computing	High-performance computing for CAE	\$0.10/core-hour/GB/day \$0.27/core-hour/50GB/day

These service providers include established companies such as Amazon, Google, and Salesforce as well as emerging startup companies such as Sabalcore and TeamPlatform. These companies may shape the CBDM arena over the next few years.

In addition to the above example service providers, Dassault Systemes is a key player among the few companies who currently provide advanced cloud-based product portfolios. Figure 2-1 illustrates the evolution of the products from the Dassault Systemes. The most recent product developed by Dassault Systemes is the 3DEXPERIENCE platform [148]. This platform is a business experience platform available on premise and in public cloud to enable users to perform design ideation via social media, to perform 3D modeling, engineering analysis, simulation, data management, and product lifecycle management.

Figure 2-1 Evolution of Dassault Systemes products [148]

As stated before, the social innovation platform, 3DSwYm, incorporates semantic search, business processes, and information intelligence experience, and leverages the power of the virtual community for innovation. 3DSwYm is offered as SaaS, and is hosted on a cloud infrastructure. Specifically, 3DSwYm integrates social media features such as newsfeeds, wikis, forums, chat rooms, and instant messaging that help design engineers transform customer needs to innovative design concepts and reduce design cycles. The content and simulation platform delivered on the 3DEXPERIENCE platform includes 3DVIA, DELMIA, and SIMULIA. For example, DELMIA enables NC machining simulation, ergonomics analysis, assembly process simulation, and supply chain planning in the cloud.

2.5 Summary

This chapter reviewed the state-of-the-art research in cloud computing, collaborative design, distributed manufacturing, and CBDM. To identify research gaps, current research projects and progress associated with CBDM in academia and industry were also carefully reviewed. Based on the literature review, the following research gaps were identified:

- To systematically develop a conceptual framework that defines the computing architecture, information and communication, the design and manufacturing process, the programming model, data storage, and the business model of an idealized CBDM system;
- To develop a new approach that can visualize distributed and collaborative design processes, measure tie strengths in a complex and large design team, detect design communities with common design interests or activities in CBD settings;
- To develop a new approach that helps identify potential manufacturing bottlenecks that determine manufacturing capacity scalability prior to the implementation and deployment of CBM systems.

CHAPTER 3

A CONCEPTUAL FRAMEWORK FOR CLOUD-BASED DESIGN AND MANUFACTURING

Based on the literature review in Chapter 2, it is apparent that increasing attention from both industry and academia is being paid to CBDM. In particular, several pilot projects in academia and industry have already been launched. However, an ongoing debate on CBDM in the research community still revolves around several aspects such as definitions, key characteristics, computing architectures, programming models, file systems, operational processes, information and communication models, and new business models pertaining to CBDM. One question, in particular, has often been raised: *Is cloud-based design and manufacturing actually a new paradigm, or is it just "old wine in new bottles"?* This complex research question is further decoupled into the following research sub-questions:

Research Question 1.a:

- *What are the definition, characteristics, requirements, reference model, computing architecture, operational process, programming model, and business model of a Cloud-Based Design and Manufacturing (CBDM) system?*

Research Question 1.b:

- *How is a CBDM system different from a traditional collaborative design and distributed manufacturing system such as a web- and agent-based design and manufacturing system?*

Research Question 1.c:

- *What could an idealized CBDM scenario be?*

Chapter 3 answers these aforementioned research questions definitively. Specifically, based on the discussion of the key characteristics of CBDM, the derivation of the requirements that a future CBDM system should satisfy, and a thorough comparison between CBDM and other relevant systems, a hypothetical design and manufacturing scenario in a future CBDM environment is presented to justify the conclusion that CBDM can be considered as a new paradigm that is anticipated to revolutionize future design and manufacturing practice.

3.1 A Definition of Cloud-Based Design and Manufacturing

Cloud-Based Design and Manufacturing (CBDM) refers to a service-oriented product development model in which service consumers are able to configure products or services as well as reconfigure manufacturing systems through Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Hardware-as-a-Service (HaaS), and Software-as-a-Service (SaaS) in response to rapidly changing customer needs [146]. CBDM is characterized by on-demand self-service, ubiquitous access to networked data, rapid scalability, resource pooling, and virtualization. The types of deployment models include private, public, and hybrid clouds.

The above definition involves various techniques and key terminologies. In order to fully grasp the breadth and depth of CBDM, the broader definition of CBDM is further decoupled into two sub-definitions: cloud-based design (CBD) and cloud-based manufacturing (CBM).

Cloud-Based Design (CBD) refers to a networked design model that leverages cloud computing, service-oriented architecture (SOA), Web 2.0 (e.g., social network sites), and semantic web technologies to support cloud-based engineering design services in distributed and collaborative environments [5].

There are some good examples of CBD services in industry. For example, Autodesk developed a platform, Autodesk 123D, which allows users to convert photos of objects into 3D models, create or edit 3D models, and make prototypes on a 3D printer through the Internet. 100kgrarages.com enables a service consumer to find capable design service providers in a virtual community by providing consumers with each alternative service provider's profile page, which includes information such as specialties and sample designs.

Cloud-Based Manufacturing (CBM) refers to a networked manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines which enhance efficiency, reduce product lifecycle costs, and allow for optimal resource loading in response to variable-demand customer generated tasking [19].

3D Hubs [149] is a good example of CBM; it is the largest 3D printing service provider in Europe. 3D Hubs links 3D printing service providers in a local community with designers who need additive manufacturing services for testing, tooling, and manufacturing. 3D Hubs has been launched in twenty cities worldwide using a community-based 3D printing service model, where digital models can be printed only a few miles away from a customer. According to 3D Hubs, they are developing more function modules such as design for manufacturability and real time quoting.

Table 3-1 presents another two definitions related to CBM. Although each definition may focus on a unique aspect of CBM, they include common elements such as networked manufacturing, ubiquitous access, multi-tenancy and virtualization, big data and the IoT, everything-as-a-service (e.g., infrastructure-as-a-service, platform-as-a-service, hardware-as-a-service, and software-as-a-service), scalability, and resource pooling.

Table 3-1 Cloud-based manufacturing-related definitions

Reference	Definition
[21]	"Cloud manufacturing is a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g., application service providers, agile manufacturing, networked manufacturing, manufacturing grids) and enterprise information technologies under the support of cloud computing, the Internet of things (IoT), virtualization and service-oriented technologies, and advanced computing technologies."
[22]	"Cloud manufacturing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction."

Although a truly CBM system does not yet exist, a number of companies have started to develop and provide select components for CBM systems. For example, Quickparts is a cloud-based sourcing platform with a focus on low-volume production for custom manufactured rapid prototypes. Quickparts connects service consumers to providers through an instant quoting engine, which transformed sourcing processes from manual to real-time and automatic. Quickparts enables users to upload their CAD data from a variety of commercial CAD software packages such as CATIA and SolidWorks. Based on geometric analysis, Quickparts instantly generates a list of qualified service providers who can manufacture these digital models. Another cloud-based sourcing platform with a focus on high-volume production, LiveSource, developed by MFG.com, allows service consumers to have access to request for quotations being sourced by more than 200,000 global service providers. LiveSource enables service consumers to discover and collaborate with quality service providers at shorter deliver times, reduced costs, and a more flexible supply chain. In addition to the two cloud-based sourcing platforms, 3D Hubs, a web-based 3D printing platform, helps connect 3D printing service consumers with providers in the local area. According to 3D Hubs, most 3D printer owners use their devices on average less than 10 hours per week. The goal of 3D Hubs is to allow 3D printer owners establish social connections within their local 3D printing community to increase the utilization of their devices. 3D Hubs has established an innovative business model that creates and delivers value to both 3D printing service consumers and providers. First, each hub, i.e., a 3D printing service provider, decides how much they will charge to 3D print an item. Second, 3D Hubs examines whether a 3D model is watertight using a cloud-based geometric analysis tool, conducts printability analysis to verify whether the 3D model is printable, and automatically repair the 3D model if necessary. Third, once the 3D model passes inspection, it will be 3D printed by the hub. 3D Hubs adds a fifteen percent surcharge on top of the original quote.

As stated before, CBDM is a decentralized and networked design and manufacturing model based on many enabling technologies such as cloud computing, social media, the Internet of Things (IoT), and service-oriented architecture (SOA), all of which forms the backbone of this new design and manufacturing paradigm. An ongoing debate on CBDM revolves around several aspects such as definitions, key characteristics, computing architectures, programming models, file systems, operational processes, information and communication models, and new business models pertaining to CBDM. Although a few definitions for CBM have recently been proposed, they are not yet commonly accepted. Moreover, some prototype systems have been developed and are being tested in industry; however, whether or not these prototypes are truly CBDM systems remains a question. Thus, to gain a better understanding of CBDM, a thorough comparison between CBDM and other relevant design and manufacturing systems is required.

In addition, the essential characteristics of CBDM, 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 a CBDM system can provide and release engineering resources, such as design software, manufacturing hardware, as needed on demand. CBDM systems provide 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. In order to easily reach such a communication capability, broad and global network access is required. A CBDM system can provide such access to the network where service 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*: A CBDM system 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, a CBDM 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*: Design and manufacturing resources offered by service providers in CBDM are pooled to serve service consumers in a pay-per-use fashion. Resources include engineering hardware (e.g., fixtures, molds, and material handling equipment) 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. Real time sensor inputs, capturing the status and availability of manufacturing resources, ensure effective and efficient resource allocation.
5. *Virtualization*: A CBDM system provides a virtual environment through the simulation of the software and/or hardware upon which other software runs. A CBDM system enables enterprises to separate engineering software packages, computing and data storage resources from physical hardware, as well as to support time and resource sharing.

3.2 A Vision for CBDM

3.2.1 A Reference Model for CBDM

To illustrate the vision of a future CBDM system, a high-level, systematic conceptual reference model (see Figure 3-1) is proposed to clarify the component parts of CBDM. Mirroring the NIST cloud computing conceptual reference model [150], the CBDM conceptual reference model defines a set of actors, activities, and functions involved in CBDM systems. Four major actors are defined in the reference model: (1) cloud consumer, (2) cloud provider, (3) cloud broker, and (4) cloud carrier. Table 3-2 lists the four major actors and their corresponding definitions.

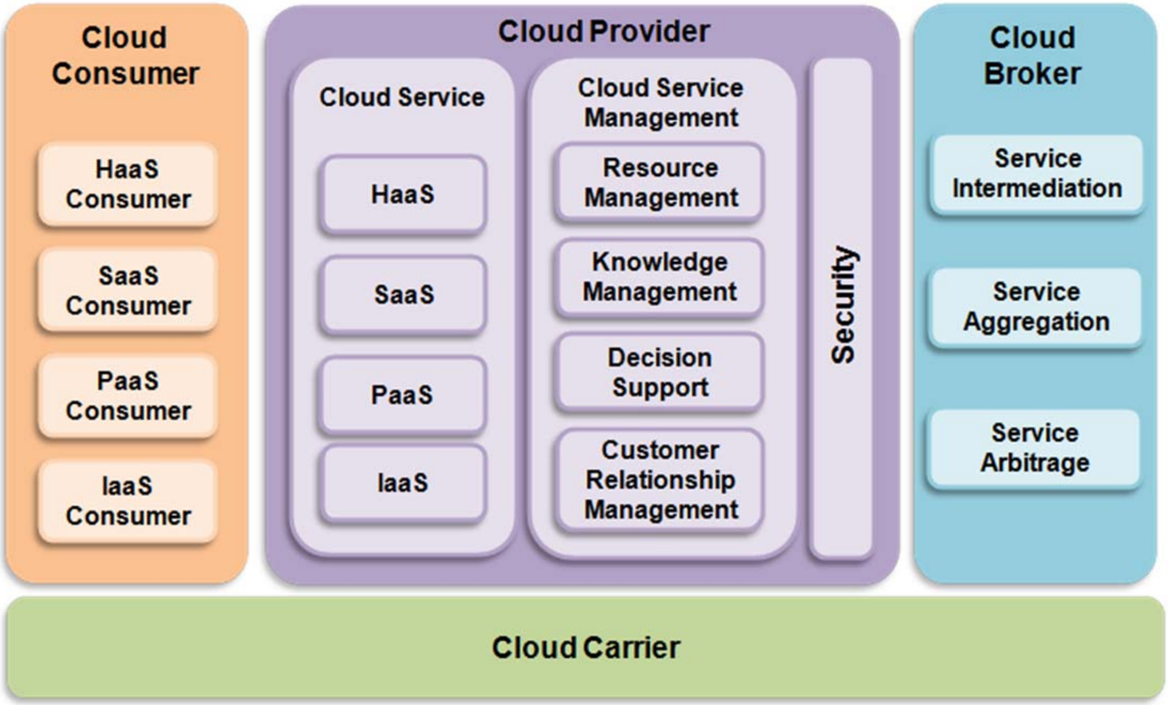


Figure 3-1 CBDM conceptual reference model

Table 3-2 Actors in the CBDM Conceptual Reference Model

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

The interaction and communication among the actors is shown in Figure 3-1. A service consumer may request four types of 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. The four types of CBDM services and their corresponding activities are presented in Table 3-3.

Table 3-3 Major Activities in the CBDM Conceptual Reference Model

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

A cloud provider provides design and manufacturing services through service management, including resource management, knowledge management, decision support, and customer relationship management. A service provider must also manage security, ranging from physical security to virtual security. A cloud broker manages CBDM services through service intermediation, service aggregation and service arbitrage.

3.2.2 A Holistic View of CBDM

In addition to the reference model, Figure 3-2 presents a holistic view of CBDM including example services (i.e., IaaS, PaaS, HaaS, and SaaS) and a knowledge management system. The example services provided in each service model will be described in more detail as follows:

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.

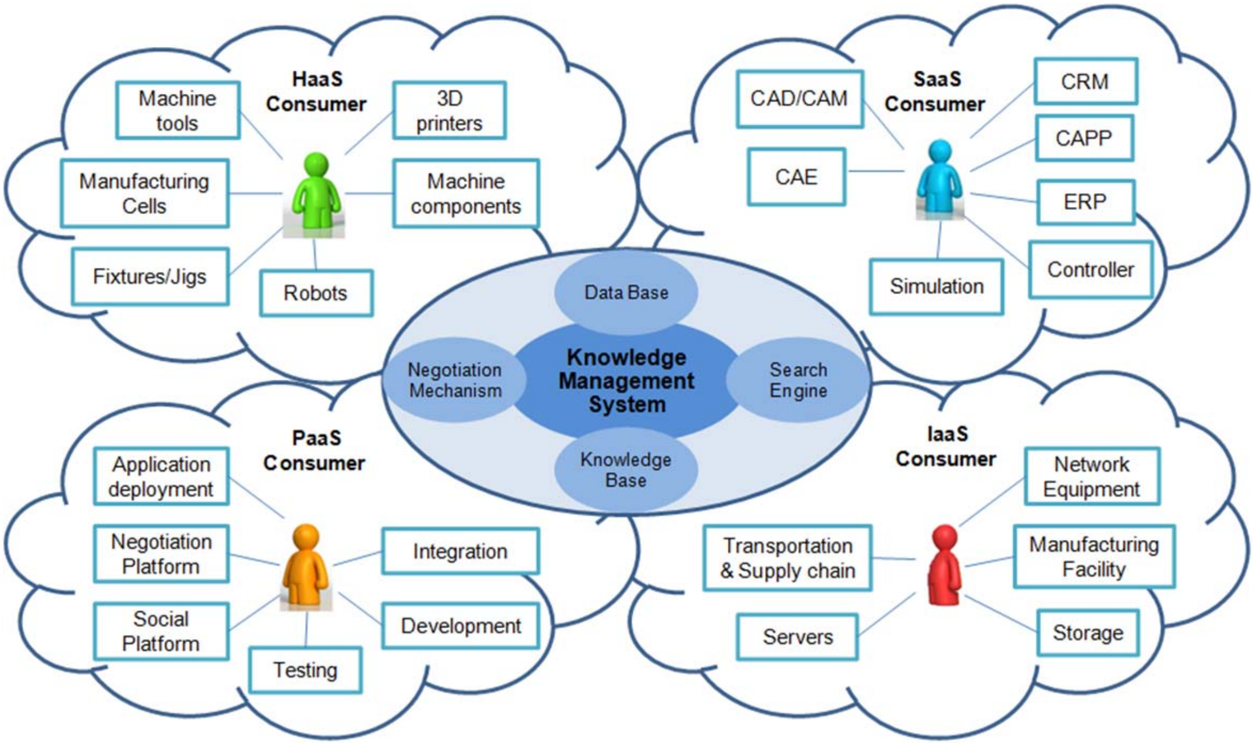


Figure 3-2 A holistic view of CBDM

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.

Hardware-as-a-service (HaaS)

HaaS delivers hardware sharing services, e.g., machine tools, hard tooling, and manufacturing processes, to service consumers. The consumers are able to rent and release hardware from providers without purchasing them. The Cubify.com 3D online printing service 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. 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 consumers. The 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. The consumers of SaaS can be designers, engineers and managers, who need access to software applications.

As previously stated in Section 3.2.1 and summarized in Section 2.4.2, a number of manufacturing companies are developing, testing, and commercializing products and services associated with all of the four service models. These services have been primarily deployed in four cloud deployment models, including the private cloud, public cloud, hybrid cloud, and community cloud. For example, during companies' initial adaptation to the cloud, many organizations have concerns related to data security. These concerns can be addressed by deploying the private cloud where service hosting is build and maintained for a specific client. Security issues are addressed through secure-access VPN or by the physical location within the client's firewall system. The private cloud is also well suited for mission-critical applications. The public cloud services are generally offered on a pay-per-usage model. However, security is the major concern with the public cloud deployment model because public cloud service providers own and operate the IT infrastructure at their data center and provide users with access to their data only via the Internet. The community cloud shares IT infrastructure and data centers across several organizations from a specific community with common or similar core business benefits and policy considerations. The hybrid cloud deployment model is a composition of private, public, and community cloud services, offering the benefits of multiple deployment models.

According to the holistic view of CBDM, in order to fully develop and implement CBDM, major research opportunities or research gaps lie in the knowledge management system (KMS), the core of a CBDM system as shown in Figure 3-2. A KMS refers to an ICT system that captures, develops, shares, and effectively uses organizational knowledge [151-153]. Knowledge management is primarily concerned with the representation, organization, acquisition, creation, usage, and evolution of knowledge in its many forms [154]. In the context of CBDM, a KMS along with databases, knowledge bases, intelligent search engines, and negotiation platforms is intended to offer integrated knowledge management services to cloud providers and consumers for creating, sharing, and reusing design- and manufacturing-related knowledge. Specifically, at the systems level, the primary objectives of a KMS for CBDM include (1) improving the flow of information between internal and external individuals in a collaboration network and (2) managing the flow of raw materials, work-in-process inventory, and finished products in a manufacturing supply chain network. At the low level, the primary objectives of a KMS for CBDM include (1) representing knowledge explicitly via ontologies and (2) applying logical rules to deduce new knowledge. For instance, one component of a KMS for CBDM is a knowledge-based intelligent search engine. The search engine is intended to help users search for useful design information and manufacturing resources. Another component of a KMS for

CBDM is a negotiation platform which is intended to support negotiation processes so that both service providers and consumers can find an optimal solution (i.e., minimal cost and lead time, and higher service quality). Key enabling technologies for KMSs include ontologies and semantic web, big data analytics, cyber-physical systems (CPS), Internet of Things (IoT), and simulations. More details about future research opportunities or gaps related to CBDM will be presented in Section 3.6.

As knowledge management itself is a very broad area, this dissertation focuses on two specific research issues related to knowledge management at the systems level including (1) information flow management in Chapter 5 and (2) material flow management in Chapter 6, respectively. With respect to information flow management, one of the primary objectives of future KMSs for CBDM is to capture and visualize information flow between individuals in complex and distributed collaboration networks, detect communities for these collaboration networks, identify subject-matter experts in these communities, and eventually to improve the effectiveness and efficiency of communication and collaboration for CBDM. With respect to material flow management, another primary objective of future KMSs for CBDM is to manage the flow of material in interconnected manufacturing networks such that manufacturers can search for suitable manufacturing suppliers and scale up and down their manufacturing capacity more cost-effectively and efficiently. By combining with cloud-based discrete-event simulation tools, KMSs are intended to simulate material flow, identify manufacturing bottlenecks, and plan manufacturing capacity scalability prior to implementation.

3.2.3 Information Flow in CBDM

In addition to the holistic view of CBDM, Figure 3-3 illustrates how CBDM systems may be developed from the perspective of information flow.

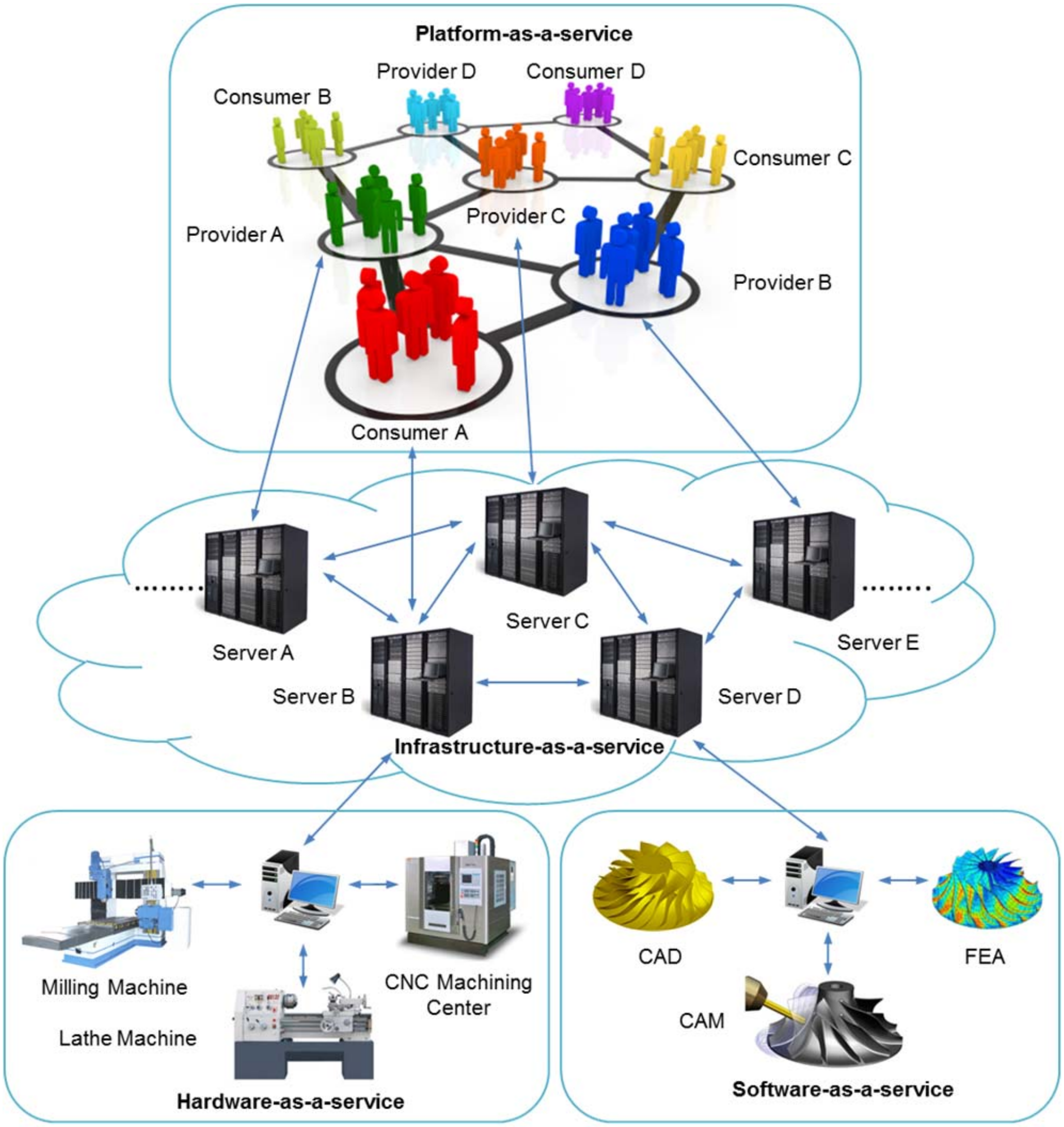


Figure 3-3 Information flow in CBDM [5]

A web portal offered as a PaaS component serves as the front end of CBDM systems; that is where service consumers and providers interact and communicate with each other on customer needs, function requirements, constraints etc. The IT infrastructure, computing resources, manufacturing hardware, and application software provided through IaaS, HaaS, and SaaS respectively represent the back end of CBDM systems. An example information flow in CBDM is as follows; Consumer 'A' submits an RFQ for designing and machining a turbine blisk prototype to a CBDM system. The search engine returns a list of alternative design and machining service providers (e.g., providers ‘B’ and ‘C’) based on the RFQ specifications. The geometric modeling as well as structure and thermal analyses are conducted via CAD and FEA software running in the cloud. The design service providers reply to the RFQ estimated prices for their designs based on the design requirements. In parallel, the machining service providers reply to the RFQ estimated prices and lead times based on some rough design requirements such as material, dimensions, volume, and quality. Once the detailed design (i.e., 3D digital models and CAD drawings) is finished by the design service provider, more accurate machining time can be estimated based on tool path planning and simulation.

Table 3-4 Key characteristics and comparison

Characteristics	**Web-based**	**Agent-based**	**Cloud-based**
Scalability	X	X	X
Agility	X	X	X
High performance computing		X	X
Networked environment		X	X
Affordable computing			X
Ubiquitous access			X
Self-service			X
Big data			X
Search engine			X
Social media			X
Real-time quoting			X
Pay-per-use			X
Resource pooling			X
Virtualization			X
Multi-tenancy			X
Crowdsourcing			X
Infrastructure-as-a-service			X
Platform-as-a-service			X
Hardware-as-a-service			X
Software-as-a-service			X

3.3 Characteristics and Requirements for CBDM

According to the existing definitions for CBDM presented before, Table 3-4 lists some common key characteristics of CBDM that they share and compares CBDM with other relevant distributed design and manufacturing systems such as web- and agent-based systems. As shown in Table 3-4, CBDM provides significantly more benefits than web- and agent-based systems. Based on the key characteristics listed in Table 3-4, a requirements checklist (see Table 3-5) that a future CBDM system should satisfy is defined.

Table 3-5 A requirements checklist for CBDM systems

Requirement	Requirement description
R1.	Should provide social media to support communication, information and knowledge sharing in the networked design and manufacturing environment
R2.	Should provide cloud-based distributed file systems that allow users to have ubiquitous access to design- and manufacturing-related data
R3.	Should have an open-source programming framework that can process and analyze big data stored in the cloud
R4.	Should provide a multi-tenancy environment where a single software instance can serve multiple tenants
R5.	Should be able to collect real-time data from manufacturing resources (e.g., machines, robots, and assembly lines), store these data in the cloud, remotely monitor and control these manufacturing resources
R6.	Should provide IaaS, PaaS, HaaS, and SaaS applications to users
R7.	Should support an intelligent search engine to users to help answer queries
R8.	Should provide a quoting engine to generate instant quotes based on design and manufacturing specification

The purpose of the requirements checklist is to clarify whether or not a given design and manufacturing system falls into the realm of CBDM. Each requirement is detailed as follows:

- Requirement 1 (R1): To connect individual service providers and consumers in a networked design and manufacturing setting, a CBDM system should support social media-based networking services. Social media applications such as Quirky allow users to utilize/leverage crowdsourcing processes in design and manufacturing. In addition, social media does not only connect individuals; but it also connects design- and manufacturing-related data and information, enabling users to interact with a global community of experts on the Internet.

- Requirement 2 (R2): To allow users to collaborate and share 3D geometric data instantly, a CBDM system should provide elastic and cloud-based storage that allows files to be stored, maintained, and synchronized automatically.
- Requirement 3 (R3): To process and manage large datasets, so called big data, with parallel and distributed data mining algorithms on a computer cluster, a CBDM system should employ an open-source software/programming framework that supports data-intensive distributed applications. For example, MapReduce is one of the most widely used programming models in cloud computing environments, as it is supported by leading cloud providers such as Google and Amazon [155, 156].
- Requirement 4 (R4): To provide SaaS applications to customers, a CBDM system should support a multi-tenancy architecture. Through multi-tenancy, a single software instance can serve multiple tenants via a web browser. According to Numecent [157], a cloud platform, called Native as a Service (NaaS), is developed to deliver native Windows applications to client devices. In other words, NaaS can "cloudify" CAD/CAM software such as SolidWorks without developing cloud-based applications separately. With such a multi-tenant platform, such programs can be run as if they were native applications installed on the user's device.
- Requirement 5 (R5): To allocate and control manufacturing resources (e.g., machines, robots, manufacturing cells, and assembly lines) in CBDM systems effectively and efficiently, real-time monitoring of material flow, availability and capacity of manufacturing resources become increasingly important in cloud-based process planning, scheduling, and job

dispatching. Hence, a CBDM system should be able to collect real-time data using IoT technologies such as radio-frequency identification (RFID) and store these data in cloud-based distributed file systems.

- Requirement 6 (R6): To implement a service-oriented architecture model in design and manufacturing, a CBDM system should provide for users X-as-a-service (everything as a service) applications such as IaaS, PaaS, HaaS, and SaaS.
- Requirement 7 (R7): To assist users to find suitable manufacturing resources in the cloud, a CBDM system should provide an intelligent search engine for design and manufacturing to help answer users' queries [158].
- Requirement 8 (R8): To streamline workflow and improve business processes, a CBDM system should provide an online quoting engine to generate instant quotes based on design and manufacturing specifications.

3.4 Comparing CBDM with Web- and Agent-Based Design and Manufacturing

In addition to the essential characteristics of CBDM and systematic requirements checklist presented in the previous section, differences and similarities between CBDM and web- and agent-based systems will be articulated from a number of perspectives, including (1) computing architecture, (2) design communication, (3) sourcing process, (4) information and communication infrastructure, (5) programming model, (6) data storage, and (7) business model.

3.4.1 Computing Architecture

From a computing perspective, the difference between web- and agent-based applications and cloud-based applications is two-fold: multi-tenancy and virtualization. Figure 3-4 illustrates a unified computing architecture for CBDM systems that is distinguished from web- and agent-based design and manufacturing systems.

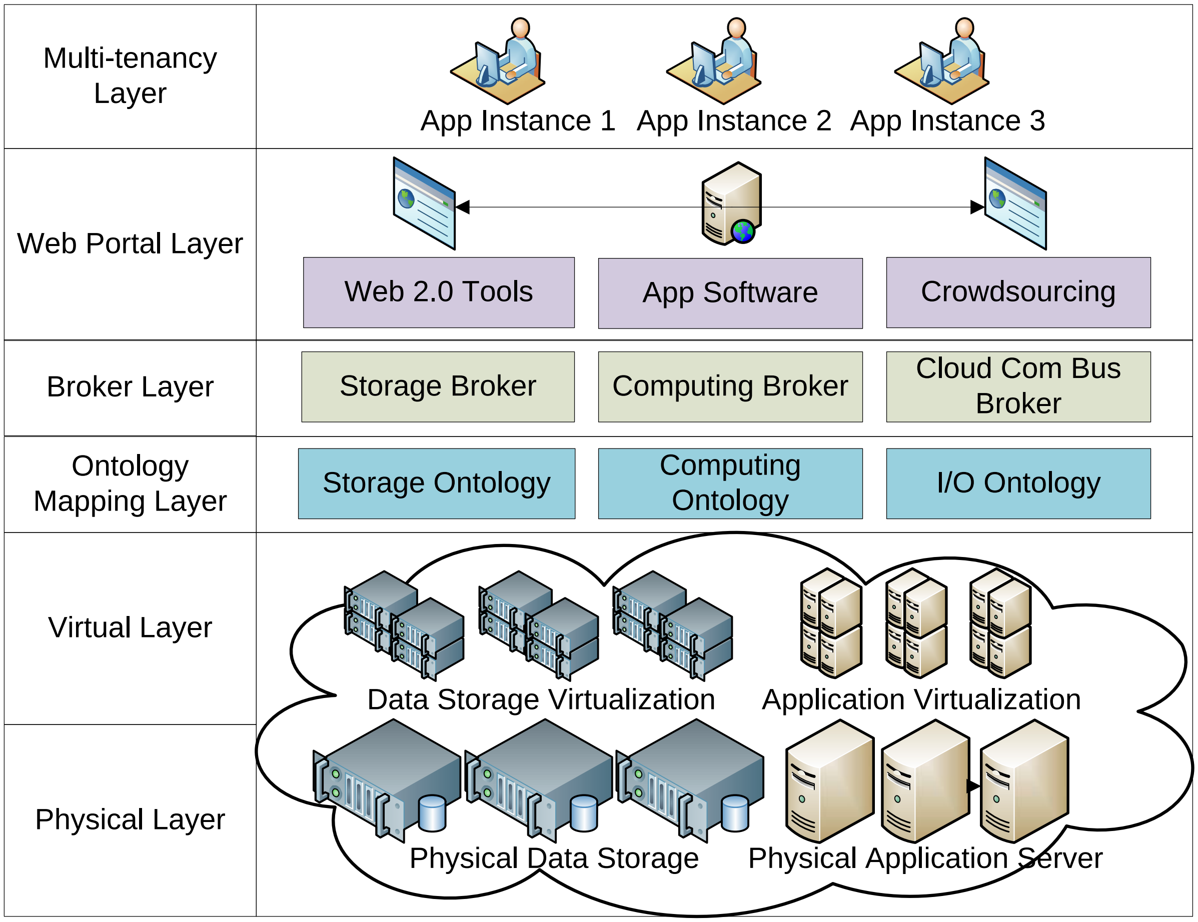
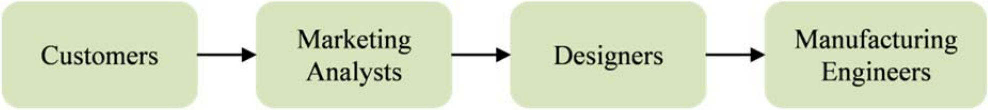


Figure 3-4 A computing architecture for CBDM systems

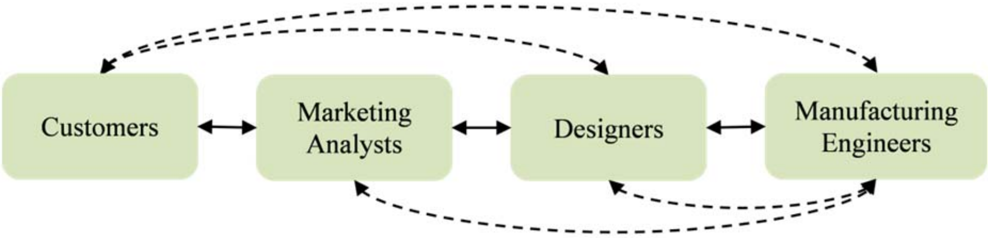
As previously stated, in the proposed computing architecture, multi-tenancy enables a single instance of the application software to serve multiple tenants. To share computing and ICT resources in cloud computing, multi-tenancy is the most fundamentally used technology for its security and cost efficiency. To provide an interface such as social media and crowdsourcing platforms between service providers and consumers, the web portal of CBDM systems is developed using Web 2.0 technology and associated application software. To improve the negotiation process between service providers and consumers as well as enhance security and privacy in CBDM systems, a cloud broker (e.g., cloud-based storage and computing brokers) can help users identify, customize, and integrate existing design and manufacturing services. For instance, a cloud broker provides services that allow users to analyze the information and material flow in CBDM systems. Moreover, to develop CBDM systems using the semantic web, ontology mapping provides a common layer from which multiple ontologies could be accessed and hence users can exchange design- and manufacturing-related information in a semantically sound manner. In addition, as shown in the virtual and physical layers in Figure 3-4, virtualization can improve the efficiency and availability of computing and ICT resources by re-allocating hardware dynamically to applications based on their need. Virtualization enables enterprises to separate engineering software packages, computing resources, and data storage from physical computing hardware as well as to support time and resource sharing.

3.4.2 Design Communication

From a communication perspective, one of the ultimate goals of research on engineering design is to improve communication in the design process. As stated before, the design of any product is an inherently social, technical process. The key issue in improving design communication is the extent to which design engineers fully understand a complex design process, in particular, design tasks that need to be finished, individuals from whom specific information can be accessed, the extent to which acquired information is distorted, and influence of the distorted information on design [159]. In traditional collaborative design settings, communication can be seen as a one-way process with a linear sequence of design phases as shown in Figure 3-5 (a). Because of the use of social media in CBD settings, design communication can be improved through multiple information channels (e.g., social network sites and product review sites) in which information flow can take place in multiple directions as shown in Figure 3-5 (b) [5]. For instance, social media allows design engineers to collaborate with customers concurrently by receiving instant feedback from customers.



(a) A linear sequence of design phases in traditional design



(b) A linear sequence of design phases with more information channels in CBD

Figure 3-5 Design communication

Moreover, traditional computer-aided application tools (e.g., CAD/CAE/CAM) were standalone systems and designed for single user without communicating and collaborating with others [160-162]. In CBD settings, engineering design requires more communication and collaboration within and across organizations on the modeling, analysis, and optimization of a design. As stated in Section 3.4.1, the use of virtualization and multi-tenancy in CBDM allows for simultaneous concurrency in CAD, CAE, and CAM tools. Specifically, computer-aided design, engineering analysis, and manufacturing tools in CBDM settings will allow users in a cross-disciplinary design team to simultaneously create and modify design features of a product model. In addition, according to a recent survey, to communicate in traditional design settings, design engineers spend an average of 15% of their time at work on the phone and receive 50 emails average per day. Communication tools (e.g., instant messaging, virtual meeting, screen sharing, and social network sites) integrated in computer-aided application tools allow for multiple information transmission channels that can significantly improve productivity.

3.4.3 Sourcing Process

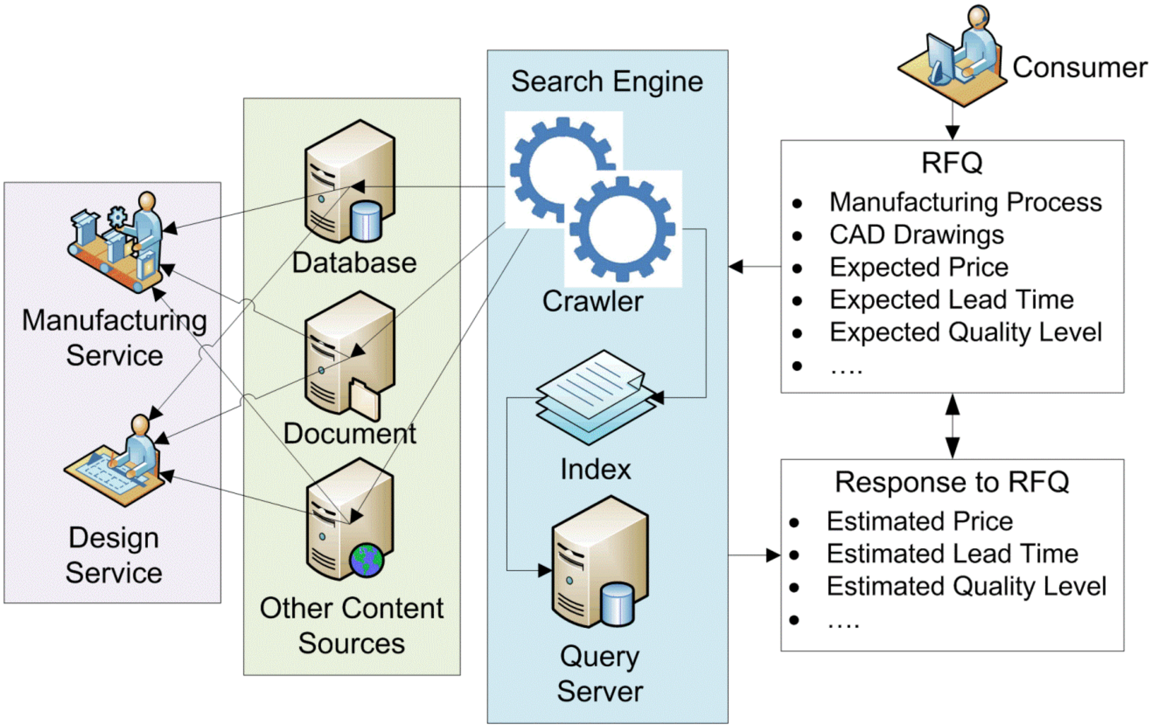


Figure 3-6 A crowdsourcing process for RFQs in CBDM systems

From a sourcing process perspective, CBDM can leverage the power of the crowd. For instance, CBDM enables service consumers to quickly and easily locate qualified service providers who offer design and manufacturing services such as CNC machining, injection molding, casting, or 3D printing through a cloud-based sourcing platform. Figure 3-6 illustrates the cloud-based sourcing process, which enables consumers to submit requests for quotes (RFQs) to a search engine and receive a list of qualified service providers. The search engine consists of a crawler, indices, and query servers. The crawler gathers manufacturing-related data (e.g., process variables, machine specifications) from databases, document servers, and other content sources, and it stores them in the index. The index ranks these data based on metrics (e.g., price, quality, and geographic location) specified by the users. A query server is the front end of the search engine; it delivers to consumers the results of a search query as a response to the RFQs; the results are based on the specifications such as expected prices, lead times, and quality levels. However, with regard to web- and agent-based design and manufacturing systems, it is not feasible to implement such a computationally expensive sourcing platform that connects service consumers and providers worldwide. Moreover, in comparison with commercial quoting systems such as Quickparts.com and MFG.com, the proposed cloud-based sourcing platform can not only conduct quoting for design and manufacturing services such as rapid prototyping, injection molding, and casting, but also conduct manufacturing and computing resource allocation, and scheduling activities. Further, in contrast with existing 3D printing services where users upload design files and print objects from a single site, CBDM allows users to print their designs at any 3D printer in the cloud rather than at one particular site.

3.4.4 Information and Communication Infrastructure

From an information and communication infrastructure perspective, CBDM employs the IoT (e.g., RFID), smart sensor, and wireless devices (e.g., smart phone) to collect real-time design- and manufacturing-related data as shown in Figure 3-7. The essence of IoT and embedded sensors is to capture events (e.g., inventory level), to represent physical objects (e.g., machine tools) in digital form, and finally to connect machines with people. For instance, IoT allows engineers to have access to data such as machine utilization, equipment conditions, and the percentage of defective products from any location. With the big data generated by the IoT-related devices, engineers may apply big data analytics for forecasting, proactive maintenance, and automation. However, such seamless connections cannot be provided in web- and agent-based design and manufacturing systems because of their limited data acquisition and computing capabilities.

Figure 3-7 Information and communication infrastructure in CBDM systems

3.4.5 Programming Model

From a programming model perspective, MapReduce [155], a parallel programming model, enables CBDM systems to process large datasets which web- and agent-based manufacturing systems are not able to deal with. One of the most well-known open source implementations of the MapReduce model is Hadoop [163]. Similar to other parallel programming models, Hadoop divides computationally extensive tasks into small fragments of work, and each work unit is processed on a computer node in a Hadoop cluster. The MapReduce framework is implemented through two core processes named Map and Reduce. Specifically, in a Map process, a master node receives an input task, divides it into smaller sub-tasks, and distributes them to worker nodes. The worker nodes process the smaller sub-tasks, and send the answer back to the master node. In a Reduce process, a master node receives the answers of all the sub-tasks and combines them to generate the result of the original task. Such a parallel programming model enables CBDM to handle big data generated in design and manufacturing.

3.4.6 Data Storage

From a data storage perspective, with regard to web- and agent-based design and manufacturing, product-related data are stored at designated servers, and users know where these data are as well as who is providing them. However, with regard to CBDM, networked enterprise data are stored not only on users' computers, but also in virtualized data centers that are generally hosted by third parties (see the virtual and physical layers in Figure 3-4). Physically, these data may span across multiple servers. In other words, the users may neither exactly know who the service providers are nor where the data are stored. However, the data may be accessed through a web service application programming interface (API) or a web browser. The advantages of cloud-based data storage are: (1) cloud-based data storage provides users with ubiquitous access to a broad range of data stored in the networked servers via a web service interface; (2) data storage can easily scale up and down as needed on a self-service basis; (3) users are only charged for the storage they actually use in the cloud.

3.4.7 Business Model

From a business model perspective, the significant difference between CBDM and web- and agent-based design and manufacturing is that CBDM involves new business models; but web- and agent-based design and manufacturing paradigms do not. That is, CBDM does not simply provide new technologies; it also involves how design and manufacturing services can be delivered (e.g., IaaS, PaaS, HaaS, and SaaS), how services can be deployed (e.g., private cloud, public cloud and hybrid cloud), and how services can be paid for (i.e., pay-per-use). For example, a key driver of CBDM is the pay-per-use model that has the potential to reduce up-front investments on IT and manufacturing infrastructure for small- and medium-sized enterprises (SMEs). Instead of purchasing manufacturing equipment and software licenses, CBDM users can pay a periodic subscription or utilization fee with minimal upfront costs. Likewise, scalability and elasticity allow users to avoid over purchase of computing and manufacturing capacities.

3.5 Cloud-Based Design and Manufacturing Scenario

In this section, a hypothetical design and manufacturing scenario in a future CBDM environment based on currently existing and potentially new cloud-based service offerings is presented. The example scenario is meant to help clarify the vision of CBDM and demonstrate its unique value.

In this example scenario, the design task is to develop a next-generation smart delivery product, technically called unmanned aerial vehicles (also referred to as drones as shown in Figure 3-8), that can deliver packages from a distribution center to customers faster and at a reasonable price. The design brief is as follows:

"*The Federal Aviation Administration (FAA) currently has strict regulations for drones. In five years or so, the FAA will address current and future policies, regulations, technologies, and procedures related to the commercial use of drones in the United States. The design task is to conceptualize, design, and prototype a product that can carry a package up to 10 pounds, deliver it in 20 miles in radius within an hour.*"

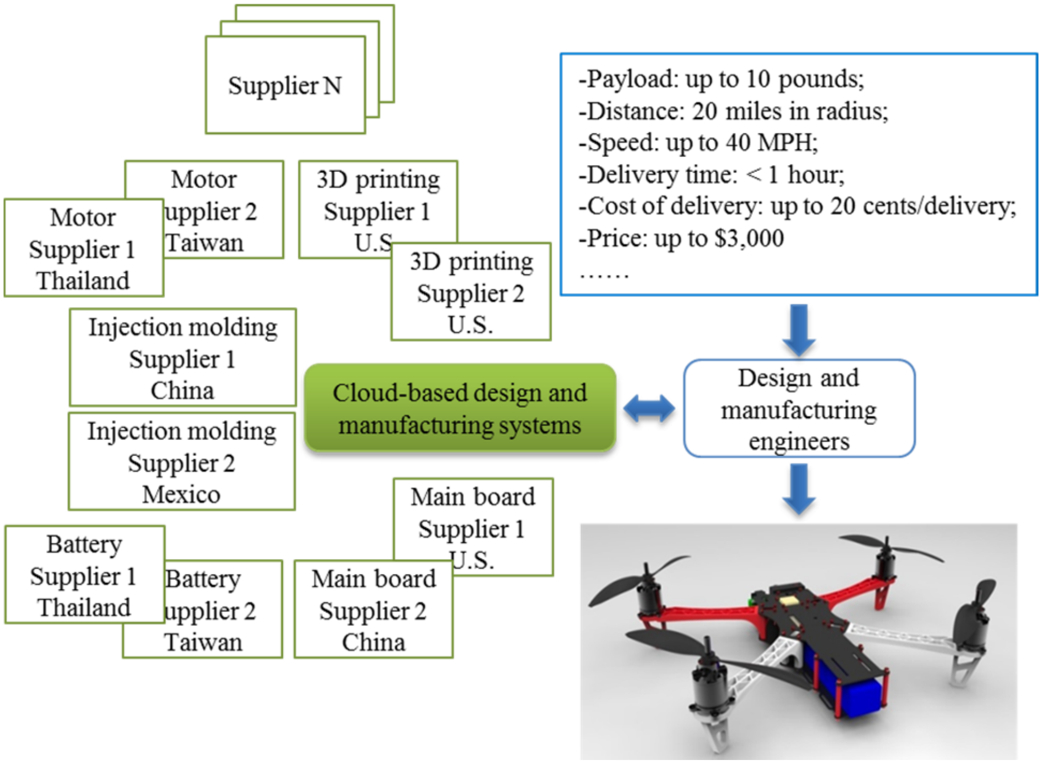


Figure 3-8 Cloud-based design and manufacturing for drones

Figure 3-8 shows the hypothetic scenario for developing the next-generation smart delivery drone using CBDM. More technical details about the example CBDM scenario will be described in the following sections.

3.5.1 Architecture of an Integrated CBDM System

This section presents how the integration of existing and potentially new services and technologies may enhance the drone development process. The notional architecture of an integrated CBDM system, as shown in Figure 3-9, is proposed to illustrate the service models (i.e., IaaS, PaaS, HaaS, and SaaS), the existing and potentially new service providers, and the delivery drone development process.

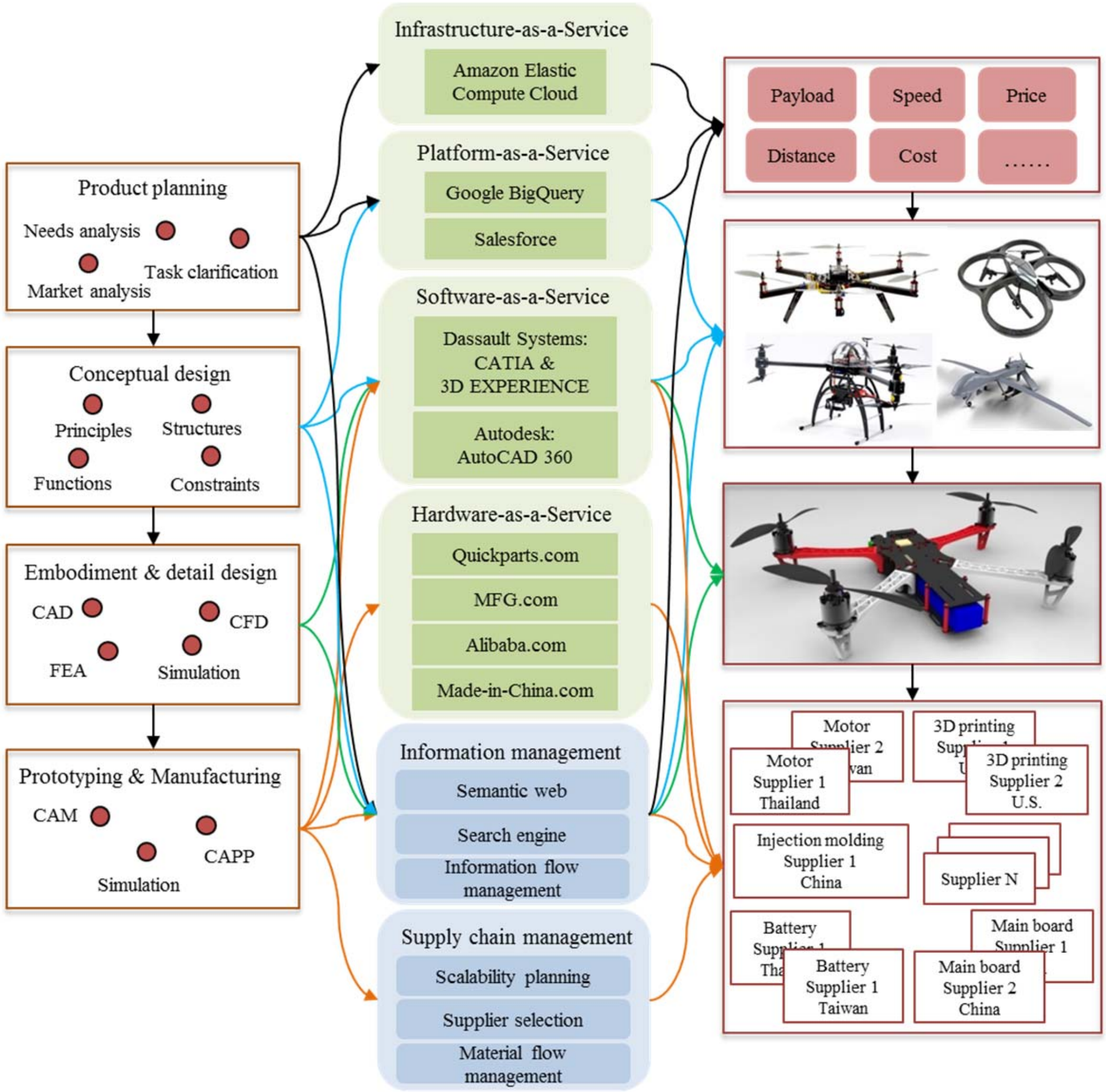


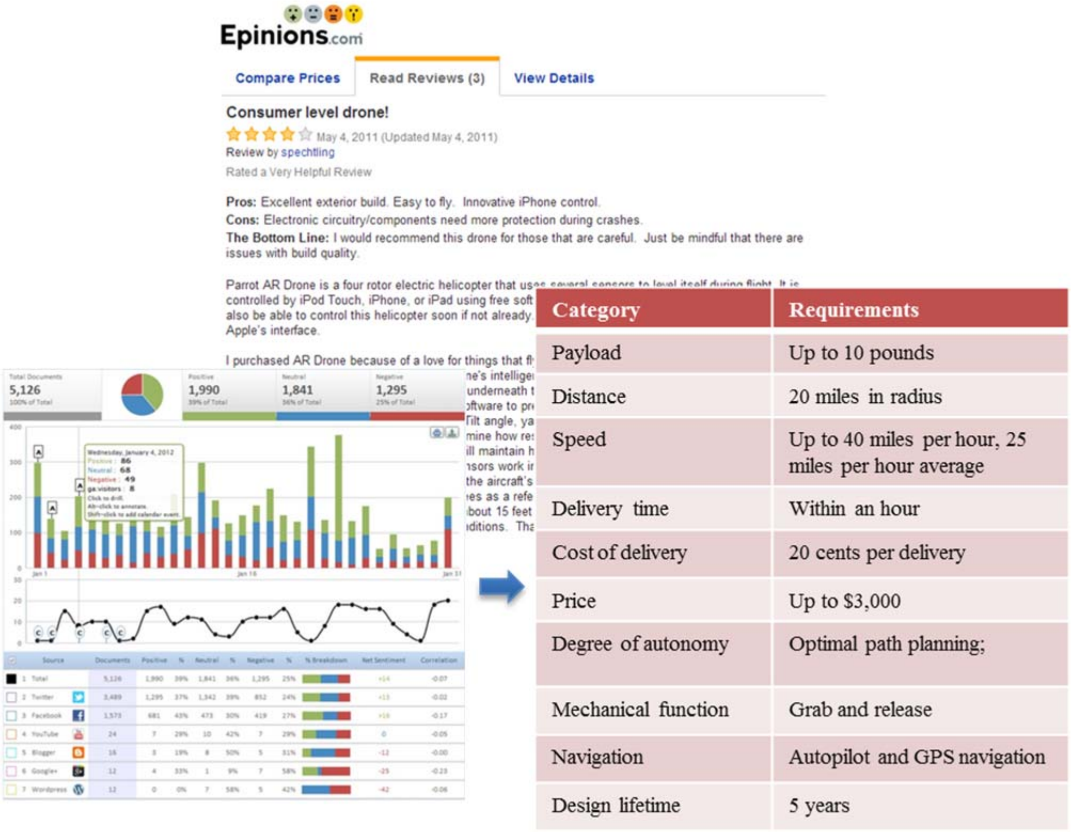
Figure 3-9 Notional system architecture of an integrated CBDM system

Specifically, in the product planning stage, the team analyzes customer needs and clarifies development tasks using IaaS and PaaS provided by Amazon Elastic Compute Cloud, Google BigQuery, and Salesforce. For instance, Amazon allows the team to store large datasets collected from Epinions and Social.com in the cloud-based storage. Google BigQuery and Salesforce.com allow the team to process these massively large datasets. Through the IaaS and PaaS, the team generates design requirements on payload, distance, speed, delivery time and cost, price, degree of autonomy, navigation, design lifetime, and so on more effectively and efficiently. In the conceptual design stage, based on these design requirements, the team proposes function structures, working principles, engineering and economic constraints using PaaS and SaaS. For instance, Autodesk, the provider of SaaS, allows the team to capture drone design concepts digitally and quickly create 3D concept models. Dassault Systemes, the provider of both PaaS and SaaS, allows the team to build custom social media (e.g., wikis and online forum) for enhancing design ideation and sharing design experience. Through the PaaS and SaaS, the team proposes four design concepts: HexaCopter, Quadcopter, Tricopter, and Wing drones as shown in Figure 3-9. In the embodiment and detail design stages, based on the proposed design concepts, the team develops preliminary and definitive layouts using CAx application tools (e.g., CAD, FEA, and CFD) using SaaS. For instance, both Dassault Systemes and Autodesk allow the team to have access to CAD drawing files, to perform computational fluid dynamics (CFD) and finite element analysis (FEA) simulations for the drone design using browsers on a pay-per-use basis. In the prototyping and manufacturing stages, the team develops a prototype of the drone and manufacturing process plans for mass production using SaaS and HaaS. For instance, Quickparts.com, MFG.com, Alibaba.com and Made-in-China.com, the providers of HaaS, allow the team to source manufacturing tasks to qualified suppliers and manufacturers using the instant quoting engine. Quickparts also allows the team to perform manufacturability analysis for the drone parts before 3D printing.

In addition to the existing cloud-based commercial software systems and services, some new modules of the CBDM system are needed including information and supply chain management. As shown in Figure 3-9, the cloud-based information management module allows the team to exchange and share drone development-related information throughout the drone development process. Semantic web-based design and manufacturing knowledge representation can significantly automate the design and manufacturing processes and increase productivity using the machine-readable knowledge representation scheme. The semantic search engine allows design and manufacturing engineers to improve search accuracy by using semantics rather than using ranking algorithms. The information management module also allows engineers to capture the correct information from the right individual based on social network analysis. This unique feature can significantly improve communication and collaboration in the design and manufacturing process. Moreover, the cloud-based supply chain management module allows for manufacturing capacity scalability planning and control by simulating the material flow in the CBDM process and optimizing supplier selection. In Sections 3.5.2 and 3.5.3, the benefits of developing the drone using a CBDM system are presented from multiple perspectives in more detail.

3.5.2 Cloud-Based Design

From a requirements elicitation perspective, CBD allows design engineers to conduct market research more effectively and efficiently through social media. Specifically, they can use business-targeted market research platforms such as HootSuite [164], Epinions [165], and Salesforce.com to collect customer feedback and responses on existing and new features of drones. For instance, HootSuite allows the design team to collect massive customer feedback and reviews across most of the major social networks such as Twitter, Facebook, Google plus as well as social marketing sites such as Foursquare [166]. Similarly, social media-based market research platforms (e.g., social.com, radian 6, and buddy media) provided by Salesforce allow the design team to identify lead users for design innovation by creating engaging Facebook tabs rather than by performing survey of large user populations. After collecting these data from social media, design engineers can elicit design requirements and customer preference using cloud-based big data analytics tools such as Google BigQuery [167]. For instance, Google BigQuery allows for processing these massively large datasets using the MapReduce framework, a parallel and distributed programming model.



Consumer level drone!

May 4, 2011 (Updated May 4, 2011)

Review by spechtling

Rated a Very Helpful Review

Pros: Excellent exterior build. Easy to fly. Innovative iPhone control.

Cons: Electronic circuitry/components need more protection during crashes.

The Bottom Line: I would recommend this drone for those that are careful. Just be mindful that there are issues with build quality.

Parrot AR Drone is a four rotor electric helicopter that us
controlled by iPod Touch, iPhone, or iPad using free soft
also be able to control this helicopter soon if not already
Apple's interface.

I purchased AR Drone because of a love for things that fl

Category	Requirements
Payload	Up to 10 pounds
Distance	20 miles in radius
Speed	Up to 40 miles per hour, 25 miles per hour average
Delivery time	Within an hour
Cost of delivery	20 cents per delivery
Price	Up to $3,000
Degree of autonomy	Optimal path planning;
Mechanical function	Grab and release
Navigation	Autopilot and GPS navigation
Design lifetime	5 years

Figure 3-10 Requirements elicitation based on customer reviews

As shown in Figure 3-10, these data analytics generated by Google BigQuery allow design engineers to derive the functional requirements of the drone more effectively and efficiently.

From a conceptual design perspective, cloud-based crowdsourcing platforms allow the design team to solicit new design ideas from more sources such as customers, users, and hobbyists, thereby enhancing ideation for product innovation. For example, the design team can launch such a cloud-based crowdsourcing platform, similar to Local Motors' open-source platform, to source collaborative design ideas from an online community of designers, engineers, and fabricators. Such a crowdsourcing platform can help the design team generate more innovative drone design concepts as shown in Figure 3-11.

Figure 3-11 Design concepts for delivery drones

From a design communication perspective, cloud-based information management tools allow for enhanced information flow management that can significantly improve design productivity. From this aspect, collaborative design can be modeled as an information-driven process among design activities. Participants in collaborative design can be viewed as a social network in which design-related information are transmitted from one to another. In this context, having access to the right design information from the right designer – the correct product specifications and the correct version of a drawing or model – is imperative for collaborative design. Through social network analysis, CBD has the potential to help design engineers capture the correct design information from the right individual in an escalating virtual and social environment. The graph theory and data mining tools in SNA allow for visualizing information flow in the drone design network, detecting groups of design engineers with common design interests and activities while design activities are being conducted. For instance, Figure 3-12 illustrates that multiple design sub-groups (e.g., hardware group for frame, manipulator, propeller design and software group for navigation and motion control systems) are detected while the drone is being designed. These data mining and visualization technologies used in CBD have the potential to significantly increase the productivity for the drone design process by allowing design engineers to search for the right design information from the right designer.

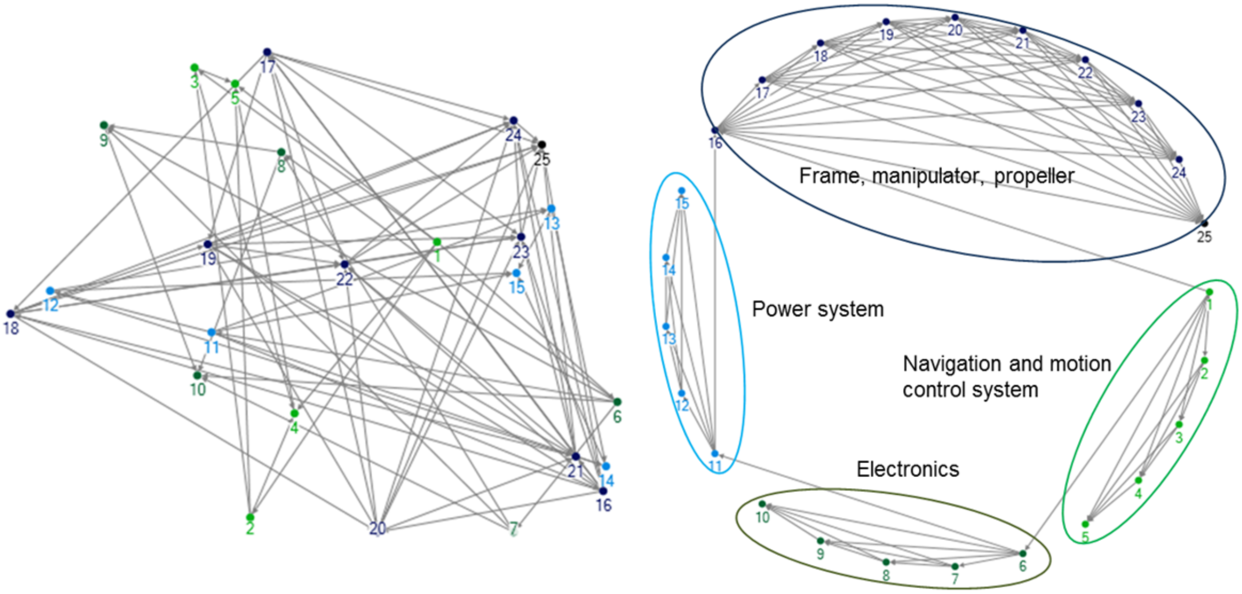


Figure 3-12 Information flow visualization and community detection

As the second challenge pertaining to CBD identified in Chapters 1 and 2, a new approach that can visualize distributed and collaborative design processes, measure tie strengths in a complex and large design team, detect design communities with common design interests or activities is presented using two illustrative examples in Chapter 5. This approach is the kernel of the cloud-based information management tool that helps improve design communication and collaboration.

From a computer-aided design perspective, the traditional collaborative design process is typically expensive because it requires substantial computing resources, data consistency, transparent communication and seamless information sharing. As stated before, web- and agent-based collaborative design platforms enable authorized users in geographically different locations to have access to design-related data such as CAD drawing files stored at designated servers and to perform computationally extensive simulation and analysis simultaneously and collaboratively through the client-server architecture. CBD has the potential to allow the distributed design team to conduct these design activities more cost-effectively and efficiently by using cloud-based CAx software such as CATIA V6 and AutoCAD 360.

For instance, CATIA V6 provides the design team with a flexible subscription pricing model, namely pay-per-use, without upfront investments in CAx software. Specifically, the 3DEXPERIENCE cloud-based platform enables the design team to perform computing-intensive computational fluid dynamics (CFD) simulation and finite element analysis (FEA) for the drone design by utilizing high performance and highly scalable computing resources provided by the Amazon Elastic Compute Cloud (Amazon EC2). Virtualization and multi-tenancy technologies used in CBD allow design engineers to simultaneously create and modify design features of a drone CAD model while ensuring data consistency.

3.5.3 Cloud-Based Manufacturing

After the detail design phase is finished, the design team needs to build a prototype in a CBM setting. Figure 3-13 shows a simplified drone model with a few labeled parts. Some of the mechanical parts such as the propellers and frame of the drone can be 3D printed (see Figure 3-14). Others such as the shield can be injection molded.

From a rapid prototyping perspective, CBM allows the design team to build the prototype more efficiently and cost effectively without large upfront investment in manufacturing equipment. The design team can manufacture the major mechanical components of the drone through cloud-based sourcing platforms (Quickparts, MFG.com, Alibaba.com [168], and i.materialise [169]).

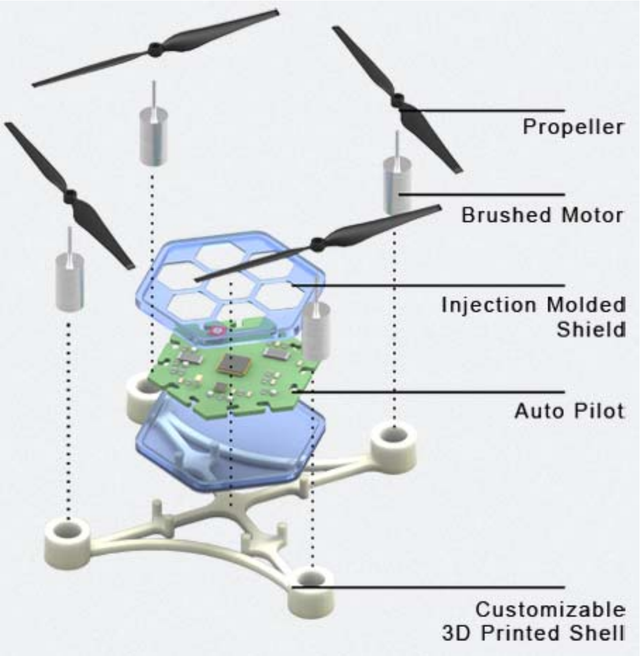


Figure 3-13 Build a simplified drone model using 3D printing and injection molding [170]

Figure 3-14 Build the propeller of the drone using 3D printing [171]

For instance, Quickparts connects the design team to hundreds of 3D printing service providers through an instant quoting engine. Quickparts enables design engineers to upload their CAD files of the drone design created by CATIA and SolidWorks, to perform geometric and printability analysis, and finally to receive a list of qualified service providers instantly. The geometric and manufacturability analysis significantly improves the design for manufacturability process and increases manufacturing efficiency and productivity. In addition to 3D printing, MFG.com allows the design team to discover global suppliers who deliver a variety of manufacturing services such as injection molding, casting, and machining for manufacturing some components of the drone. Moreover, Alibaba.com and Made-in-China.com [172] allow the team to discover suppliers who provide electrical and electronics components (e.g., motion control board, camera, pressure, temperature and speed sensors, and autopilot management unit). Sourcing manufacturing tasks and electronics components to service providers not only allows the design team to save upfront investment in 3D printers and injection molding machines but also allows them to focus on design innovation.

From a manufacturing automation perspective, the cyber-infrastructure of CBM along with semantic web-based manufacturing knowledge representation has the potential to automate manufacturing processes. Specifically, the machine-readable knowledge representation scheme, referred to as web service description language (WSDL), and universal description discovery and integration (UDDI) allow manufacturing service providers to publish their manufacturing services in a machine-readable language. Further, the formal representation of manufacturing resources enables the automatic retrieval of the required manufacturing services based on the semantic matchmaking of required and published manufacturing service specifications [173]. For instance, in this example scenario, CBM allows the team to automatically retrieve a list of 3D printers that are capable of building the propellers based on the published manufacturing specifications such as build time and costs. Figure 3-14 shows some of the manufacturing specifications including build material, maximum model dimension, and layer resolution.

From a manufacturing capacity scalability perspective, CBM allows the development team to leverage more cost-effective manufacturing services from global manufacturing suppliers (see Figure 3-8) and to rapidly scale up and down manufacturing capacity. In this example scenario, after considerable testing and prototyping, if the drone is deemed commercially viable, the team will introduce the drone into the market. In the introduction stage, customers are few and sales are low. If the drone is popular with consumers, then market demand will start to increase and sales will start to rise. At this stage, the team will have to scale manufacturing capacity and put the drone into mass production. To achieve this goal, for instance, the frame and propellers can be sourced to 3D printing suppliers in U.S.; the shield can be sourced to injection molding suppliers in Mexico; the battery can be sourced suppliers in Thailand; some of the electronic components such as the main board can be sourced to China. Moreover, manufacturing capacity can be rapidly scaled up when needed, because the team can almost always find a list of qualified service providers whose manufacturing capacity is not fully utilized using the aforementioned cloud-based global sourcing platforms. Even if most manufacturing service providers are running at their full capacity, in order to make more profits or receive larger orders, these service providers may still prioritize manufacturing tasks and reallocate their manufacturing capacity to more profitable businesses.

From a manufacturing supply chain perspective, CBM has the potential to optimize complex material flow in the cloud-based sourcing process, thereby increasing manufacturing productivity. As stated before, CBM allows for rapid manufacturing capacity scalability by sourcing manufacturing tasks to global suppliers. Scaling up and down manufacturing capacity for the drone requires detecting manufacturing bottlenecks and optimizing manufacturing supply chain. To achieve this goal, material flow that transforms raw material to parts, to sub-assembly, to assembly, and finally to end-products between service providers and consumers needs to be planned and controlled. To systematically plan and control the material flow in the manufacturing supply chain, a third-party entity, also referred to as a CBM broker, provides approaches that allow for modeling, analyzing, and optimizing the material flow prior to implementation. By simulating manufacturing processes, the team observes that building the propellers and frame and transporting them back to the assembly plant take longer time than average cycle time, thereby becoming manufacturing bottlenecks. Through the simulation, the team can select optimal suppliers for the propellers and frame by taking manufacturing and transportation times and costs into account.

As the third challenge pertaining to CBM identified in Chapters 1 and 2, a new approach that helps identify potential manufacturing bottlenecks that determine manufacturing capacity scalability prior to the implementation and deployment of CBM systems is presented using an illustrative example in Chapter 6. This approach is the kernel of the cloud-based discrete event simulation tool that simulates manufacturing operation scenarios in CBM settings.

The above hypothetical example scenario in a future CBDM environment illustrates how the proposed CBDM paradigm has the potential to enhance the product realization process from multiple perspectives. In particular, it is demonstrated that CBDM has the potential to significantly enhance design innovation and increase design efficiency, to reduce prototyping costs and enhance design for manufacturability, to increase digital manufacturing productivity, and to enable manufacturing capacity scalability in comparison with traditional collaborative design distributed manufacturing paradigms.

3.6 Research Opportunities in CBDM

To bridge the gap between currently existing technologies, services, infrastructures and our vision of CBDM, it is worthwhile to discuss how future and emerging technologies such as cyber-physical systems (CPS), the internet of things (IoT), and big data can help achieve and improve CBDM as follows:

- CPS are expected to play a major role in the design and development of future CBDM systems. Specifically, CPS have the potential to integrate design- and manufacturing-related knowledge and principles, connect both cyber and physical components, and enhance the interaction among complex physical machinery, networked sensors, and engineering software. Significant progress in embedded systems, sensor and mobile networks has been made in advancing CPS over the last five years. However, scientific foundations for supporting the modeling, analysis, and design of CPS have not yet been fully developed. In particular, developing a truly CBDM system requires significant advances in CPS with respect to interoperability, real-time embedded systems, sensor and actuator technology, information and communication infrastructure, reliability, and cyber security. For instance, interoperability in CPS needs to be addressed such that CBDM systems can seamlessly communicate, execute computer programs, and transfer data among various functional units as well as to perform automatic logical inference and knowledge discovery. Meanwhile, cyber-security in CPS needs to be addressed at many levels including system integrity, data security, intellectual property, and privacy. To address rapidly evolving cyber and physical threats, it is crucial to develop formal trust models between actors (e.g., service consumers and providers) in CBDM systems and quantitative approaches to CPS vulnerability assessments.

- IoT is another key enabling technology to improve manufacturing automation, supply chain management, remote maintenance and diagnostics in the future development and implementation of CBDM. Specifically, because IoT is characterized by ubiquitous computing (e.g., embedded wireless sensors and actuators) and pervasive sensing technologies (e.g., Radio-Frequency Identification tags), it has the potential to automate manufacturing processes by connecting humans, machines, manufacturing processes, and design- and manufacturing-related massive datasets. With respect to ubiquitous computing, most of the existing wireless sensor network techniques are based on the IEEE 802.15.4 standard, which only defines the physical and MAC layers for low-power, low bit rate communications [174]. Therefore, standards that define the physical and MAC layers for high-power, high bit rate communications need to be addressed. With respect to pervasive sensing, IP addressing policy is still an open issue. Currently, the IPv4 protocol identifies an object or a node in a sensor network through a 4-byte address. As an increasing number of objects need to be identified in CBDM networks, new IP addressing policies need to be addressed. In addition to RFID, new technologies in pervasive sensing need to be addressed to support machine to machine, machine to infrastructure, machine to environment, human to human, and human to machine communications from anywhere at any time. These new technologies in sensing and communication protocols will enable CBDM systems to track and trace specific objects, monitor and synchronize material flow in manufacturing, and support cloud-based remote maintenance and diagnostics.

- Because manufacturing generates data from a multitude of sources and stores more data than any other sector, new techniques for collecting, processing, and analyzing big data will significantly impact on CBDM with respect to design innovation, manufacturing intelligence, cost reduction, productivity, and efficiency. Existing techniques that can be used to analyze big data in manufacturing include association rule learning, classification, cluster analysis, data fusion and data integration, data mining, generic algorithms, neural networks, regression, simulation, and time series analysis. However, new techniques in big data analytics, network analysis, sentiment analysis, and visualization are required to support future CBDM systems. For example, semantic-based big data analytics can help forecast sales volumes based on various market and economic variables and determine what key measurable manufacturing parameters most influence customer satisfaction. Future advances in pattern recognition, sentiment analysis, and recommendation systems for big data will enable engineers to extract crucial customer needs from the increasing volume of customer- and user-generated data to refine existing designs and develop new products. New algorithms in social network analysis will allow for visualizing information flow, identifying key opinion leaders to target for marketing, and detecting bottlenecks in enterprise information flows [175].
- Because various parties in CBDM systems will generate multiple ontologies and some of these ontologies will describe similar domains but using different terminologies, it is important to link and integrate data from various ontologies and create semantic correspondences between multiple ontologies. Ontology matching/mapping is the process

of generating these correspondences between semantically related entities of ontologies. Therefore, to support the seamless sharing of information and knowledge in CBDM, ontology matching is one of the enabling technologies that can help match, integrate, merge, and align heterogeneous ontologies. According to recent surveys [176-180] on ontology matching, among several dozens of existing ontology matching systems, seven particular ontology matching systems have been identified. These ontology matching systems can handle ontologies in OWL, RDFS, and XML and output 1-to-1 and n-to-m alignments between concepts and relations. The types of data these systems can process include strings, structure, data instances, and models. Moreover, to manage heterogeneous ontologies created for CBDM, future challenges need to be addressed include large-scale matching evaluation, matching with background knowledge, matcher selection, combination and tuning, social and collaborative matching, and alignment management.

As previously highlighted, this dissertation addresses the following two specific research issues related to KMSs for CBDM in Chapters 5 and 6, respectively.

- The modeling and analysis of information flow in distributed collaboration networks in the context of CBD;
- The modeling and analysis of material flow in distributed manufacturing supply chain networks in the context of CBM.

3.7 Summary

The objective of Chapter 3 was to answer Research Question 1: *Is cloud-based design and manufacturing actually a new paradigm, or is it just "old wine in new bottles"*? In order to thoroughly answer this question, it was further divided into the following three research sub-questions:

Research Question 1.a:

- *What are the definition, characteristics, requirements, reference model, computing architecture, operational process, programming model, and business model of a Cloud-Based Design and Manufacturing (CBDM) system?*

Research Question 1.b:

- *How is a CBDM system different from a traditional collaborative design and distributed manufacturing system such as a web- and agent-based design and manufacturing system?*

Research Question 1.c:

- *What could an idealized CBDM scenario be?*

In this chapter, these aforementioned research questions were answered definitively. With respect to research question 1.a, the definitions related to CBDM were discussed and compared. Common key characteristics of CBDM were identified, including scalability, agility, high performance and affordable computing, networked environments, ubiquitous access, self-service, big data, search engine, social media, real-time quoting, pay-per-use, resource pooling, virtualization, multi-tenancy, crowdsourcing, IaaS, PaaS, HaaS, and SaaS. In addition, a system requirements checklist that a future CBDM system should satisfy was defined. The requirements checklist could serve as a benchmark for developing a future CBDM system.

With respect to research question 1.b, CBDM was compared to web- and agent-based approaches from a number of perspectives including computing architecture, design communication, sourcing process, information and communication, programming model, data storage, and business model. By comparison with web- and agent-based systems, CBDM can significantly improve computing performance, the effectiveness and efficiency of communication and collaboration, the efficiency of manufacturing sourcing processes as well as allow for ubiquitous access to heterogeneous and distributed large datasets.

With respect to research question 1.c, a hypothetical design and manufacturing scenario in future CBDM environments based on currently existing and potentially new cloud-based service offerings was presented. The example scenario, the development of a delivery drone, was meant to help clarify our vision of CBDM and demonstrate its potential value.

Based on the answers to research questions 1.a, 1.b, and 1.c, it was concluded that CBDM can be considered a new paradigm that is anticipated to drive the next paradigm shift in design innovation and digital manufacturing.

CHAPTER 4

A CLOUD-BASED DESIGN AND MANUFACTURING SYSTEM PROTOTYPE

Based on the requirements checklist identified in Chapter 3, a CBDM prototype system, called DMCloud, was developed for the Defense Advanced Research Projects Agency (DARPA). The implementation of the prototype served as a pilot study and represents the first attempt at building a CBDM system. The objective of developing the prototype system was to deploy and integrate design and manufacturing resources such as CAD software and additive manufacturing equipment into one thousand high schools across the U.S. The goal was to engage students from these participating high schools in a series of collaborative design and distributed manufacturing experiments. 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.

4.1 Overview of DMCloud

Similar to cloud computing, a CBDM system can be public, private or hybrid. The 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, additive manufacturing (AM) machines (i.e., 3D printers), and engineering software through a partnership constituting a network of high schools dispersed across the U.S. 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. 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.

4.2 System Architecture of DMCloud

As shown in Figure 4-1, 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.

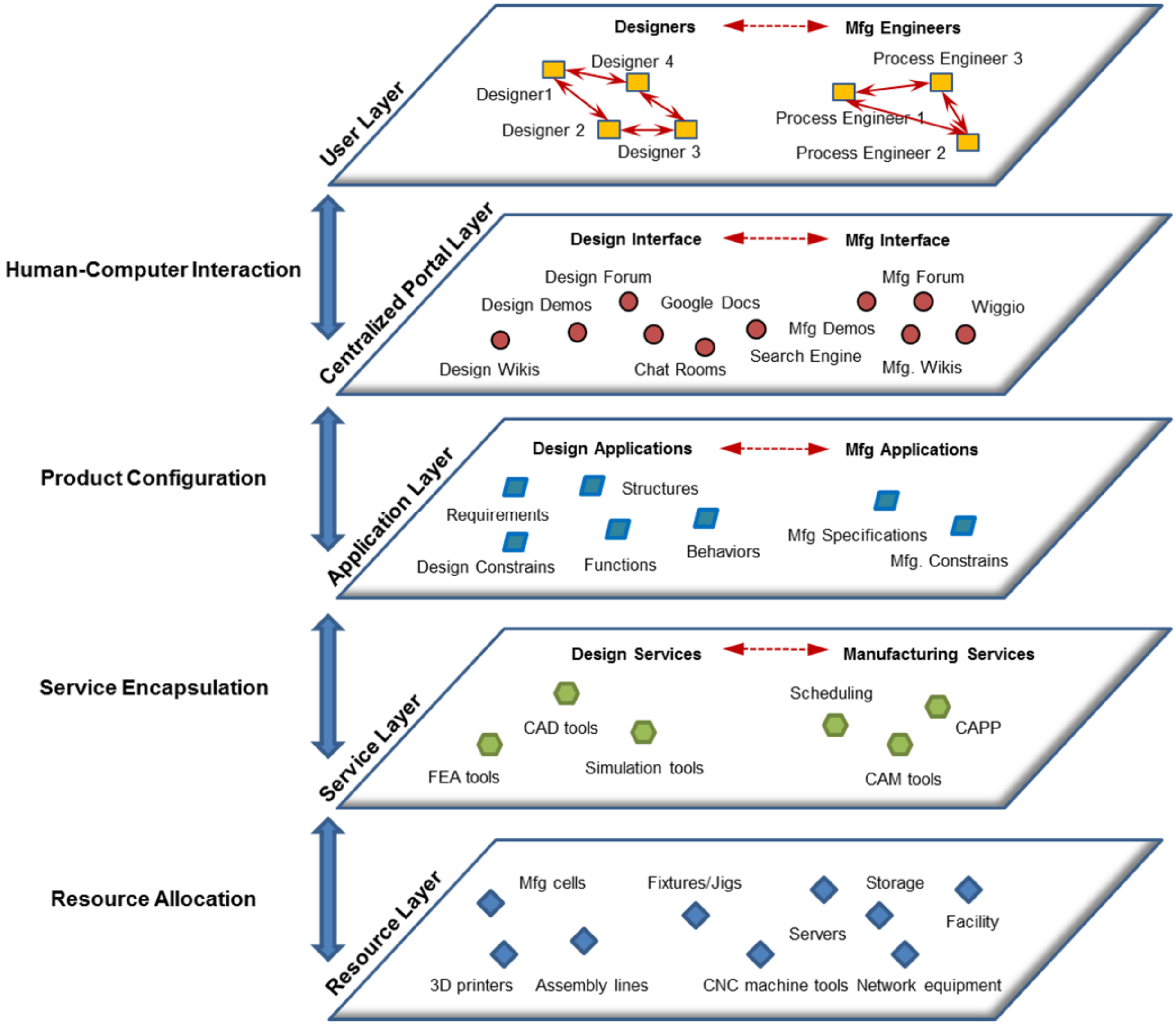


Figure 4-1 System architecture of the DMCloud system

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 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 constrains, as well as corresponding manufacturing specifications and constrains.

(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, and network equipment.

4.3 Workflow and Services in the DMCloud

The overall workflow of the DMCloud is illustrated in Figure 4-2.

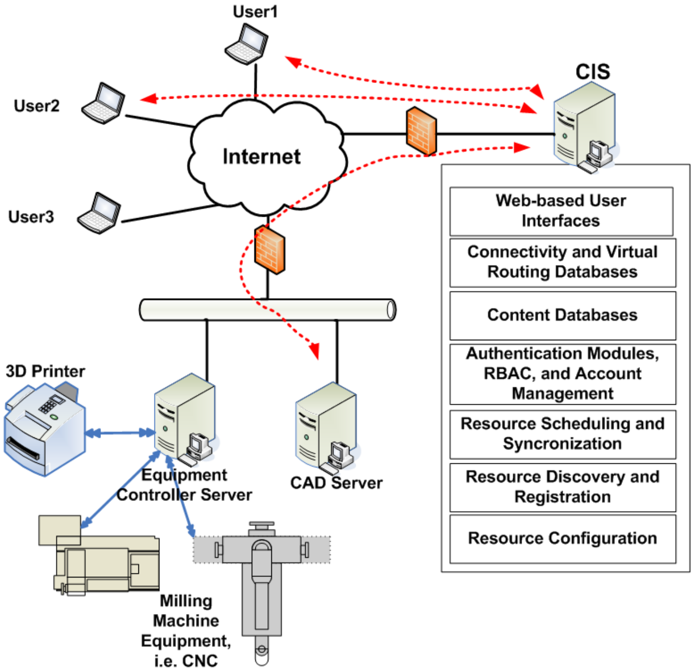
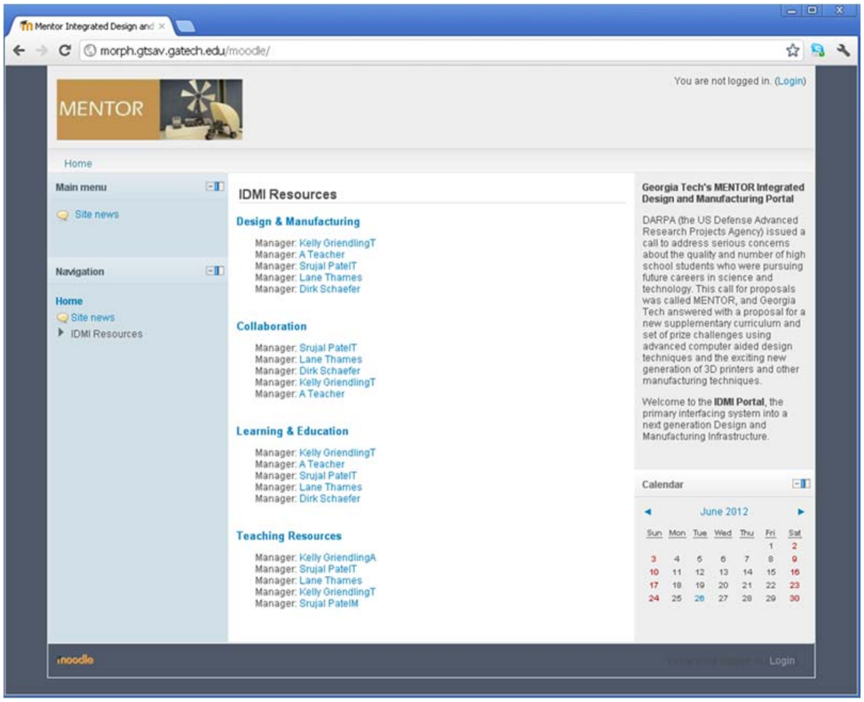


Figure 4-2 Workflow of the DMCloud system [146]

The DMCloud consists of a centralized interfacing server (CIS) incorporated with the Moodle learning management system. As shown in Figure 4-2, 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 CATIA access to design 3D models through the online portal as shown in Figure 4-3 and Figure 4-4.



You are not logged in. (Login)

IDMI Resources

Design & Manufacturing

Manager: Kelly GriendlingT
Manager: A Teacher
Manager: Srujal PatelT
Manager: Lane Thames
Manager: Dirk Schaefer

Collaboration

Manager: Srujal PatelT
Manager: Lane Thames
Manager: Dirk Schaefer
Manager: Kelly GriendlingT
Manager: A Teacher

Learning & Education

Manager: Kelly GriendlingT
Manager: A Teacher
Manager: Srujal PatelT
Manager: Lane Thames
Manager: Dirk Schaefer

Teaching Resources

Manager: Kelly GriendlingA
Manager: Srujal PatelT
Manager: Lane Thames
Manager: Kelly GriendlingT
Manager: Srujal PatelM

Georgia Tech's MENTOR Integrated Design and Manufacturing Portal

DARPA (the US Defense Advanced Research Projects Agency) issued a call to address serious concerns about the quality and number of high school students who were pursuing future careers in science and technology. This call for proposals was called MENTOR, and Georgia Tech answered with a proposal for a new supplementary curriculum and set of prize challenges using advanced computer aided design techniques and the exciting new generation of 3D printers and other manufacturing techniques.

Welcome to the **IDMI Portal**, the primary interfacing system into a next generation Design and Manufacturing Infrastructure.

June 2012

Sun	Mon	Tue	Wed	Thu	Fri	Sat
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
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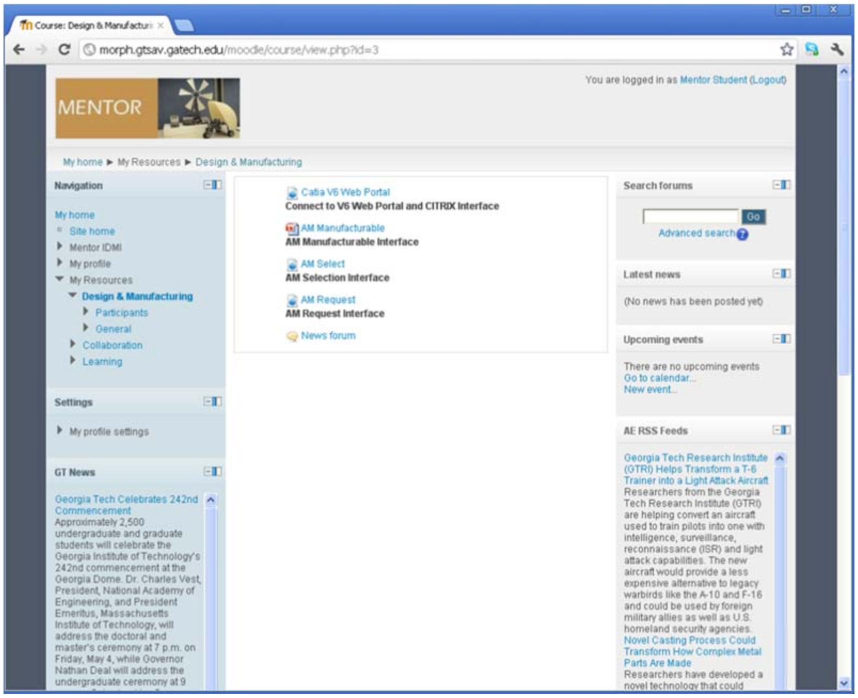
Figure 4-3 Main menu of the DMCloud portal



You are logged in as Mentor Student (Logout)

Catia V6 Web Portal
Connect to V6 Web Portal and CITRIX Interface

AM Manufacturable
AM Manufacturable Interface

AM Select
AM Selection Interface

AM Request
AM Request Interface

News forum

(No news has been posted yet)

There are no upcoming events

Georgia Tech Celebrates 242nd Commencement
Approximately 2,500 undergraduate and graduate students will celebrate the Georgia Institute of Technology's 242nd commencement at the Georgia Dome. Dr. Charles Vest, President, National Academy of Engineering, and President Emeritus, Massachusetts Institute of Technology, will address the doctoral and master's ceremony at 7 p.m. on Friday, May 4, while Governor Nathan Deal will address the undergraduate ceremony at 9

Georgia Tech Research Institute (GTRI) Helps Transform a T-6 Trainer into a Light Attack Aircraft
Researchers from the Georgia Tech Research Institute (GTRI) are helping convert an aircraft used to train pilots into one with intelligence, surveillance, reconnaissance (ISR) and light attack capabilities. The new aircraft would provide a less expensive alternative to legacy warbirds like the A-10 and F-16 and could be used by foreign military allies as well as U.S. homeland security agencies.
Novel Casting Process Could Transform How Complex Metal Parts Are Made
Researchers have developed a novel technology that could

Figure 4-4 Design & manufacturing module of the DMCloud portal

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 Figure 4-4) 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 sub-systems to advertise service availability and associated service usage parameters.

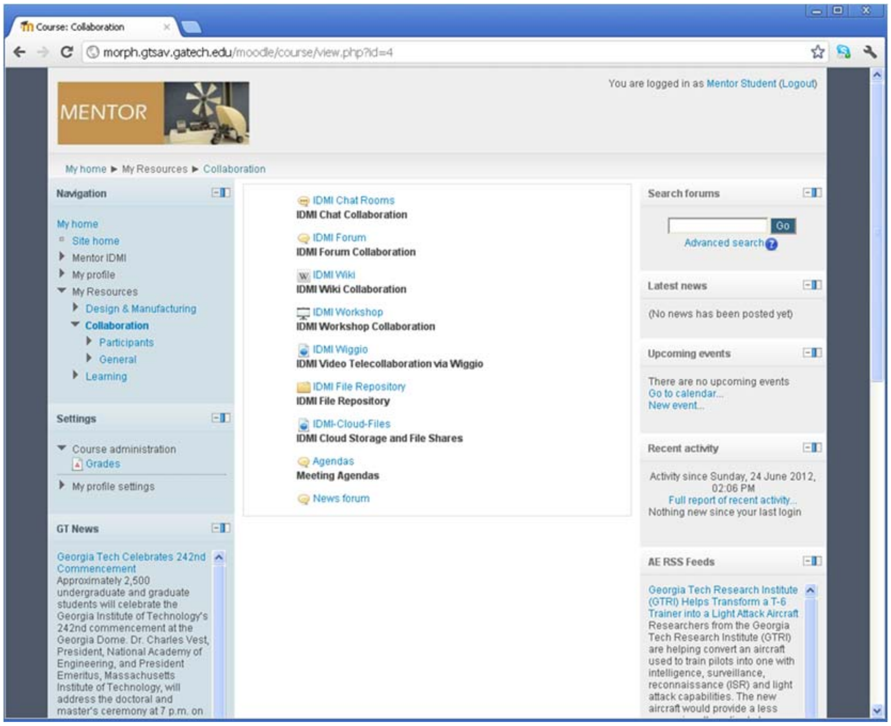
  c) AM-Request: allow service consumers to request AM services and other DMCloud resources from service providers.

  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 Figure 4-5, 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.



You are logged in as Mentor Student (Logout)

IDMI Chat Rooms
IDMI Chat Collaboration

IDMI Forum
IDMI Forum Collaboration

IDMI Wiki
IDMI Wiki Collaboration

IDMI Workshop
IDMI Workshop Collaboration

IDMI Wiggio
IDMI Video Telecollaboration via Wiggio

IDMI File Repository
IDMI File Repository

IDMI-Cloud-Files
IDMI Cloud Storage and File Shares

Agendas
Meeting Agendas

News forum

(No news has been posted yet)

There are no upcoming events

Activity since Sunday, 24 June 2012, 02:06 PM

Nothing new since your last login

Georgia Tech Celebrates 242nd Commencement
Approximately 2,500 undergraduate and graduate students will celebrate the Georgia Institute of Technology's 242nd commencement at the Georgia Dome. Dr. Charles Vest, President, National Academy of Engineering, and President Emeritus, Massachusetts Institute of Technology, will address the doctoral and master's ceremony at 7 p.m. on

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Figure 4-5 Social networking tools in the DMCloud

4.4 Discussion

Since a truly 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 Section 4, through design and manufacturing experiments in the real world. As a first step to understand the fundamentals of CBDM, the primary value of our DMCloud is highlighted from the following perspectives:

(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.

4.5 Summary

In this chapter, a prototype CBDM system, referred to as DMCloud, was presented. An overview of the DMCloud was provided, including the overall workflow and current services it provides. Specifically, the prototype enabled 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. This prototype can be considered as the initial step for developing a truly CBDM system.

CHAPTER 5

MODELING AND ANALYSIS OF CLOUD-BASED DESIGN COLLABORATION NETWORKS

Although social network sites have been integrated into the prototype system as described in Chapter 4, supporting design communication and collaboration effectively and efficiently is still challenging. In particular, information sharing is critical to effective and efficient communication in distributed and collaborative product development processes that require seamless flow of information among participants. In general, the most useful design- and manufacturing-related information and knowledge reside in individuals who create, recognize, archive, access, and apply information in conducting design and manufacturing activities. The movement of the information across individuals and organizational boundaries depends on the information sharing behaviors of these individuals and organizations. In order to enhance information sharing, it is crucial to not only provide collaborators with access to explicitly documented digital information but, most importantly, to generate visualized social network data that indicate information is exchanged between whom and to what extent in a large-scale and complex collaboration network. Moreover, such visualized network data help reveal who creates, controls, facilitates, and inhibits the information flow, identify expertise networks and individuals who can play critical roles in accelerating information flow or fostering innovation, and identify who has similar information needs or uses [181].

The objective of Chapter 5 is to address some fundamental research issues pertaining to design communication and collaboration: how information flows through socio-technical systems and how different individuals or organizations can play distinct roles in this process to enhance design communication and collaboration. To address these issues, a social network analysis-based approach is proposed. Specifically, as the first step of the approach, the Adamic and Adar index score is calculated to measure tie strength between actors in a design network. Mark Granovetter introduced the notion of tie strength. From the perspective of social science, the strength of a tie refers to "a (probably linear) combination of the amount of time, the emotional intensity, the intimacy (mutual confiding), and the reciprocal services which characterize the tie" [182]. Weak ties can help expedite the transfer of information and knowledge across individuals and organizations. Specifically, more novel information flows to individuals through weak rather than strong ties. Based on the measurement of tie strengths using the Adamic and Adar index score, an implicit design network can be formally transformed into an explicit social network as the second step of the approach. The third step is to measure the social network using quantitative measures (e.g., degree, betweenness centrality, and closeness centrality) in SNA. These measures help CBD system designers understand the overall collaboration structure and the relationships between actors in the collaboration network. The last step of the approach is to detect community structure that help CBD system designers identify collaboration communities with common interests and/or activities and key actors who play critical roles in product development processes.

Based on the systematic SNA-based approach, a software tool that runs in the back end of CBD systems can be further developed to improve design communication and collaboration while design activities are being conducted in the social media-supported CBD environment. The potential uses of the SNA-based approach are as follows:

- To visualize communication and collaboration patterns and explore more effective and efficient communication and collaboration mechanisms and principles;

- To identify experts and group leaders who can improve knowledge creation, transfer, and sharing processes as well as detect isolated teams or individuals as the bottlenecks of information sharing and knowledge acquisition;
- To accelerate the flow of information and knowledge across functional and organizational boundaries;
- To develop trust models for building trust online communities that inspire members to share information and knowledge.

Specifically, Research Question 2 and its hypothesis are formulated as follows:

<u>Research Question 2.a</u>:

- *What indices can be used to measure tie strengths between actors effectively in CBD?*

<u>Hypothesis 2.a:</u>

- *The Adamic and Adar index can be used to measure tie strengths between actors effectively in CBD.*

<u>Research Question 2.b:</u>

- *How can information flow for communication and collaboration in CBD be modeled and analyzed?*

<u>Hypothesis 2.b:</u>

- *The measurement of centrality and community detection methods in social network analysis can be used to model and analyze information flow for design communication and collaboration in CBD.*

To validate the hypotheses, the Adamic and Adar index is proposed to measure tie strengths between actors in a design team or design network. An implicit design network is then mapped into an explicit and formal social network based on the index. The process of transforming customer needs, to functional requirements, to design parameters, and to process variables is visualized using Social Network Analysis (SNA). Further, using the quantitative measures (e.g., centrality and cluster coefficient) in SNA, the social network at both actor and system levels is analyzed, and design communities with common design interests are detected. The SNA-based approach is demonstrated by means of two illustrative examples.

5.1 Cloud-Based Design

Cloud-Based Design (CBD) refers to a networked design model that leverages cloud computing, service-oriented architecture (SOA), Web 2.0 (e.g., social network sites), and semantic web technologies to support cloud-based engineering design services in distributed and collaborative environments.

Torlind and Larsson [183] described engineering design as "fundamentally a socio-technical activity" in which engineers gather, process, and share information about customer needs, function requirements, design parameters, and process variables as well as make collective decisions in order to satisfy customer needs. In the context of CBD, this statement is especially true as social media is being integrated to enhance design ideation, innovation, and collaboration [184]. One of the most well-known industry practices is Yammer [6], a so-called "Facebook for the workplace". Yammer is a platform designed to streamline communication and collaboration processes by bringing together people, content, and conversations across entire product development processes. Another example is Quirky, an industrial design company that utilizes a social media site to bring innovative product ideas to real life. Quirky allows designers and design teams to conduct engineering design modeling and analysis by using cloud-based computer-aided design and finite element analysis tools such as Dassault Systems' CATIA V6.

Meanwhile, Dassault Systems also introduced an online social innovation platform, 3DswYm, for sharing design-related information and experiences via commonly-used social media tools such as wikis and blogs. In addition, General Electric (GE) and Massachusetts Institute of Technology (MIT) are developing a new crowdsourcing platform to support DARPA's ongoing adaptive vehicle make portfolio [185]. Their crowdsourcing platform allows a global community of experts to design and rapidly manufacture complex industrial products and systems such as aviation systems by connecting individuals in an online community.

Because of the increasing number of design participants and teams involved in CBD, it is crucial to increase the effectiveness and efficiency of design communication and collaboration. The engineering management literature shows that effective and efficient communication and collaboration is one of the most important success factors that affect productivity, lead-time, and costs. Dong [186] reveals that almost all successful product design teams have high-levels of communication and collaboration because seamless information sharing supports the creation of a shared understanding of engineering problems between engineers. McKinsey [187] suggests that a 'well-connected' design network plays a critical role in the decision-making process of marketing, conceptual, embodiment, and detail design phases based on their recent survey. However, the challenge in understanding communication and collaboration mechanisms lies in mapping distributed and collaborative design teams into a network as well as capturing the process of transforming customer needs, to functional requirements, to design parameters, and to process variables as shown in Figure 5-1.

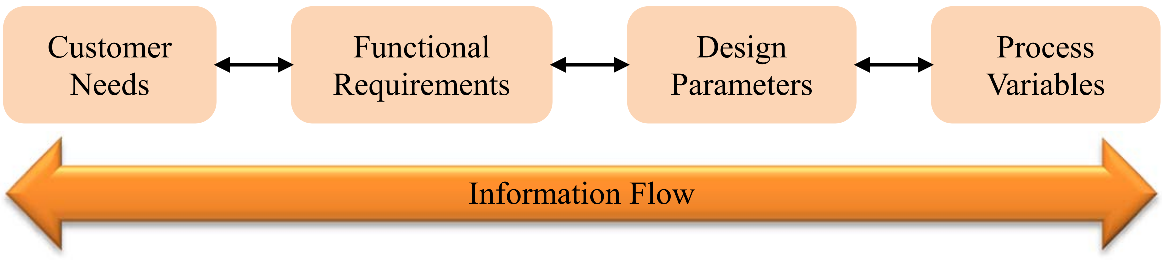


Figure 5-1 Information flow in engineering design processes

In the context of CBD, supporting design communication and collaboration include the following two aspects:

- To analyze the transformation of information among product modules that share design variables [188-193];
- To analyze the transformation of information among individuals or design teams at different design phases (e.g., concept design and embodiment design) [194, 195].

This chapter is focused on the second aspect because of the socio-technical nature of engineering design processes in CBD.

While some qualitative studies suggest how human and organizational systems could be restructured to improve productivity [196], only few investigate how information transformation in a design process can be formally modeled and analyzed in a quantitative way. Although social network analysis (SNA) has been used to study inter-firm relationships of interconnected buyers and suppliers in supply chain management [197], few studies apply SNA in the context of engineering design. In particular, there has been limited study of measuring tie strengths between engineers and mapping initially disconnected individuals and teams in a design network into a social network in the context of distributed and collaborative design. This is largely because (1) there is no formal framework for investigating communication and collaboration mechanisms in distributed and collaborative design; (2) there is a lack of clarification with respect to indices for measuring tie strengths between individuals or design teams; and (3) it is still very challenging to conduct large-scale real-world industrial case studies. The objective of this chapter is to address the first two issues as a first step towards supporting communication and collaboration.

5.2 A Social Network Analysis Approach

In this section, a generic SNA-based approach to support design communication and collaboration in CBD settings is presented. The potential users of the approach include systems analysts and users of CBD platforms. For instance, a systems analyst monitors the exchange of data between designers participating in a distributed and collaborative design process and evaluates the performance of design communication and collaboration. The systems analyst tracks data such as electronic files (e.g., CAD and FEA files) that are being shared among designers. Based on these data, the systems analyst defines an index to measure tie strengths between two individuals or design teams. Based on the values of the index, one can map an implicit design network into an explicit and formal social network. One can further formally analyze the social network by utilizing quantitative SNA measures (e.g., degree, centrality and cluster coefficient). Then, the social network can be visualized and further analyzed with community detection algorithms that capture the information flow, identify key design participants, also referred to as actors, and detect design communities with common interests. Based on these results, the systems analyst can identify potential communication and collaboration problems through strong and weak ties accordingly. The detailed steps of the SNA-based approach are presented in Table 5-1. More details about the key steps of the approach will be presented in two application examples in Sections 5.3.1 and 5.3.2, respectively.

Table 5-1 The SNA-based approach for improving design communication and collaboration

Social Network Analysis for CBD	
1:	Identify actors in a cloud-based design project
2:	Define an index for measuring tie strengths between actors
3:	Observe cloud-based social collaboration events and collect social collaboration data
4:	Model a design collaboration network as a formal social network
5:	Calculate the quantitative measures in SNA
6:	Detect communities with common interests or tasks and key actors in the communities
7:	Detect triggering conditions for automatic alerts
8:	If triggering conditions are detected, perform corresponding interventions

5.2.1 Measuring Tie Strengths

Social network data are typically gathered through questionnaires and interviews in which actors are asked to identify the frequency of communication with others as well as mediums of interaction. It is commonly agreed that social network data collected through questionnaires and interviews are not perfectly accurate due to the fact that responses are subjective in nature. Gupte and Eliassi-Rad [198] introduced an axiomatic approach of measuring tie strength between actors in social networks. A list of axioms is used to evaluate specific measures of tie strengths between two actors. We extend that line of work by studying specific indices for tie strengths in the context of distributed and collaborating engineering design. In this section, we review some of the axioms defined by [198] to help clarify the index that is used in the application examples.

Axiom 1 (Isomorphism): Suppose we have two graphs G and H and a mapping of vertices such that G and H are isomorphic. Let vertex u of G map to vertex a of H and vertex v to b. Then, the tie strength between u and v in the graph G, denoted by $\mathrm{TS_G(u,v)}$, is equal to the tie strength between a and b in the graph H, denoted by $\mathrm{TS_H(a,b)}$. This relationship can be formally denoted by $\mathrm{TS_G(u,v) = TS_H(a,b)}$. In the context of engineering design, design teams A and B can be represented by two graphs G and H, respectively. Two engineers in design team A can be represented by two vertices u and v in the graph G. Similarly, another two engineers in design team B can be represented by two vertices a and b in the graph H. Axiom 1 suggests that the tie strength between the two engineers in design team A is equal to the tie strength between the two engineers in design team B if G and H are isomorphic.

Axiom 2 (Baseline): If there are no events (an event is defined as a circumstance participated by a set of individuals for a certain purpose), then the tie strength between vertices u and v in the graph, denoted by $\mathrm{TS}_{\emptyset}(\mathrm{u},\mathrm{v})$, is equal to zero. This is formally denoted by $\mathrm{TS}_{\emptyset}(\mathrm{u},\mathrm{v}) = 0$. If there are only two actors u and v and a single event they attend, then their tie strength, denoted by $\mathrm{TS}_{\{\mathrm{u},\mathrm{v}\}}(\mathrm{u},\mathrm{v})$, is equal to one. This is formally denoted by $\mathrm{TS}_{\{\mathrm{u},\mathrm{v}\}}(\mathrm{u},\mathrm{v}) = 1$. In the context of engineering design, Axiom 2 suggests that the tie strength between any two engineers in a design team is equal to zero if the two designers do not participate in any design-related events. This axiom also suggests that the tie strength between two engineers in a design team is equal to one if there are only two engineers in the design team and they only attend one single design-related event.

Axiom 3 (Frequency): All other things being equal, the more events common to u and v, the stronger the tie strength between u and v. In the context of engineering design, Axiom 3 suggests that the tie strength between two engineers in a design team will be greater if they share more common design-related events and all other conditions remain the same.

Axiom 4 (Intimacy): All other things are being equal, the fewer actors there are to any particular event attended by u and v, the stronger the tie strength between u and v. In the context of engineering design, Axiom 4 suggests that the tie strength between two engineers in a design team will be greater if fewer engineers participate in the common design-related events they share. In fact, Axiom 4 is a special case of Axiom 2. The special case is that the tie strength between two engineers in a design team is equal to one if there are only two engineers in the design team and they only attend one single design-related event.

Axiom 5 (Popularity): Consider two events P and Q. If the number of actors attending P is larger than that of actors attending Q, then the total tie strength created by event P is more than that created by event Q. In the context of engineering design, Axiom 5 suggests that the total tie strength created by a particular design-related event P is more than that created by another one Q if more engineers participate in event P.

Axiom 6 (Conditional independence of vertices): The tie strength of a vertex u to other vertices does not depend on events that u does not attend; it only depends on events that u attends. In the context of engineering design, Axiom 6 suggests that the tie strength of an engineer to others does not depend on the design-related events that this engineer does not attend.

Axiom 7 (Conditional independence of events): The increase in tie strength between u and v due to an event P does not depend on other events but on the existing tie strength between u and v. In the context of engineering design, Axiom 7 suggests that the increase in tie strength between two engineers does not depend on other design-related events.

Axiom 8 (Submodularity): The marginal increase in tie strength of u and v due to an event Q is at most the tie strength between u and v if Q was the only event. If G is a graph and Q is a single event, then $\mathrm{TS}_{\mathrm{G}}(\mathrm{u},\mathrm{v}) + \mathrm{TS}_{\mathrm{Q}}(\mathrm{u},\mathrm{v}) \geq \mathrm{TS}_{\mathrm{G+Q}}(\mathrm{u},\mathrm{v})$. In the context of engineering design, Axiom 8 suggests that the marginal increase in tie strength between two engineers due to a common design-related event they share is at most the tie strength between the two engineers if this event is the only one they attend.

According to Gupte and Eliassi-Rad [198], although plenty of generic measures of tie strength exist and each of the axioms is fairly intuitive, only some of the well-accepted measures of tie strength satisfy all the aforementioned axioms. These measures include (1) *Delta*, (2) *Adamic and Adar*, (3) *Linear*, and (4) *Max*. The detailed and formal proofs can be referred to [198]. In the following indices, $|\mathrm{P}|$ denotes the number of actors in the event P. The neighborhood of a vertex u in a graph is denoted by $\Gamma(\mathrm{u})$. The tie strength between two vertices u and v in a graph is denoted by $\mathrm{TS}(\mathrm{u},\mathrm{v})$.

The *Delta index* defines tie strength as:

$$\mathrm{TS}(\mathrm{u},\mathrm{v}) = \sum_{\mathrm{P}\in\Gamma(\mathrm{u})\cap\Gamma(\mathrm{v})} \frac{1}{\binom{|\mathrm{P}|}{2}} \tag{5-1}$$

The *Adamic and Adar index* defines tie strength as [199]:

$$\mathrm{TS}(\mathrm{u},\mathrm{v}) = \sum_{\mathrm{P}\in\Gamma(\mathrm{u})\cap\Gamma(\mathrm{v})} \frac{1}{\log|\mathrm{P}|} \tag{5-2}$$

The *Linear index* defines tie strength as:

$$\mathrm{TS}(\mathrm{u},\mathrm{v}) = \sum_{\mathrm{P}\in\Gamma(\mathrm{u})\cap\Gamma(\mathrm{v})} \frac{1}{|\mathrm{P}|} \tag{5-3}$$

The *Max index* defines tie strength as:

$$\mathrm{TS}(\mathrm{u},\mathrm{v}) = \max_{\mathrm{P}\in\Gamma(\mathrm{u})\cap\Gamma(\mathrm{v})} \frac{1}{|\mathrm{P}|} \tag{5-4}$$

Based on these formally defined tie strengths, an implicit design network can be formally mapped into an explicit social network. The following simple example illustrates how a design network can be mapped into a social network based on tie strengths in more detail. Table 2 lists five actors and the events they attended. These events include sharing a particular digital file (denote by P1), making comments on a particular post (denote by P2), participating in a particular virtual meeting (denote by P3), a particular virtual conference call (denote by P4), and a particular poll (denote by P5). Given the original data related to actors and events and the *Adamic and Adar index* scores in Table 5-2, an implicit design network can be mapped into an explicit social network (see Figure 5-2) using two approaches: (1) preserving all edges with positive *Adamic and Adar index* scores and (2) removing edges below a certain threshold score value.

Table 5-2 Adamic and Adar index scores

Connections		# of actors in P1	# of actors in P2	# of actors in P3	# of actors in P4	# of actors in P5	Adamic and Adar Index
Actor ID	Actor ID						
1	2	3	3	0	0	0	4.1918
1	3	3	3	0	0	0	4.1918
1	4	0	0	3	2	0	5.4178
2	3	3	3	0	0	0	4.1918
4	5	0	0	3	0	2	5.4178

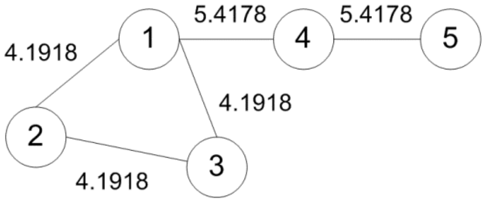


Figure 5-2 Model a design network as a social network based on Adamic and Adar index

Both approaches have advantages and disadvantages. With respect to the first approach, the advantage is that it preserves all the original information sharing behaviors using weighted edges in the social network without data filtering. In other words, edges with low index scores (i.e., weak ties) will not be removed in the social network. From the application perspective, it is helpful to preserve these weak ties because actors with weak ties may play dominant roles in the dissemination of information. However, the disadvantage is that this approach cannot filter ineffective information sharing behaviors. For example, in a situation where two actors who have shared very little useful information in reality, the corresponding two nodes still will be connected using edges in the corresponding social network based on a positive index score, although the tie strength between the two actors is very weak. Actually, because of very limited amount of useful information being shared between them, the weak tie strength between the two actors can be ignored and the corresponding nodes may not necessarily be connected in the social network. Accordingly, in this case, some researchers suggest taking a certain percentage of the maximum tie strength as a threshold score and to remove edges with tie strengths below the threshold score. This approach (i.e., the second approach) can preserve most of original information behaviors while filtering out too weak ties. However, the disadvantage is that certain critical information sharing behaviors between key actors may also be removed because of low index scores. Based on a thorough literature review, the issue about how to choose a proper threshold score (i.e., how much percentage of the maximum tie strength) is still mostly an open question and not well understood.

Since there is no reliable, validated information on how to choose a proper threshold score in the context of our application examples, and more importantly, because choosing an inappropriate threshold score would introduce errors, we will not set a specific threshold score in out examples, but preserve all of the edges with positive tie strengths in the social network.

5.2.2 Measuring Social Networks

The next step of the approach is to analyze the explicit social network using the following measures at both actor and group levels. In this section, some of the well-defined quantitative measures from SNA [200] are reviewed to help clarify the uses of these measures in the application examples.

Degree: Degree of a vertex of a network is the number of edges incident to the vertex. In this study, degree gauges how many connections a particular actor possesses. A higher degree reflects more connections that an actor is tied to. In contrast, an actor with low degree is considered peripheral in a social network. Further, degree also refers to the extent to which an actor influences other actors with respect to the sharing of information and decision making, as the actor has more direct connections thereby more likely having more critical information that others may not know about. For instance, a subgroup leader in a distribute design team will more likely have a higher degree as this leader is in a position that calls for meetings, gathers information from other groups to his group members, and delivers information from his group members to other groups.

Graph Density: Graph density is the average of the standardized actor degree indices as well as the fraction of possible ties present in the network for the relation under study. In other words, it measures how many edges in a network compared to the maximum possible number of edges. Graph density takes on value between zero (empty graph) and one (complete graph).

Betweenness Centrality: Betweenness defines the extent to which an actor lies between other actors in a network. This measure takes into account the connectivity of the actor's neighbors, giving a higher value for actors which bridge clusters. This measure also indicates the number of actors which the actor is connected to indirectly through the direct links [200].

Actor betweenness centrality is defined as:

$$C'_B(\mathrm{n}_i) = \frac{C_B(\mathrm{n}_i)}{[(\mathrm{g}-1)(\mathrm{g}-2)/2]}, \tag{5-5}$$

where $\mathrm{C'_B(n_i)}$ is the standardized actor betweenness index for $\mathrm{n_i}$. $\mathrm{C_B(n_i)}$ is the actor betweenness index for $\mathrm{n_i}$. g is the number of actors. The calculation of $\mathrm{C_B(n_i)}$ is discussed in more detail in [70].

Group betweenness centrality is defined as:

$$C_B = \frac{2\sum_{i=1}^{g}[C_B(\mathrm{n}^*) - C_B(\mathrm{n}_i)]}{[(\mathrm{g}-1)^2(\mathrm{g}-2)]}, \tag{5-6}$$

where $\mathrm{C_B}$ is the index of group betweenness. $\mathrm{C_B}(\mathrm{n}^*)$ is the largest realized actor betweenness index for the set of actors.

Betweenness can be viewed as indicating how much “gatekeeping” an actor does for the other actors. It measures how important the actor is with respect to the flow of information. An actor with high betweenness can control the flow of information as the actor acts as a hub or pivot that transmits information across the network. Further, from the structural position perspective, the actor with high betweenness is more likely one of the key actors in the network as the actor affects the downstream actors’ access to information from upstream actors. For instance, in a design network, the structural position of designers is between market analysts and manufacturing engineers as designers transform function requirements to design parameters. Therefore, designers become a hub between market analysts and manufacturing engineers. If a designer with high betweenness transmits design-related information slowly or delivers some wrong information, the design becomes the bottleneck of the information flow in the network. As a result, the gap in the information flow can easily lead to poor communication and collaboration.

Closeness Centrality: Closeness centrality defines the degree to which an actor is near all other actors in a network. This measure indicates the ability to access information through the grapevine of network members. In other words, closeness indicates how quickly an actor accesses information from the network. Closeness centrality is the inverse of the sum of the shortest distance between each actor and every other actor in the network.

Actor closeness centrality is defined as:

$$C'_C(\mathrm{n}_i) = \frac{g-1}{[\sum_{j=1}^{g} d(\mathrm{n}_i, \mathrm{n}_j)]}, \tag{5-7}$$

where $\mathrm{C}'_{\mathrm{C}}(\mathrm{n_i})$ is the standardized index of actor closeness. $\mathrm{d}(\mathrm{n_i}, \mathrm{n_j})$ is the number of lines in the geodesic linking actors i and j. The details about how to calculate $\mathrm{d}(\mathrm{n_i}, \mathrm{n_j})$ can be found in.

Group closeness centrality is defined as:

$$C_C = \frac{\sum_{i=1}^{g}[\mathrm{C}'_C(\mathrm{n}^*) - \mathrm{C}'_C(\mathrm{n}_i)]}{[(\mathrm{g}-2)(\mathrm{g}-1)]/[(2\mathrm{g}-3)]}, \tag{5-8}$$

where $\mathrm{C_C}$ is the index of group closeness. $\mathrm{C}'_{\mathrm{C}}(\mathrm{n}^*)$ is the largest standardized actor closeness in the set of actors.

Clustering Coefficient: Clustering coefficient of an actor is the ratio of number of connections in the neighborhood of an actor and the number of connections if the neighborhood was fully connected. Clustering coefficient identifies how well connected the neighborhood of an actor is. If the neighborhood is fully connected, the cluster coefficient is one. A value close to zero means that there are hardly any connections in the neighborhood of the actor. A higher clustering coefficient indicates a greater cliquishness [200]. In other words, it is the measure of the degree to which nodes in a graph tend to cluster together. In the context of CBD, an actor with low cluster coefficient is more likely one of the group leaders as the neighborhood (group members) of the group leader is generally fully connected.

5.2.3 Detecting Community Structure

In this section, two of the most popular algorithms for identifying communities are briefly reviewed. In the seminal paper in the field of community detection, Girvan and Newman [62] proposed an algorithm to identify edges lying between communities and their successive removal, a procedure that after some iterations leads to the isolation of the communities. The intercommunity edges are detected using the edge betweenness as a metric that represents the importance of the role of the edges in processes where signals are transmitted across the graph following paths of minimal length. The *Girvan-Newman algorithm* based on betweenness is stated as follows:

Girvan-Newman algorithm proposed in [62]

```
1:  Calculate the betweenness for all edges in the network
2:  Remove the edge with the highest betweenness
3:  Recalculate betweennesses for all edges affected by the removal
4:  Repeat from step 2 until no edges remain
```

As stated in the literature review, this algorithm has been applied successfully to a variety of networks, including networks of email messages, networks of collaborations between scientists and musicians, and gene networks. However, this algorithm is not efficient when applied to large networks because it requires a large amount of computational resources. In order to address this issue, Clauset, Newman, and Moore [76] proposed a more efficient algorithm based on another metric, referred to as modularity. Modularity is a property of a network and a specific proposed division of that network into communities. The modularity-based algorithm is detailed as follows:

Let A_{vw} denote an element of the adjacency matrix of a network.

$$A_{vw} = \begin{cases} 1 & \text{if vertices v and w are connected,} \\ 0 & \text{otherwise.} \end{cases} \tag{5-9}$$

Suppose that the vertices are divided into communities such that vertex v belongs to community c_v and the vertex w belongs to community c_w, respectively. Then, the fraction of edges that fall within communities is defined as follows [76]:

$$\frac{\sum_{vw} A_{vw}\delta(\mathrm{c}_v,\mathrm{c}_w)}{\sum_{vw} A_{vw}} = \frac{1}{2m}\sum_{vw} A_{vw}\delta(\mathrm{c}_v,\mathrm{c}_w), \tag{5-10}$$

where the $\delta-$function $\delta(\mathrm{i},\mathrm{j})$ is 1 if $i=j$ and 0 otherwise, and $m=\frac{1}{2}\sum_{vw} A_{vw}$ is the number of edges in the graph.

Let k_v denote the degree of a vertex x.

$$k_v = \sum_{w} A_{vw} \tag{5-11}$$

The probability of an edge existing between vertices v and w if connections are made at random but respecting vertex degree is $k_v k_w / 2m$.

The modularity Q is defined as:

$$Q = \frac{1}{2m}\sum_{vw}[\mathrm{A}_{vw} - \frac{k_v k_w}{2m}] \times \delta(\mathrm{c}_v,\mathrm{c}_w) \tag{5-12}$$

Let e_{ij} denote the fraction of edges that join vertices in community i to vertices in community j.

$$e_{ij} = \frac{1}{2m}\sum_{vw} A_{vw}\delta(\mathrm{c}_v,\mathrm{i})\delta(\mathrm{c}_w,\mathrm{j}) \tag{5-13}$$

Let a_i denote the fraction of ends of edges that are attached to vertices in community i. $\delta(\mathrm{c}_v,\mathrm{c}_w) = \sum_i \delta(\mathrm{c}_v,\mathrm{i}) \times \delta(\mathrm{c}_w,\mathrm{i})$. Thus,

$$\begin{aligned} Q &= \frac{1}{2m}\sum_{vw}[\mathrm{A}_{vw} - \frac{k_v k_w}{2m}] \times \delta(\mathrm{c}_v,\mathrm{c}_w) \\ &= \frac{1}{2m}\sum_{vw}[\mathrm{A}_{vw} - \frac{k_v k_w}{2m}] \times \sum_i \delta(\mathrm{c}_v,\mathrm{i}) \times \delta(\mathrm{c}_w,\mathrm{i}) = \sum_i (\mathrm{e}_{ii} - a_i^2) \end{aligned} \tag{5-14}$$

In addition, we define

$$\Delta Q_{ij} = \begin{cases} 1/2m - k_i k_j/(2\mathrm{m})^2 & \text{if i and j are connected,} \\ 0 & \text{otherwise.} \end{cases} \tag{5-15}$$

For each i, $a_i = \frac{k_i}{2m}$.

A max-heap H contains the largest element of each row of the matrix ΔQ_{ij} along with the labels i, j of the corresponding pair of communities.

The *Clauset-Newman-Moore algorithm* based on modularity is defined as follows:

Clauset-Newman-Moore algorithm proposed in [76]

```
1:  Calculate the initial values of $\Delta Q_{ij}$ and $a_i$, and populate the max-heap $H$ with the largest
    element of each row of the matrix $\Delta Q$
2:  Select the largest $\Delta Q_{ij}$ from $H$, join the corresponding communities, update the matrix
    $\Delta Q$, the heap $H$ and $a_i$, and increment $Q$ by $\Delta Q_{ij}$
3:  Repeat step 2 until only one community remains
```

5.3 Application Examples

In this section, two application examples are presented to demonstrate how the proposed approach can help understand design communication and collaboration mechanism in CBD settings. In our application examples, actors are engineering graduate students in an engineering design class. This class was composed of both on-campus and distance learning students. These students are required to design two mechanical product prototypes in a CBD environment which consisted of a variety of social media tools (e.g., Wiggio, Google Drive, and others). Design activities in these design projects involved the core phases of the Pahl & Beitz systematic design approach starting from product planning and clarification of task, to conceptual design, embodiment design, and to detail design. The dataset of Example 1 was collected in spring 2011. There were 31 students in class and the students were divided into two competing sub-groups.

The dataset of Example 2 was collected from the spring 2012 cohort. There were 39 students in class and all the students teamed up to form one mass-collaborative group. The projects conducted in the two examples were:

(1) Example 1: Designing a hydroelectric footwear (Spring 2011);

(2) Example 2: Designing a wind-based electricity generation device (Spring 2012).

Both projects were conducted in a CBD environment where a variety of social media tools such as Wiggio, Google Drive, and Dropbox were used to share design-related data. Geographic locations of participating students are shown in Figure 5-3.

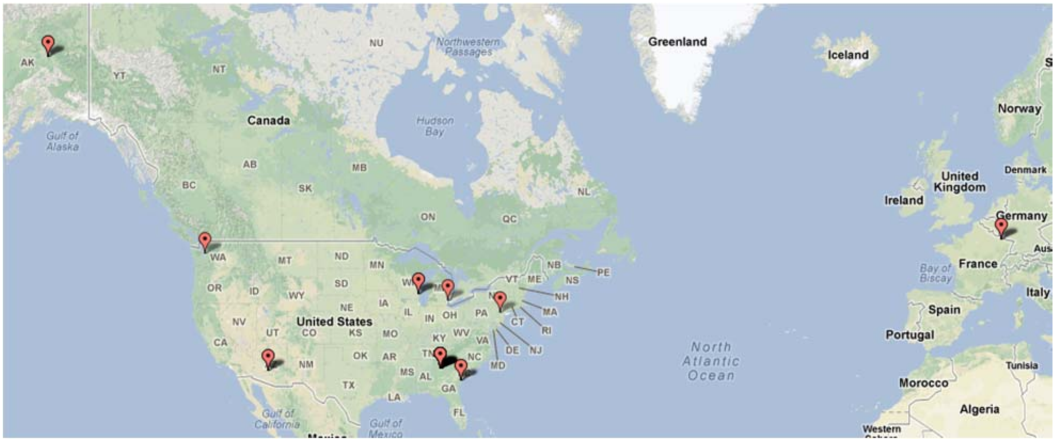


Figure 5-3 Geographic locations of participating students

The on-campus students were located in Atlanta Georgia in the United States; the distance learning students came from Georgia Tech Lorraine campus in Metz (France), Georgia Tech Savannah campus, Flanders in New Jersey, Fairbanks in Alaska, Phoenix in Arizona, and Milwaukee in Wisconsin. Second, the projects in the two application examples were focused on engineering design problems. The students were also required to build proof-of-concept prototypes to validate their design concepts using 3D printing technology. Therefore, these two design scenarios are very similar to what happens in real-world cases from industry.

5.3.1 Measuring Tie Strengths

Based on the approach presented before, *Step 1* is to define a specific index to measure tie strength. *Step 2* is to collect raw data about actors and ties that can map an implicit social network into an explicit social network. According to Gupte and Eliassi-Rad, only four indices satisfy all of the axioms. Tie strengths are measured in the application examples using these four indices and then conduct a sensitivity analysis to test the effect of changes in the number of events on the number of edges in the application examples. The *Delta*, *Max*, *Linear*, and *Adamic and Adar* index scores for example 1 are shown in Appendix A.1. Although the index scores for each connection based on these four indices are different, the number of edges is identical. For example, the *Delta*, *Max*, *Linear*, and *Adamic and Adar* index scores for measuring the tie strength between actors 1 and 2 is 28.0000, 0.3333, 28.0000, and 176.0559, respectively. Since all of the index scores are greater than zero, an edge is identified between nodes 1 and 2 in the social network. According to Appendix A.1, the same number of edges, fifty-one, is identified based on these four indices. Further, changes in the number of events (e.g., files, posts, meetings, calls, and polls) are made by -5% and -10%.

Table 5-3 Sensitivity analysis of indices for the number of edges in example 1

The number of events change by	Number of edges in example 1			
	Delta index	Max index	Linear index	Adamic and Adar index
-5%	51	51	51	51
-10%	51	51	51	51

As shown in Table 5-3, the number of edges that are identified remains the same, fifty-one. According to the result of the sensitivity analysis, it is found that these four indices are very robust.

Considering these four indices are all robust measures of tie strengths, all of them are perhaps applicable. However, according to Shannon's information theory and one of the two axioms in axiomatic design (the information axiom), the most important quantities of information are *Entropy*, the amount of information in common between two random variables. The *Entropy* is mathematically expressed in the form of common logarithm. Because the *Adamic and Adar index* is also defined using common logarithm, this index intuitively includes the quantification of information that is shared in design communication. Therefore, the *Adamic and Adar index* is used to measure tie strengths in the application examples. The *Adamic and Adar index* scores for examples 1 and 2 are shown in Appendix A.1 and A.2, respectively.

5.3.2 Measuring Social Networks and Detecting Community Structure

Based on the index scores in Appendix A.1 and A.2, the implicit design networks can be mapped into two explicit social networks. *Step 3* is to calculate the measures (e.g., degree, centrality, and cluster coefficient) of the explicit social networks. *Step 4* is to visualize the social networks, capture information flow, and detect key actors and communities with common design interests. The major measures that are used in these examples include (1) vertices and edges, (2) degree, (3) graph density, (4) betweenness and closeness centrality, and (5) clustering coefficient. A SNA tool, NodeXL [201], developed by Smith's team at the Microsoft Research, is used to perform Steps 3 and 4.

The general network statistics is listed in Table 5-4. The minimum, maximum, average, and median betweenness centrality, closeness centrality, and clustering coefficient are listed in Table 5-5. Appendices B.1 and B.2 list all the data related to these network measures for Examples 1 and 2, respectively.

Table 5-4 General network statistics in Examples 1 & 2 at the group level

Example 1		**Example 2**	
Graph Metrics	Value	Graph Metrics	Value
Vertices	31	Vertices	39
Total Edges	51	Total Edges	106
Graph Density	0.109	Graph Density	0.143

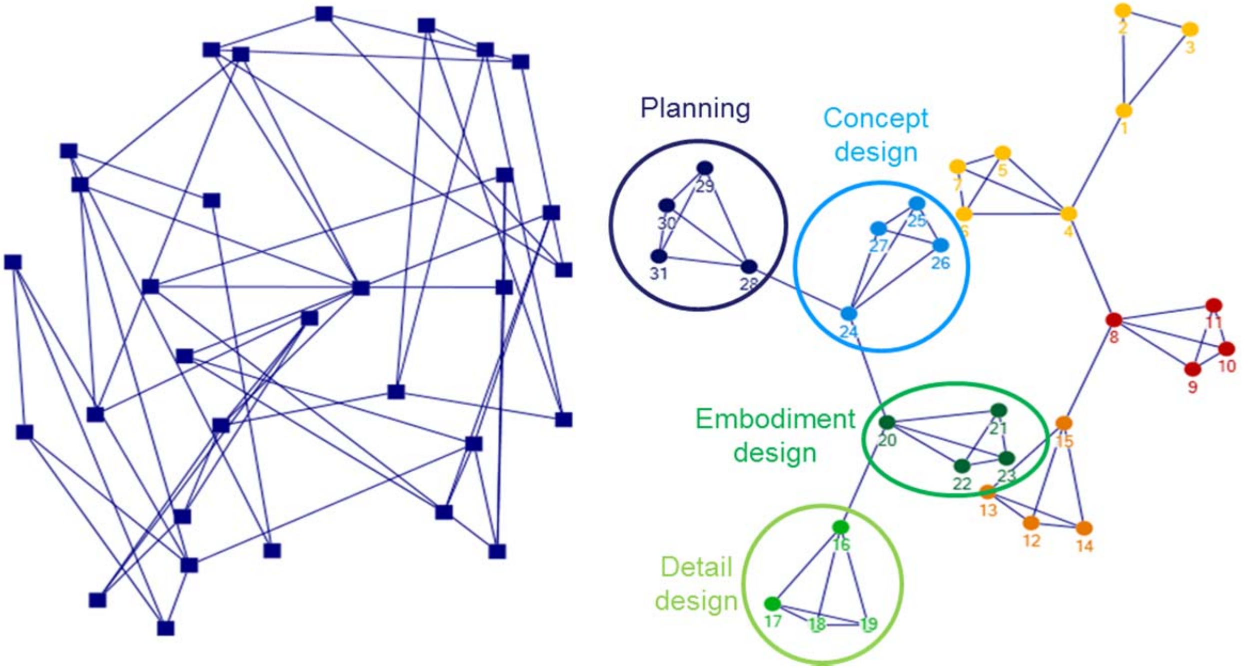
Table 5-5 Centrality and clustering coefficient in Examples 1 & 2 at the group level

Example 1		**Example 2**	
Centrality	Value	Centrality	Value
Minimum Betweenness Centrality	0.000	Minimum Betweenness Centrality	0.000
Maximum Betweenness Centrality	68.000	Maximum Betweenness Centrality	165.000
Average Betweenness Centrality	12.355	Average Betweenness Centrality	27.000
Median Betweenness Centrality	0.000	Median Betweenness Centrality	0.000
Minimum Closeness Centrality	0.021	Minimum Closeness Centrality	0.010
Maximum Closeness Centrality	0.040	Maximum Closeness Centrality	0.016
Average Closeness Centrality	0.026	Average Closeness Centrality	0.011
Median Closeness Centrality	0.025	Median Closeness Centrality	0.010
Minimum Clustering Coefficient	0.300	Minimum Clustering Coefficient	0.470
Maximum Clustering Coefficient	1.000	Maximum Clustering Coefficient	1.000
Average Clustering Coefficient	0.840	Average Clustering Coefficient	0.898
Median Clustering Coefficient	1.000	Median Clustering Coefficient	1.000

Table 5-6 Network measures for vertices for Examples 1 & 2 at the vertex (actor) level

Example 1				**Example 2**			
Vertex	Degree	Betweenness	Cluster Coefficient	Vertex	Degree	Betweenness	Cluster Coefficient
1	3	24.000	0.333	A	10	105.000	0.533
4	5	57.000	0.300	E	11	136.000	0.491
8	5	61.000	0.300	J	12	165.000	0.470
15	4	33.000	0.500	P	10	105.000	0.533
16	4	36.000	0.500	A1	12	165.000	0.470
20	5	68.000	0.300	G1	11	136.000	0.491
24	5	68.000	0.300	L1	10	105.000	0.533
28	4	36.000	0.500	P1	11	136.000	0.491

In Example 1, eight actors (vertices 1, 4, 8, 15, 16, 20, 24, and 28) are identified as the key actors in the information flow based on their relatively high betweenness scores (see Table 5-6) in comparison with the average betweenness score: 12.355 (see Table 5-5).

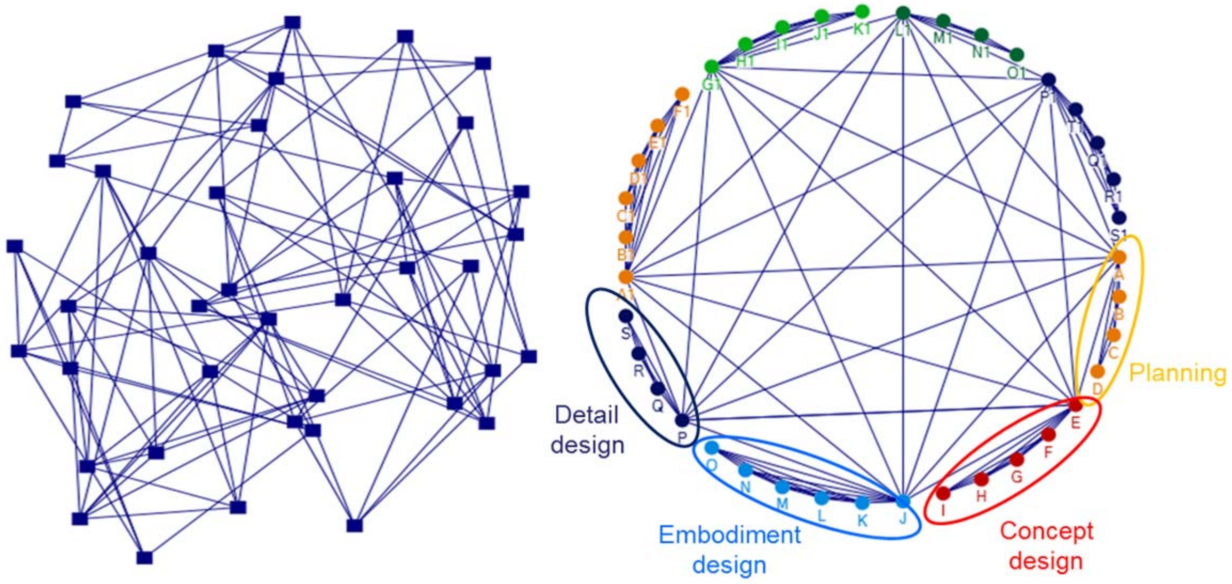


(a) Before community detection for Example 1 (b) After community detection for Example 1

Figure 5-4 Community detection with Clauset-Newman-Moore algorithm

Moreover, two separate groups with eight clusters of actors were successfully detected using SNA as illustrated in Figure 5-4 (a) & (b). Group 1 was composed of vertices 16 to 31. Group 2 was composed of vertices 1 to 15. Four clusters were detected for Group 1. The information flow started with the product planning subgroup (vertices 28, 29, 30, and 31 in dark blue), to the concept design subgroup (vertices 24, 25, 26, and 27 in light blue), the embodiment design subgroup (vertices 20, 21, 22, and 23 in dark green), and to the detail design subgroup (vertices 16, 17, 18, and 19 in light green). Similarly, another four clusters were detected for Group 2.

Since Groups 1 and 2 were competitive groups, there was no communication between them. As a result, the two groups were not connected with each other.



(a) Before community detection for Example 2 (b) After community detection for Example 2

Figure 5-5 Community detection with Clauset-Newman-Moore algorithm

In Example 2, the general graph metrics and statistics for group centrality are listed in the right two columns of Tables 5-4 and 5-5. Similarly, eight actors (vertices A, E, J, P, A1, G1, L1, and P1) are identified as the key actors in the information flow based on their relatively high betweenness scores (see Table 5-6) in comparison with the average betweenness score: 27.000 (see Table 5-5). Four clusters of actors were successfully detected for two subgroups, A and B in a single team, respectively, as shown in Figure 5-5 (a) & (b). For subgroup A, the information flow started with product planning (vertices A, B, C, and D in orange), to concept design (vertices E, F, G, H and I in red), embodiment design (vertices J, K, L, M, N, and O in light blue), and to detail design (vertices P, Q R, and S in dark blue). Similarly, another four clusters were detected for subgroup B. Subgroups A and B were connected with each other through subgroup leaders of the team (i.e., vertices A, E, J, P, A1, G1, L1, and P1) by utilizing some of the information sharing tools as described before.

5.3.3 Interpretation of Results

According to the approach in Section 3, *Step 5* is to interpret results and identify potential solutions for enhancing communication and collaboration. The general graph metrics in Table 5-5 and the statistics for centrality in Table 5-6 at the group level provide insights for understanding the overall collaboration structure of the network. At the same time, some of the graph metrics at the actor (vertex) level are also very valuable to capture individual actors' roles as shown in Table 5-6, including degree, betweenness centrality, and cluster coefficient. The following measures have been found to be important for understanding the overall collaboration structure:

- *Vertices, Edges, Graph density;*
- *Betweenness centrality, closeness centrality, clustering coefficient at the group level;*

Moreover, the results in Figure 5-4 and Figure 5-5 suggest that the Clauset-Newman-Moore algorithm can detect the communities effectively. As illustrated in Figure 5-4 (a) and (b), the Clauset-Newman-Moore algorithm identified eight actors in Example 1 who have relatively higher degree, betweenness centrality, and lower cluster coefficient at the actor level (as shown in Table 5-6) by comparing with the statistics for general metrics and centrality at the group level (as shown in Tables 5-4 & 5-5). We found that the actors as shown in Table 5-6 (vertices 1, 4, 8, 15, 16, 20, 24, and 28) are subgroup leaders who communicate with other actors more often, and have access to more information and resources. The same conclusion holds in Example 2. As illustrated in Figure 5-5 (a) and (b), there are also eight subgroup leaders (vertices A, E, J, P, A1, G1, L1, P1) but with higher betweenness and closeness centrality than those of subgroup leaders in Example 1 due to the fact that more communications (e.g., data exchange, file sharing, online group discussion) between individual actors are enabled by the CBD systems. The following measures have been found to be the most important for detecting communities and key actors:

- *Degree;*
- *Betweenness centrality and clustering coefficient at the actor level;*

One of the main findings based on the results is that the communication and collaboration mechanisms in CBD settings can be visualized and further be analyzed using SNA. More specifically, the implicit network structures for the two examples were visualized using the SNA tool as shown in Figures 5-4 and 5-5. Based on the visualized network as well as the measures in SNA as shown in Tables 5-4, 5-5, and 5-6, the structural positions of individual actors in the social networks were revealed which helps gain insights into the effectiveness of communication and collaboration in engineering design. For instance, in Example 1, the actors with ID 1, 4, 8, 15, 16, 20, 24, and 28 as shown in Figure 5-4 were identified as the critical players who possess some of the significant design-related information as well as have better control over information flow. In other words, these actors could also be the potential ones becoming the bottleneck of the flow of information in the network. Furthermore, take Group 2 in Example 1 for example, the information flow that was detected turns out to be consistent with that of Pahl & Beitz systematic design method, starting from the product planning (vertices 28, 29, 30, and 31 in dark blue), concept design (vertices 24, 25, 26, and 27 in light blue), embodiment design (vertices 20, 21, 22, and 23 in dark green), and to detail design (vertices 16, 17, 18, and 19 in light green). As the students are required to use the Pahl & Beitz systematic design method, the SNA-based approach is validated to be effective for capturing and measuring information flow in engineering design processes in the context of CBD. Furthermore, individuals with common design activities were also detected. Based on the visualized social networks and clusters, which designers are conducting similar design activities and where to find the information that are needed can be effectively identified.

With respect to collaboration patterns, it is found that CBD environments help enhance communication and collaboration among participants as it transformed engineering design collaboration from a conventional sequential pattern into a parallel one as shown in Figure 5-5 (b). CBD allows designers to quickly access, edit, and share product design-related information through a set of social media tools. Due to the ubiquitous computing environment in CBD, the sequence of interactions among individuals or design teams is not always unidirectional from planning, concept design, embodiment design, and to detail design. Instead, it could be multi-way interactions as detected in Example 2. As shown in Figure 5-5, the actors with ID A, E, J, P, A1, G1, L1, and P1 are fully connected, which means the collaboration pattern is not a sequential interaction but concurrent information sharing among participants. Such a multi-way interaction or parallel information sharing is very desirable because different perspectives from different individuals for the same information can enhance design for X (e.g., manufacturability, reliability, and variety).

5.4 The Potential Use of the SNA-Based Approach Incorporating Text Mining

Although the previously proposed SNA-based approach cannot identify what topical content individuals and groups are discussing and sharing with each other, text mining techniques are proven that concepts, topics, and key words can be extracted from various data sources such as text documents, emails, social network sites, and web pages. Therefore, to identify domain experts and their specific domain knowledge, a specific text mining technique, namely, tag cloud or word cloud, is combined with the SNA-based approach. A tag cloud is one of the data mining techniques that can be used to visualize the topical content of any text documents. More specifically, a tag cloud is a visual representation for text data which can be used to extract important terms or keywords and visualize them based on their importance. The font size of a tag in a tag cloud indicates the importance of a keyword. For instance, as shown in Figure 5-6, a tag cloud is generated from a text document related to 3D printing. The tag cloud extracts a number of keywords that are frequently shown in the text document, including *inkjet printing*, *prototyping*, *electron beam*, *sintering*, *manufacturing*, *stereolithography*, and so on. Based on the font size of each tag in the tag cloud, *inkjet printing* and *stereolithography* are the most important keywords.

Figure 5-6 A tag cloud capturing keywords in a text document related to 3D printing

5.4.1 General Trigging Conditions for Improving Collaboration

Before illustrating how SNA can be combined with tag cloud to improve design communication and collaboration, we first develop a set of general triggering conditions for improving design collaboration. From the design collaboration perspective, the general triggering conditions include (1) the connectivity within a group is too low (Case 1), (2) the size of a group is too large or too small (Case 2), (3) the connectivity across groups is too low (Case 3), (4) tie strengths between actors are too weak or too strong (Case 4), and (5) the role of actors is mismatched (Case 5). We also develop a set of corresponding interventions in response to the above general triggering conditions if they occur. Specifically, in Case 1 where the connectivity within a group is too low, the intervention is to connect more actors of the group. In Case 2 where the connectivity across groups is too low, the intervention is to connect more actors with one another. In Case 3 where the size of a group is too large or too small, the intervention is to break down large groups or combine some small groups into a large group. In Case 4 where tie strengths between actors are too week or too strong, the intervention is to enhance or reduce information sharing behaviors. In Case 5 where the role of actors is mismatched, the intervention is to exchange actors and assign the actors with the right tasks or roles.

5.4.2 An Example of Hypothetical Application Scenario

To illustrate how the SNA-based approach combined with text mining can be used to improve design communication and collaboration in CBD settings, we develop an example of hypothetical design scenario. The objective of presenting the hypothetical design scenario is to demonstrate the SNA-based approach has the potential to model and analyze information flow across multi-disciplinary development teams, identify domain experts and group leaders, and improve design communication and collaboration in a CBD setting.

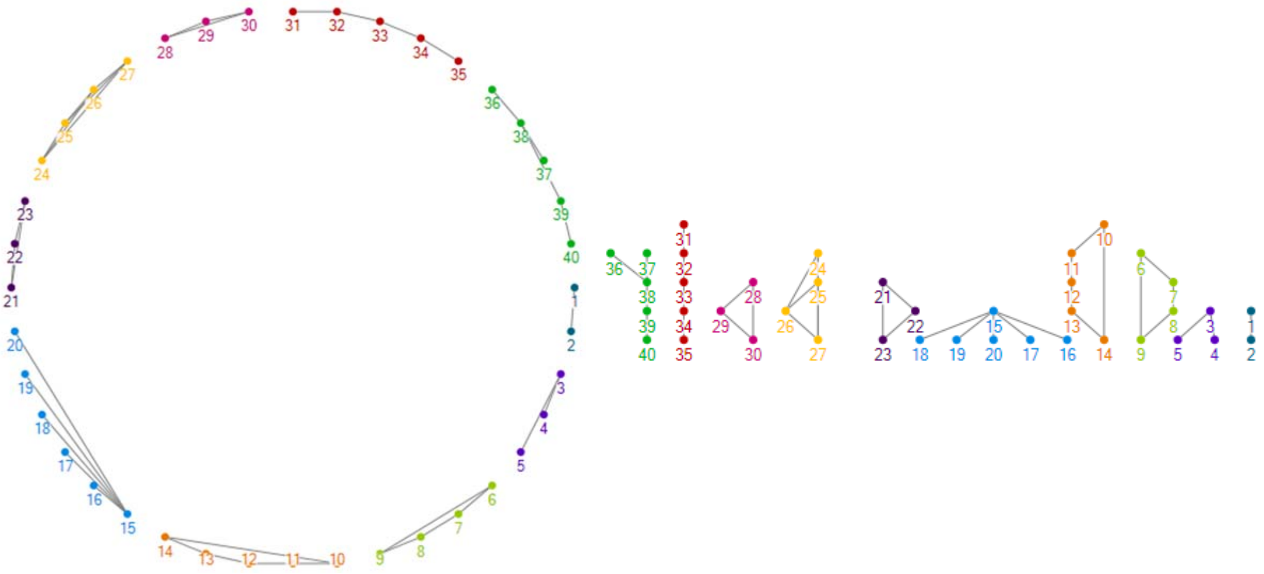
In the hypothetical scenario, suppose that the United States Postal Service (USPS) launches a design project: developing the next-generation of smart delivery drones. The new delivery drone design should meet all the requirements presented in Chapter 3. The delivery drone design should be finished within 6 months. USPS plans to crowdsource the drone design online by utilizing the cloud-based social collaboration platform developed by Quirky or Yammer. The platform is intended to help self-organizing design teams from a community of engineers to work together. In this community, one of them is assigned as the lead project engineer by USPS based on his or her design experience and expertise before the project starts. The lead project engineer distributes the initial design brief to a qualified crowd and selects 40 best-qualified individuals to form a design team. This design team represents a modern form of a learning organization as introduced by Peter Senge. One major goal of a learning organization is to promote a more interconnected way of performing businesses such as engineering design. For example, the roles and responsibilities of individuals except the pre-selected lead project engineer are assigned based on the respective competencies of the selected individuals in the design team in a mostly self-organized way. The roles and responsibilities of individuals may change as the design project continues in comparison with the fact that the structure of a traditional organization and the roles of individual engineers in the traditional organization are rigid.

Specifically, with respect to the managerial role of the lead project engineer, the lead project engineer is responsible for communicating and coordinating with USPS, reporting project progress to them periodically, and ultimately taking responsibility for the success of the entire delivery drone project. With respect to the technical role of the lead project engineer, the lead project engineer is responsible for monitoring the entire design process, interpreting the SNA and text mining results, and making decisions on interventions based on these results. As stated previously, beside the management role of the pre-selected lead project engineer, the overall design process is largely self-organized with only a minimum but essentially necessary amount of oversight and intervention by the project lead engineer.

In addition, suppose that an open-source plug-in or add-on program is developed by the social collaboration platform provider, Quirky or Yammer, using the SNA and tag cloud combined approach presented in Section 5.2. Quirky or Yammer conducts social network analysis and text mining using the open-source plug-in program for improving communication and collaboration in the cloud-based design setting. The output of the program, including SNA and text mining results, provides the lead project engineer with potential problems associated with communication, collaboration, and engineering design. The primary features of the plug-in program include: (1) detecting communities in which engineers are grouped based on interests and engineering skill sets, (2) detecting experts and group leaders for these communities, (3) detecting triggering conditions that may lead to collaboration problems, and (4) recommending potential interventions to the lead project engineer for improving collaborative design processes automatically.

In the drone design example, while social collaboration data is collected throughout the product development process, Quirky or Yammer conducts SNA and text mining continuously in the backend of the cloud-based social collaboration platform. When Case 1 occurs, the SNA results (see Figure 5-7) are generated. In Figure 5-7, circular and chain views are two different views of the same community detection result. As shown in Figure 5-7, the plug-in program detects 10 clusters (in different colors) in which engineers communicate and collaborate with their peers locally on a small scale.

In addition to the SNA results in Figure 5-7, a tag cloud (See Figure 5-8) is generated by analyzing and mining text documents stored in the social network sites of the CBD system. As shown in Figure 5-8, at the initial design phase, the focused content primarily includes *customer needs, problem clarification, product requirements, functionality, expected price range, government regulations, division of tasks*, and so on. Based on the intervention corresponding to Case 1, the intervention is to increase the internal connectivity of each group by connecting actors with one another.

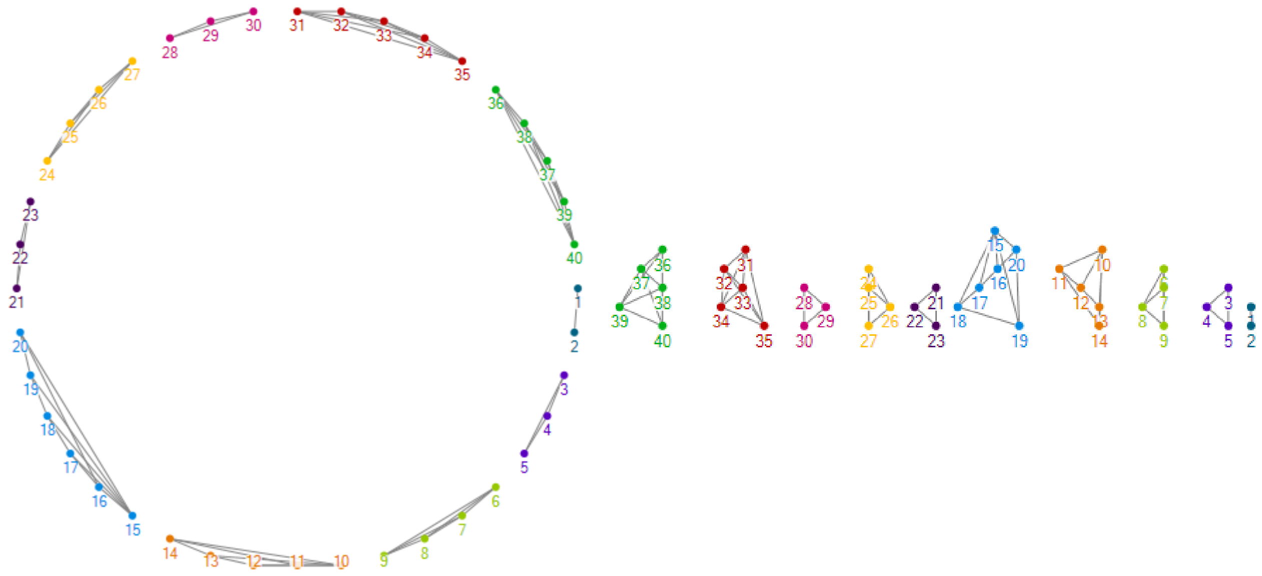


(a) Circular view (b) Chain view

Figure 5-7 Community detection after Case 1 occurs

Figure 5-8 A tag cloud generated after Case 1 occurs

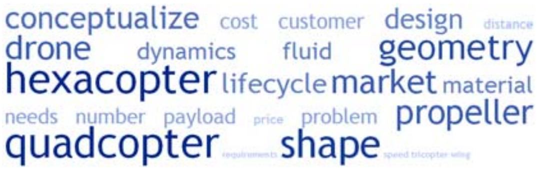
When Case 2 occurs, the plug-in program generates the SNA results, as shown in Figure 5-9 and 5-10. To assess the effectiveness of the previous action, namely, improving the connectivity of each subgroup, it is found that the number of links between individuals in each subgroup is significantly increased as shown in Figure 5-9. To detect what topical content individuals and subgroups are discussing and sharing with each other, a tag cloud is generated for each subgroup as shown in Figure 5-10.



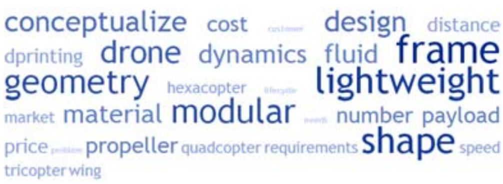
(a) Circular view (b) Chain view

Figure 5-9 Community detection after Case 2 occurs

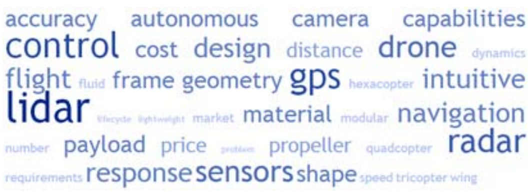
Tag cloud for subgroup 1



Tag cloud for subgroup 2

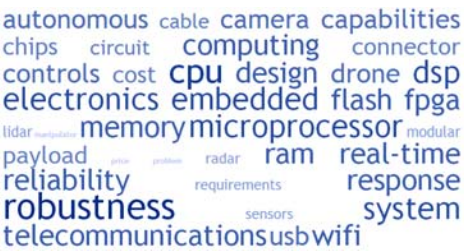


Tag cloud for subgroup 3

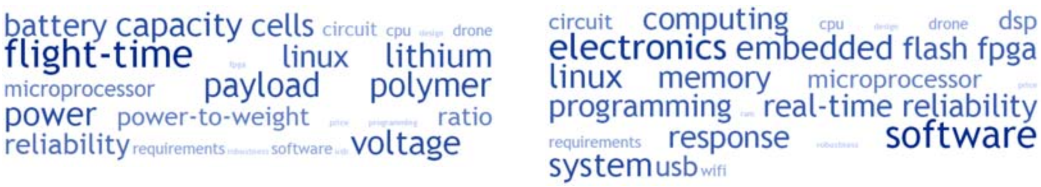


Tag cloud for subgroup 4

Tag cloud for subgroup 5



Tag cloud for subgroup 6



Tag cloud for subgroup 7

Tag cloud for subgroup 8

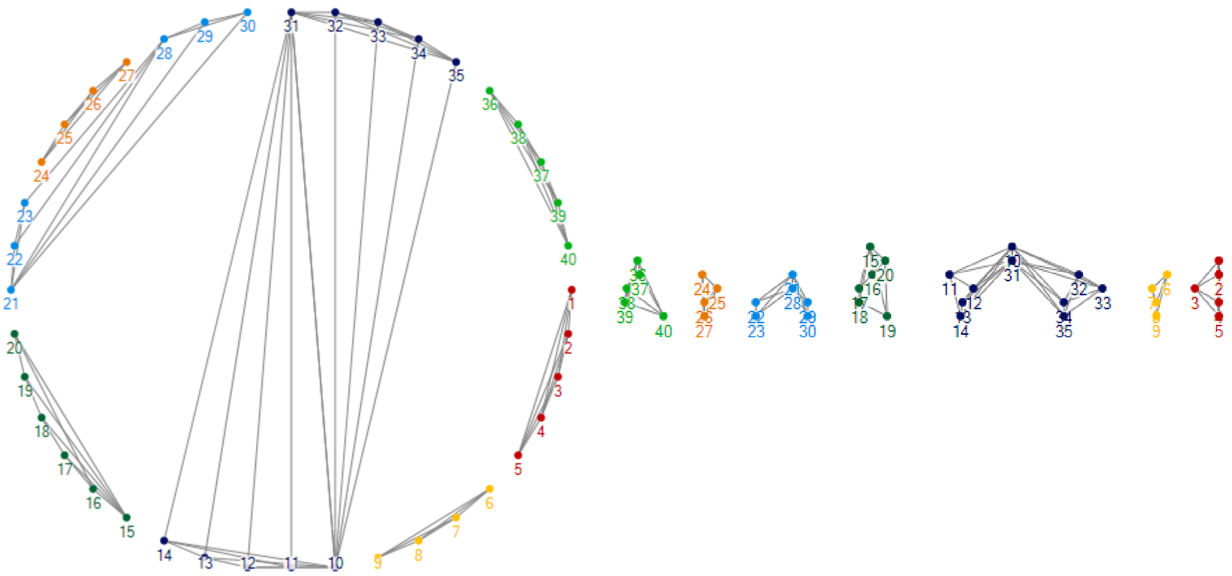
Tag cloud for subgroup 9

Tag cloud for subgroup 10

Figure 5-10 Tag cloud generated for each subgroup after Case 2 occurs

Based on these tag clouds, the frequently discussed topics or keywords for subgroups 1 to 10 are *propeller, frame, manipulator, navigation, battery and charger, electronics, and remote control*. In particular, it is found that some subgroups have common topics of interest. For example, subgroups 1 and 2 focus on the design of propellers; subgroups 4 and 9 focus on navigation; subgroups 6 and 8 focus on electronics. In addition, the finding based on Figure 5-9 is that information sharing behaviors does not occur across but only within individual organizations. Such limited information sharing across organizations will most likely result in information gaps and a decrease in effectiveness and efficiency of communication and collaboration. Therefore, to better exchange and share information related to the same topic but generated from different subgroups, the intervention is to combine small subgroups with common interests into a large group.

When Case 3 occurs, the plug-in program generates the SNA results as shown in Figure 5-11.

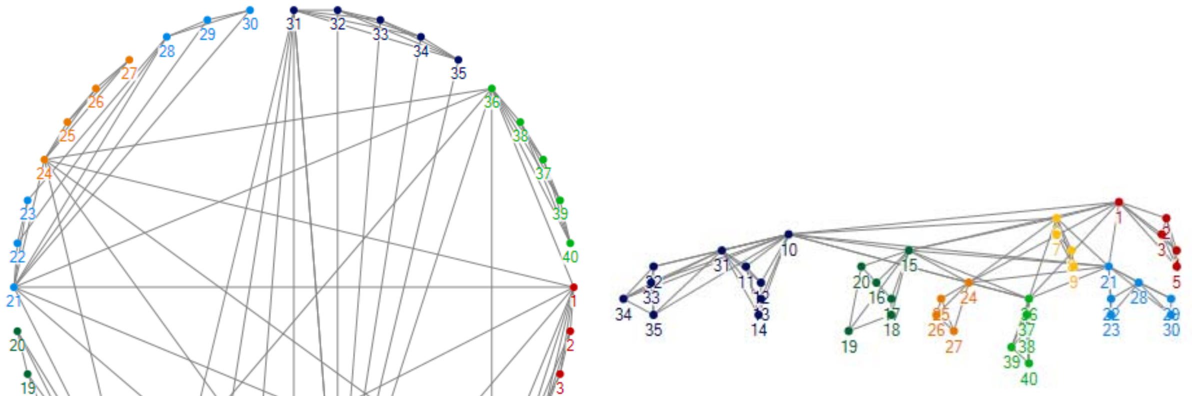


(a) Circular view (b) Chain view

Figure 5-11 Community detection after Case 3 occurs

As shown in Figure 5-11, it is found that the subgroups with common interests are successfully combined into a large one. For example, subgroup 1 with actors 1 and 2 is merged with subgroup 2 with actors 3 to 5. After merging small subgroups with common or similar topics of interest, seven engineering teams are generated focusing on the development of the propellers, frame, manipulator, navigation systems, battery and charger, electronics, and remote control transmitter. However, the seven engineering groups are completely separated because no information sharing behaviors across these teams occur. Therefore, to help integrate some tightly-coupled subsystems more effectively, the intervention is to connect these isolated groups with each other, thereby synchronizing information flow across multiple disciplines.

When Case 4 or 5 occurs, the plug-in program generates the SNA and tag cloud results, as shown in Figures 5-12 and 5-13.



(a) Circular view (b) Chain view

Figure 5-12 Community detection after the intervention in response to Case 3

As shown in Figure 5-12, the seven isolated teams are successfully connected. Experts or leaders in each domain are also detected. Finding these experts for the collaboration network is crucial because it is extremely difficult for any one single individual in the collaboration network to have a complete and accurate view of the entire drone development process. Moreover, connecting these leaders in different domains helps synchronize information and knowledge flow because these experts create useful information and knowledge and have direct access to them.

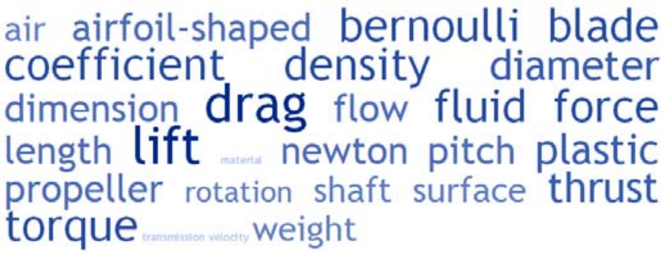


Figure 5-13 A tag cloud generated for group 1 after the intervention in response to Case 3

Figure 5-13 shows the tag cloud generated for group 1 with actors 1 to 5 at the time when performing the detail design of propellers. Similar to the previous three cases, the corresponding intervention can be performed accordingly to further improve design collaboration. We will not discuss the details about more cases in this chapter.

5.5 Summary

The objective of this chapter was to understand how design-related information flow through socio-technical systems and how different individuals or organizations can play distinct roles in this process to improve design communication and collaboration in a formal fashion. Specifically, Research Question 2 was formulated as follows:

Research Question 2.a:

- *What indices can be used to measure tie strengths between engineers in CBD?*

Research Question 2.b:

- *How can information flow for communication and collaboration in CBD be modeled and analyzed?*

The results validated the following hypotheses:

Hypothesis 2.a:

- *The Adamic and Adar index can be used to measure tie strengths in engineering design.*

Hypothesis 2.b:

- *The measurement of centrality and community detection methods in social network analysis can be used to model and analyze information flow for design communication and collaboration in CBD.*

The research described in this chapter contributes to the current body of knowledge in the sense that a generic approach is proposed for investigating communication and collaboration mechanisms in social product development settings. Specifically, tie strengths were measured using four indices that satisfy all of the axioms in social network analysis. A sensitivity analysis was conducted to test the robustness of the four indices. Based on the result of the sensitivity analysis, it was observed that all of them are applicable. Because the Entropy in Shannon's information theory and axiomatic design is expressed in the form of common logarithm and the *Adamic and Adar index* is also defined using common logarithm, the *Adamic and Adar index* was selected to measure tie strengths in our examples. Based on the *Adamic and Adar index* scores, an implicit design network can be formally transformed into an explicit social network. In the two examples, the process of transforming customer needs, to functional requirements, to design parameters, and to process variables was visualized using Social Network Analysis (SNA). Using the quantitative measures in SNA, the social networks were measured at both actor and systems levels and detected design communities with common design activities. Moreover, by combining a text mining technique, tag cloud, the SNA-based approach can not only transform an implicit collaboration network into a formal social network, visualize information flow in the social network, detect engineering communities with common or similar interests, but also identify topical content based on key words extracted from various text documents.

While the hypotheses were validated using two examples, the limitation of this study is acknowledged as follows. The application examples were not conducted in the context of real industry environments but in a graduate level engineering design course where different groups of student play different roles. Although the projects conducted in the examples were to solve engineering design related problems, the working environment can only represent the real industrial environment to a certain degree. Future work will focus on conducting real industry case studies.

CHAPTER 6

MODELING AND ANALYSIS OF CLOUD-BASED MANUFACTURING NETWORKS

Chapter 5 addressed one of the challenges pertaining to design communication and collaboration in CBD settings. As stated before, in the context of CBD, computing scalability can be achieved through virtualization. However, in the context of CBM, an important issue to be addressed is that of manufacturing capacity scalability, or in other words, how rapid manufacturing capacity scalability – a key characteristic of CBM systems, can be achieved based on physical systems, i.e., Hardware-as-a-Service (HaaS). In traditional manufacturing settings, to scale up manufacturing capacity, manufacturers purchase more manufacturing resources such as milling machines, lathes, or 3D printers to satisfy increasing market demand. However, if market demand decreases, these added manufacturing resources may well become underutilized or idle. Moreover, the acquired manufacturing resources may not even be reused for producing future product variants or completely different products.

Therefore, it is reasonable to rent manufacturing resources or sourcing manufacturing tasks that are beyond existing manufacturing capacity to third-party service providers through CBM considering the costs of ownership, operations, and maintenance. In this context, another challenge related to CBDM is how to configure or reconfigure a cloud-based manufacturing network so that it allows manufacturers to achieve rapid manufacturing scalability. The objective of Chapter 6 is to understand how CBM can help manufacturers plan manufacturing scalability by modeling and analyzing material flow in an in-house manufacturing system, identifying manufacturing bottlenecks, and crowdsourcing manufacturing tasks over a cloud-based manufacturing network.

Specifically, Research Question 3 and its hypothesis are as follows:

Research Question 3:

- *How should the manufacturing capacity scalability of a CBM system be planned prior to the implementation and deployment of a CBM system?*

Hypothesis 3:

- *Discrete-event simulation can be used to formally model and simulate the manufacturing network of a CBM system and to plan manufacturing capacity scalability by identifying manufacturing bottlenecks and reconfiguring a manufacturing network.*

To validate the hypothesis, this chapter introduces a stochastic petri nets (SPNs)-based approach for modeling and analyzing the concurrency and synchronization of the material flow in a CBM system. The proposed approach is validated using a delivery drone example. Results have shown that the SPN-based approach can be used to perform the qualitative (i.e., structural and behavioral properties) and quantitative (i.e., utilization and capacity) analysis of a CBM system. Based on the quantitative analysis, manufacturing bottlenecks that determine the capacity of a manufacturing system can be identified and managed such that manufacturers can increase the capacity of the bottlenecks on the manufacturing network, thus improving manufacturing capacity scalability.

The remainder of this chapter is organized as follows: Section 6.1 presents an emerging manufacturing paradigm, also referred to as cloud-based manufacturing (CBM). Section 6.2 presents the notion of manufacturing capacity scalability. Section 6.3 introduces the basics of Petri nets (PNs) and SPNs. Section 6.4 presents the problem formulation and the modeling and analysis of a manufacturing system for a delivery drone using SPNs. Section 6.5 presents both qualitative and quantitative analysis results based on which the process capacity of individual manufacturing resource and the overall manufacturing capacity can be measured. Section 6.6 presents the planning of manufacturing capacity scalability by scaling up the process capacity of the manufacturing bottlenecks detected in Section 6.5. Section 6.7 draws the conclusion.

6.1 Cloud-Based Manufacturing

Cloud-based manufacturing (CBM) has recently been proposed as an emerging manufacturing paradigm that can potentially change the way products are developed and produced as well as the way manufacturing services are provided and accessed. According to a survey conducted by the McKinsey Global Institute [202], cloud computing along with 3D printing is expected to have a profound impact on manufacturing and supply chains. The estimated economic value added by cloud-based 3D printing is $230 billion to $550 billion per year by 2050.

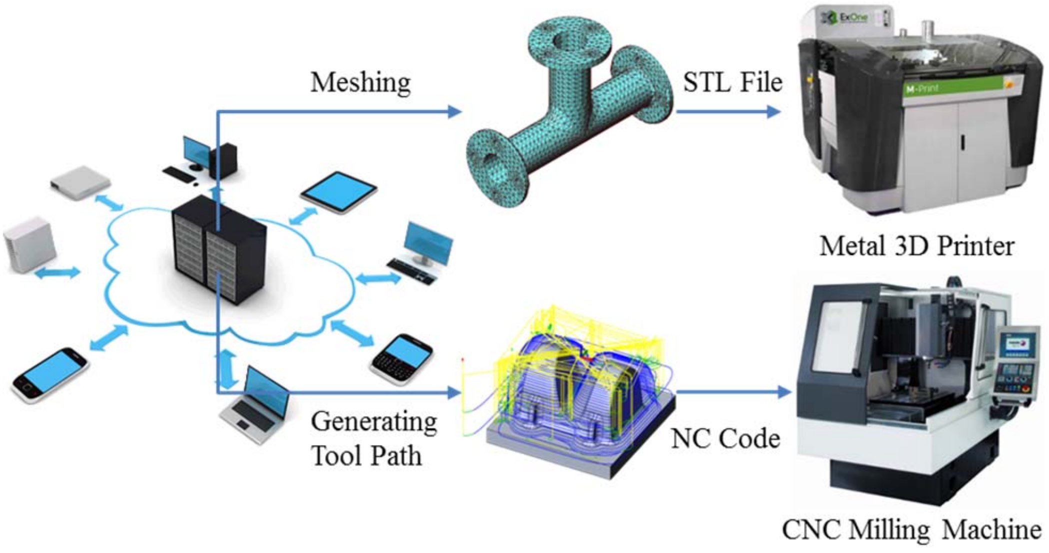


Figure 6-1 How cloud-based manufacturing works

CBM refers to “a crowdsourcing-based manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines that enhance efficiency, reduce product lifecycle costs and allow for optimal resource allocation in response to variable-demand customer generated tasking". CBM has the potential to enable service consumers to access a variety of manufacturing services such as additive manufacturing (e.g., 3D printing) and subtractive manufacturing (e.g., CNC machining) through cloud-based manufacturing processes as shown in Figure 6-1.

For instance, Shapeways and 3D Hubs, two cloud-based 3D printing service providers with different business models, connect 3D printing service consumers with providers from both the local and global area. For example, Shapeways is a cloud-based sourcing platform with a focus on low-volume production for custom manufactured rapid prototypes. Shapeways connects service consumers to a global network of 3D printing service providers through an instant quoting engine, which transformed sourcing processes from manual to real-time and automatic. Shapeways enables users to upload their CAD data from a variety of commercial CAD software packages such as CATIA and SolidWorks. Based on geometric analysis, Shapeways instantly generates a list of qualified service providers.

Similarly, 3D Hubs provide 3D printing services to consumers, but focus on building a local network of individually owned and operated 3D printers. The goal of 3D Hubs is to allow 3D printing owners to increase the utilization of their devices and establish social connections within their local 3D printing community. 3D Hubs have developed a network of 200,000 3D printers across eighty countries over the world since 2013. 3D Hubs have established an innovative business model that creates and delivers unique value to both 3D printing service consumers and providers. Figure 6-2 illustrates how 3D Hubs provide a unique business model for 3D printing by "democratizing" 3D printing services.

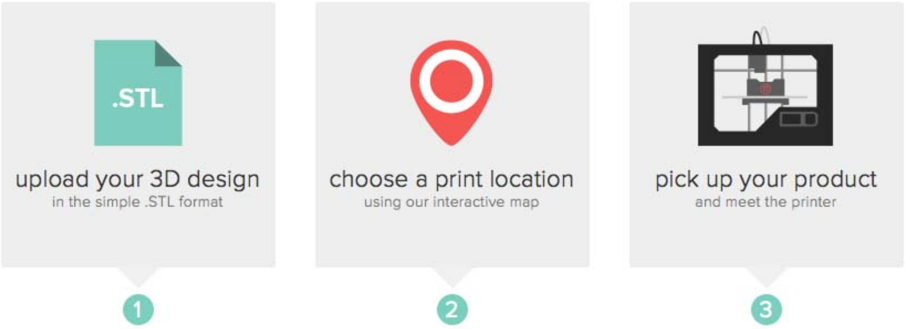
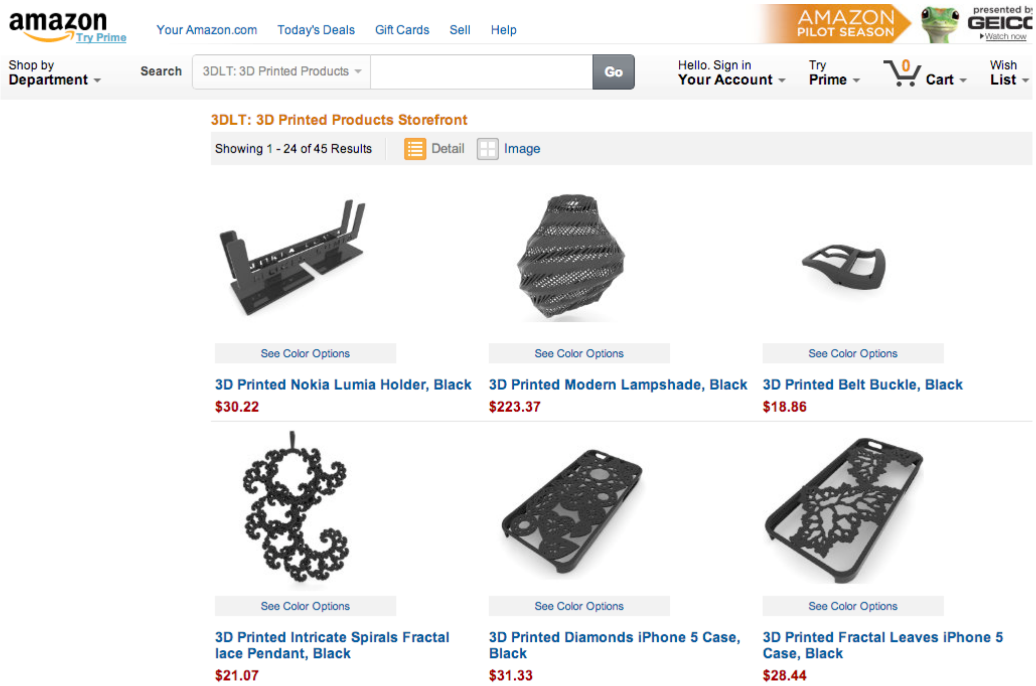


Figure 6-2 How local 3D printing works in 3D Hubs [149]

As shown in Figure 6-2, first, a hub, namely a 3D printing service provider, allows a service consumer to upload 3D models in the STL format. A cloud-based geometric analysis tool provided by 3D Hubs examines whether all of the design features of a 3D model can be produced by 3D printing and automatically suggests design modifications for the 3D model if necessary. Second, once the 3D model passes inspection, the service consumer can request for quotes from a number of local service providers and choose a specific printer available in the 3D printer network to build a part. Third, the consumer can choose to pick up the part from the local 3D printing service provider or request the provider to deliver it. At the same time, 3D Hubs add a fifteen percent on top of the original quote.

Based on the innovative cloud-based 3D printing process, 3D Hubs and its large network of 3D printing service providers have the potential to transform conventional manufacturing supply chains with multiple business functions and processes across companies, long distance shipping, and sophisticated inventory control to localized and integrated ones with on-demand and scalable manufacturing services. Specifically, material flow in conventional manufacturing supply chains starts from raw material suppliers, low-level and high-level suppliers, manufacturing, assembly, distribution, warehouse, retail, and eventually to end users. In cloud-based manufacturing supply chains, a local network of 3D printers has the potential to address complex logistics issues by bypassing some of required business segments such as distribution, warehousing, and retail. An interesting and potentially more influential example is a pilot program being initiated by Amazon in partnership with 3DLT. As shown in Figure 6-3, 3DLT allows users to simply purchase 3D digital design files and print the products instead of buying physical items directly or printing them on a third-party site such as Shapeways. Cloud-based 3D printing has the potential to deliver a just-in-time retail experience in which online e-commerce companies do not need to invest in a network of distribution centers and warehouses and manage complex logistics issues associated with them.



3DLT: 3D Printed Products Storefront

Showing 1 - 24 of 45 Results

3D Printed Nokia Lumia Holder, Black
$30.22

3D Printed Modern Lampshade, Black
$223.37

3D Printed Belt Buckle, Black
$18.86

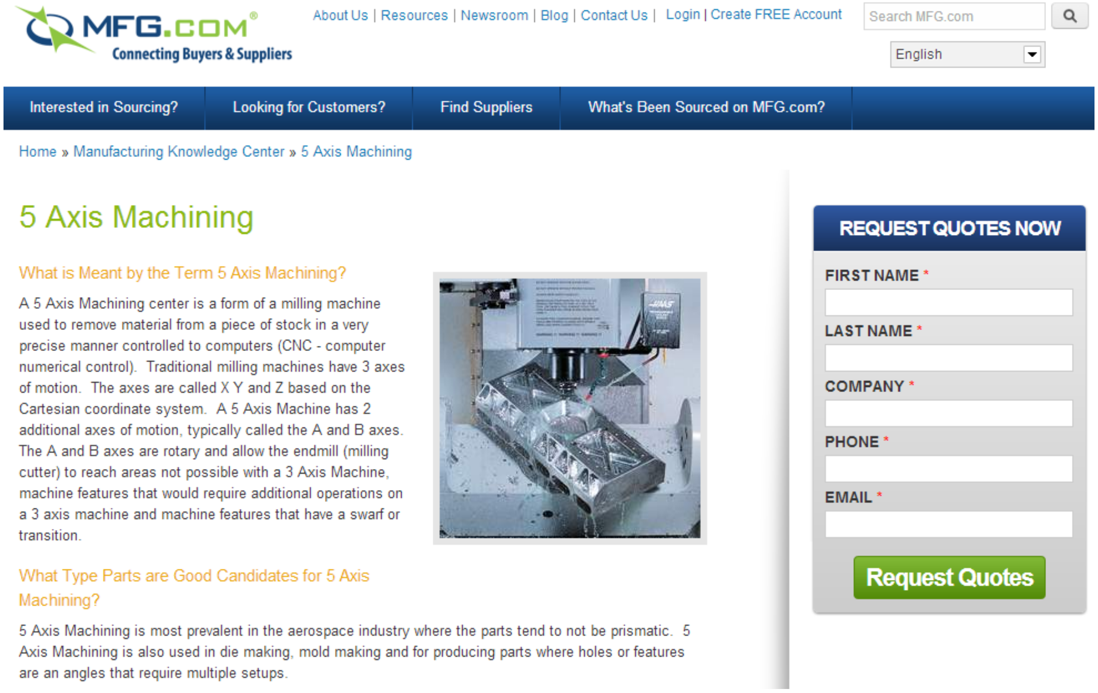
3D Printed Intricate Spirals Fractal lace Pendant, Black
$21.07

3D Printed Diamonds iPhone 5 Case, Black
$31.33

3D Printed Fractal Leaves iPhone 5 Case, Black
$28.44

Figure 6-3 Amazon's pilot program for 3D printed products [203]

In addition to the aforementioned small- and medium-volume cloud-based 3D printing services, MFG.com and Alibaba.com are two example companies connecting SMEs to large-scale manufacturers in traditional manufacturing domains such as machining, casting, injection modeling, and tooling. For example, MFG.com allows service consumers to have access to request for quotations being sourced by more than 200,000 global service providers. MFG.com enables service consumers to discover and collaborate with quality service providers at shorter deliver times, reduced costs, and a more flexible supply chain. As shown in Figure 6-4, 5-axis machining services are provided by MFG.com. As more organizations and individuals become manufacturers due to low cost small-scale and professional quality medium-scale machinery, the lines between service consumers and providers will blur. Consequently, similar to 3D Hubs, cloud-based manufacturing will provide more traditional small- and medium-volume manufacturing services through a local network of manufacturers in the near future.



5 Axis Machining

What is Meant by the Term 5 Axis Machining?

A 5 Axis Machining center is a form of a milling machine used to remove material from a piece of stock in a very precise manner controlled to computers (CNC - computer numerical control). Traditional milling machines have 3 axes of motion. The axes are called X Y and Z based on the Cartesian coordinate system. A 5 Axis Machine has 2 additional axes of motion, typically called the A and B axes. The A and B axes are rotary and allow the endmill (milling cutter) to reach areas not possible with a 3 Axis Machine, machine features that would require additional operations on a 3 axis machine and machine features that have a swarf or transition.

What Type Parts are Good Candidates for 5 Axis Machining?

5 Axis Machining is most prevalent in the aerospace industry where the parts tend to not be prismatic. 5 Axis Machining is also used in die making, mold making and for producing parts where holes or features are an angles that require multiple setups.

Figure 6-4 Connecting 5-axis machining service providers to consumers at MFG.com [131]

6.2 Manufacturing Scalability

The example cloud-based service providers stated in Section 6.1 allow manufacturing enterprises to quickly scale up and down because manufacturing resources (e.g., 3D printers and general purpose CNC machine tools) can be added, removed, and modified as needed to respond to rapidly changing market demand. In particular, these emerging services help manufacturers handle transient demand and dynamic capacity planning under emergency situations incurred by unpredictable customer needs and reliability issues.

The capacity of manufacturing systems is a metric that indicates how many objects such as parts or products can be produced per day by a manufacturing system. Manufacturing capacity needs to be adjusted in response to fluctuations in market demand. Capacity scalability refers to the adjustability of manufacturing capacity to adapt capacities to changing market demand [105, 204]. For example, as market demand increases and exceeds the designed manufacturing capacity, manufacturing capacity needs to be increased to fulfil more orders and make more profits. On the other hand, as market demand decreases and is less than the designed manufacturing capacity, manufacturing capacity needs to decrease to reduce maintenance costs or avoid waste of resources.

In this section, a list of definitions related to scalability is provided as follows:

- “Scalability refers to the ability to adjust the production capacity of a system through system reconfiguration with minimal cost in minimal time over a large capacity range at given capacity increments.” [205].
- “System scalability is defined as the design of a manufacturing system and its machines with adjustable structure that enable system adjustment in response to market demand changes. Structure may be adjusted at the system level (e.g., adding machines) and at the machine level (changing machine hardware and control hardware).” [206].
- “The notion of scalability implies that where the problem size increases, the algorithm continues to apply and, by increasing the number of computational engines proportionately, the performance of the algorithm will continue to increase.” [207].

- “Computational scalability refers to operations on the data should be able to scale for both an increasing number of users and increasing data sizes.” [208].
- “Elastic scalability implies that the resources are put to use according to actual current requirements observing overarching requirement definitions – including both up- and down-ward scalability.” [209].

Addressing the capacity scalability problem is essentially to determine when, where, and by how much the capacity of a manufacturing system should be scaled. This chapter is particularly focused on determining where and by how much the capacity of a manufacturing system should be scaled. Traditionally, capacity scalability can be achieved by two ways: (1) by scaling the capacity of individual manufacturing resource and (2) by adding or removing manufacturing resources to or from existing in-house systems. In the context of CBM, it is perhaps more cost-effective to adopt a new approach that is similar to the second one; that is crowdsourcing part of the manufacturing tasks that are beyond the existing in-house capacity to third-party service providers, namely CBM service providers. Further, it is assumed that a CBM service consumer can almost always find a few qualified service providers whose manufacturing capacity is not fully utilized using cloud-based global sourcing platforms as stated before. This assumption seems strong; however, considering the entire life cycle of a manufacturing system, the time when a manufacturing system running at the full capacity is usually short, although a manufacturing system is optimally designed. Moreover, even if a manufacturing service provider is running at the full capacity, in order to make more profits or receive larger orders, this service provider may still prioritize manufacturing tasks and reallocate their manufacturing capacity to more profitable businesses.

The following example clarifies a scenario in which manufacturing capacity can be scaled up in traditional in-house and CBM settings. Fabricating our example part requires 16 machining tasks of 30 seconds each, totaling 480 seconds. The market demand is 480 parts per 8-hour shift. Therefore, the required cycle time is 480/480 = 1 min/part or 60 seconds/part. The existing manufacturing system consists of four stages. Each stage consists of two identical machines. Each machine performs 4 tasks of 30 seconds each, totaling 120 seconds per machine. After six months, if the demand increases to 720 (720 = 480×1.5) parts per 8-hour shift, then the required cycle time is reduced to 480/720 = 0.67 min/part or 40 seconds/part. The two manufacturing system configurations are shown in Figure 6-5.

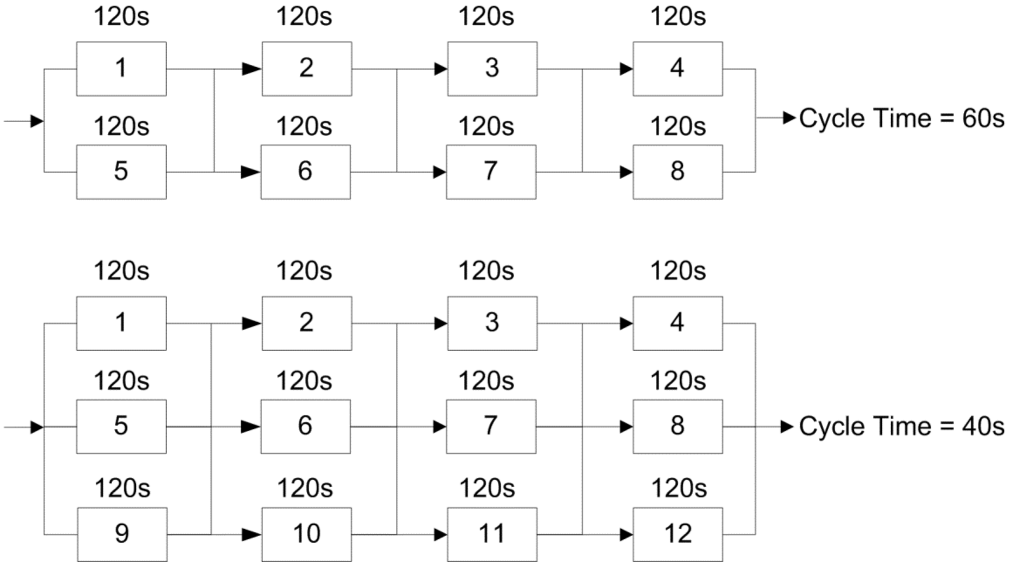


Figure 6-5 Manufacturing configurations with cycle times of 60 and 40 seconds per part

In this example, it is assumed that each machine is fully utilized. In other words, the capacity of individual machine cannot be scaled anymore. To scale up manufacturing capacity from 480 parts per 8-hour shift to 720 parts per 8-hour shift in traditional settings, one more machine needs be added in-house in each stage. However, the increased manufacturing tasks that are beyond the existing in-house capacity can be crowd-sourced to CBM service providers in CBM settings as stated before instead of in-house. For example, using a cloud-based sourcing platform, the sixteen tasks that are originally conducted in-house by machines 9, 10, 11, and 12 can be sourced to a few service providers. This example is a simplified case but can demonstrate how capacity can be scaled in traditional and CBM settings. To implement this concept in practice, many constraints (e.g., lead time and costs) need to be considered. A more complex illustrative example will be discussed in Section 6.4.

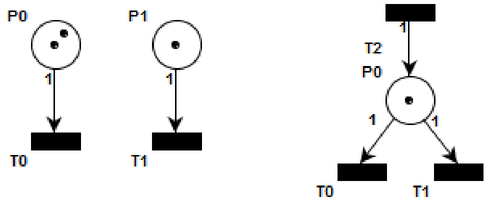
Moreover, to rapidly scale up and down manufacturing capacity, the fundamental objective is to monitor and control material flow. Material flow in its broadest sense means understanding the entire life cycle of substances; in the context of manufacturing systems, material flow refers to the transformation of raw material to parts, to sub-assembly, to assembly, and finally to end-products between service providers and consumers. The importance of modeling and analyzing material flow is that it allows for enhancing the efficiency of manufacturing processes by detecting manufacturing bottlenecks. A manufacturing bottleneck refers to a phenomenon where certain key performance indicators (KPIs) or the capacity of an entire manufacturing system is limited by a single or several components of the manufacturing system. Formally, a manufacturing bottleneck lies on the critical path of a manufacturing network and provides the lowest capacity. As a consequence, a bottleneck manufacturing process limits material flow in a manufacturing system.

The existing literature on manufacturing bottleneck detection falls into two categories: analytical and simulation-based methods. The major drawbacks associated with analytical approaches include (1) they are restricted to steady-state analysis and (2) it is very difficult to develop close-form solutions for complex manufacturing systems. As compared to analytical approaches, discrete-event simulation helps identify potential manufacturing bottlenecks that determine the capacities of both individual manufacturing processes and complex manufacturing systems. To enhance manufacturing capacity scalability of CBM systems, it is crucial to provide formal approaches that allow for modeling and simulating the material flow of a manufacturing system as well as identifying and eliminating manufacturing bottlenecks. Because Petri nets have been proven to be a well-developed mathematical theory for process modeling and a very powerful tool for describing distributed and concurrent systems using a directed bipartite graph [210, 211], it will be used to formally model and analyze the material flow in a CBM system and to plan manufacturing capacity scalability based on the qualitative and quantitative properties of a PN model.

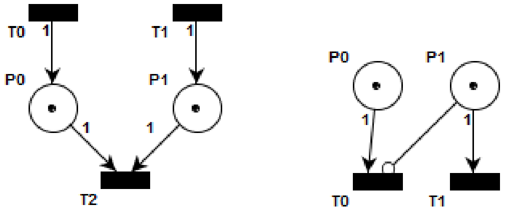
6.3 Stochastic Petri Nets

6.3.1 Basic Petri Nets

Petri nets (PNs), a mathematical and graphical modeling language, were introduced by Carl Adam Petri in the early 1960s [212]. A PN model of a system describes the states of the system and the events that can cause the system to change states. Some basic building blocks of a PN model that model concurrency, synchronization, precedence, and priority are shown in Figure 6-6. A basic PN model consists of four types of components: places, transitions, arcs, and tokens. Places (circles) are used to represent states, buffers, or locations. Transitions (bar) are used to describe events or actions that cause the change of system states. A transition has a certain number of input and output places representing the pre-states and post-states of the event, respectively. Arcs are used to connect a place with a transition or a transition with a place. Tokens are used to represent markers that reside in places. A change of state is denoted by a movement of tokens (black dots) from one place to another. The change of states is caused by the firing of a transition. A firing represents an occurrence of an event. After firing, tokens will move from input places to output places. A transition is enabled if at least one token exists in each of its input places.



(a) Concurrency (b) Synchronization



(c) Precedence (d) Priority

Figure 6-6 Basic building blocks of PNs

Making simulations of a PN model allows one to investigate different scenarios and to understand system behaviors. According to [122], the advantages of PNs are summarized as follows:

- A PN model provides a mathematical representation of a system so that structural and behavioral properties (e.g., reachability, boundedness, and liveness) can be investigated as opposed to queuing network models.
- A PN model is manageable in terms of the size. A system designer can change the number of tokens without affecting places and transitions as opposed to Markov chain models.

- A PN model allows one to model discrete and dynamic events using not only the exponent distributions but also other distributions such as triangular and binomial distributions.
- A PN model allows one to observe the stochastic processes via the firing of the transitions. For example, a system designer can develop a PN model, and then observe tokens as they move from one place to another in simulated time. Observing the tokens enables the user insight into the actual flow of the model and any potential conflicts.

Many extensions to the classical PNs (e.g., stochastic Petri nets and colored Petri nets) were developed by adding some properties that cannot be modeled in the classical PNs. For example, the colored Petri nets (CPNs) formalism not only preserve behavioral properties of PNs but also allow tokens to have a data value (called token color) attached to them. A stochastic Petri net (SPN) is a PN in which each transition is associated with an exponential distributed random variable that expresses the delay from the enabling to the firing of the transition. Because SPNs are very powerful for analyzing performances such as resource utilization and capacities for discrete-event systems, SPNs are used to model CBM systems in this chapter.

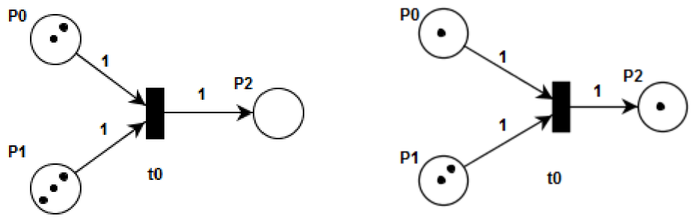
6.3.2 Stochastic Petri Nets

We are particularly interested in two types of analyses using SPNs: the qualitative and quantitative analysis. The qualitative analysis allows for verifying structural and behavioral properties such as existence of deadlocks, boundedness, and safeness. These properties can be verified by generating a reachability graph. The quantitative analysis allows for measuring system performance through simulations.

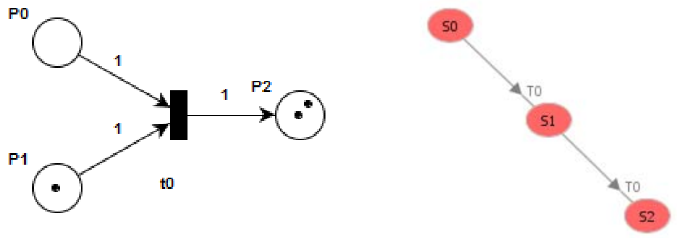
In this section, an overview of SPNs is presented. Formally, a stochastic Petri net (SPN) is defined as follows:

Definition 1 (SPN): A stochastic Petri net (SPN) is a bipartite directed graph that can be modeled as a six-tuple $(P, T, F, W, M_0, \Lambda)$ structure, where

1. $P = \{p_1, p_2, p_3, \ldots, p_m\}$ is a finite set of places. m is an integer and $m > 0$.
2. $T = \{t_1, t_2, t_3, \ldots, t_n\}$ is a finite set of transitions. n is an integer and $n > 0$. $P \cup T \neq \emptyset$, and $P \cap T = \emptyset$; In a SPN, the firing of each transition t_i is associated with a exponentially distributed firing delay which specifies the amount of time that must elapse before the transition can fire.
3. $F \subseteq (P \times T) \cup (T \times P)$ is a set of flow relations, also called arcs between places and transitions.
4. $W: F \rightarrow N$ is an output function that defines directed arcs from transitions to places.
5. The state of a SPN at any time is characterized by the distribution of tokens over the places, generally termed a marking. $M_0: P \rightarrow N$ is the initial marking. The notion $M(p) = n$ denotes the number of tokens, n, at place p in marking M.
6. $\Lambda = (\lambda_1, \lambda_2, \lambda_3, \lambda_4, \ldots, \lambda_i)$ is an array of transition firing rates associated with transitions t_i. The firing of a transition removes tokens from their input places and deposits them into their output places. The firing delay time is exponentially distributed. The distribution of the random variable x_i of the firing delay time associated with transition t_i is given by $F_{x_i}(x) = 1 - e^{-\lambda_i x}$. When modeling a manufacturing system using a SPN, λ is used for exponentially representing time spent on certain manufacturing operations such as CNC machining and additive manufacturing. For example, if a transition t_j, representing a machining operation, consumes λ_j time unit, then the distribution of the random variable x_j of the firing time associated with the transition t_j is given by $F_{x_j}(x) = 1 - e^{-x/\lambda_j}$ with the firing rate $1/\lambda_j$.



(a) An initial marking M_0 (b) A reachable marking M_1



(c) A reachable marking M_2 (d) A reachability graph

Figure 6-7 Reachability graph

To further illustrate SPNs, a simple SPN example is shown in Figure 6-7. Given that the firing rate associated with the transition t_0 is two per time unit, the SPN model can be defined as a six-tuple $(P, T, F, W, M_0, \Lambda)$ structure, where

$P = \{p_0,\ p_1, p_2\}$;

$T = \{t_0\}$;

$F = \{< p_0, t_0 >, < p_1, t_0 >, < t_0, p_2 >\}$;

$W = \{< p_0, t_0 > \mapsto 1, < p_1, t_0 > \mapsto 1, < t_0, p_2 > \mapsto 1\}$;

$M_0 = \{p_0 \longmapsto 2, p_1 \longmapsto 3, p_2 \longmapsto 0\}$; Alternatively, M_0 is denoted as $\{p_0, p_1, p_2\}$.

$\Lambda = (\lambda_1) = (2)$.

Definition 2 (Reachability): A marking M'_p is reachable from a marking M_p if there is a finite occurrence sequence that starts with M'_p and ends with M_p. A reachability graph is a rooted and directed graph. The purpose of generating a reachability graph is to identify whether an undesirable state (violation of mutual exclusion property) can occur. According to [213], the process of generating a reachability graph can be summarized as follows: (1) specify an initial marking M_0, (2) fire all the transitions that may generate new markings, and (3) take each of the new markings as a new root and generate all the reachable markings. Details about generating reachability graphs can be referred to [214, 215].

In a reachability graph, a node represents a marking; an arc represents the firing of a transition that transforms a marking to another. As shown in Figure 6-7(a), the initial marking is $\mathrm{M}_0 = (2,3,0)$. After firing the transition t_0, a new reachable marking $\mathrm{M}_1 = (1,2,1)$ is generated, as shown in Figure 6-7(b). After firing t_0 again, another new reachable marking $\mathrm{M}_2 = (0,1,2)$ is generated, as shown in Figure 6-7(c). Based on these new reachable markings, a simple reachability graph can be generated, as shown in Figure 6-7(d). This process can also be denoted as $\mathrm{M}_0 = (2,3,0) \longrightarrow \mathrm{M}_1 = (1,2,1) \longrightarrow \mathrm{M}_2 = (0,1,2)$.

Definition 3 (Boundedness and Safeness): A SPN is bounded if for each place p there is a number n such that for every reachable marking the number of tokens in p is less than n. The SPN is safe if for each place the maximum number of tokens does not exceed one. Boundedness or safeness implies the absence of overflows. Boundedness of a manufacturing resource place indicates the availability of only a single manufacturing resource.

Definition 4 (Liveness): A SPN is live if for each reachable state and every transition, there is a state reachable from which enables the transition. Liveness implies the absence of deadlocks.

6.4 Modeling a Cloud-Based Manufacturing System Using SPNs

In this section, the SPN model of material flow in a CBM system is presented. In order to analyze the SPN model, both qualitative and quantitative analyses are performed. The qualitative approach includes the analysis of behavioral and structural properties of SPNs; while the quantitative approach includes the evaluation of manufacturing system performance. Behavioral properties depend on the initial marking of a SPN; while structural properties do not depend on the initial marking but the structure of a SPN such as the layout of a manufacturing system.

6.4.1 Problem Formulation

According to Feldmann and Colombo [216], the research problem pertaining to scalability planning is formulated as follows:

Given:

- A predefined set of manufacturing resources (e.g., 3D printers) in a CBM system in which a manufacturing resource is described by a set of specifications, port-structures for connecting it to other manufacturing resources, constraints at each port-structure that describe the manufacturing resources that can be connected at that port-structure, and other structural constraints;
- A description of the CBM system layout and information about the set of tasks and functions to be performed in each manufacturing resource.

Build:

- A SPN model for each manufacturing resource of the CBM system as a basic module;
- An entire SPN model by integrating the above SPN sub-models for each manufacturing resource in a bottom-up manner.

Analyze:

- State space and reachability graph;
- Simulation results;

Plan:

- Detect manufacturing bottlenecks based on the simulation results;
- Improve manufacturing capacity scalability by reconfiguring the existing material flow of the CBM system.

The research to be conducted is designed as follows:

(1) A free open source tool, Platform Independent Petri Net Editor (PIPE) is used for modeling and analyzing SPNs. PIPE is a Java-based tool for the construction and analysis of SPN models. PIPE was developed and is still being maintained by the Imperial College London [217]. PIPE allows one to perform structural and performance-related analyses on SPN models.

(2) A case study, building a delivery drone as shown in Figure 6-8, is conducted. The delivery drone consists of mechanical and electronic components as shown in Figure 6-9 and 6-10, respectively.

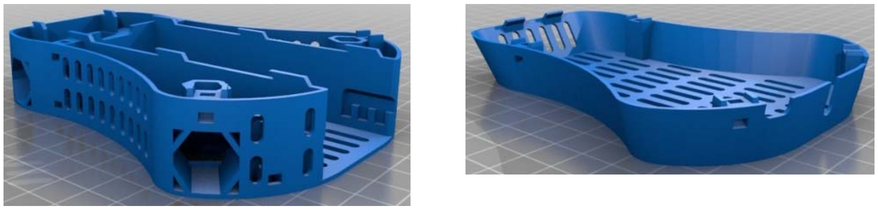
Figure 6-8 A delivery drone [218]

(3) With respect to the mechanical components such as propellers and frame, because most of these mechanical parts are made of either plastic or ABS, they can be built using additive manufacturing (AM) or 3D printing processes. As stated before, AM technology will be extensively used in CBM as it allows cloud service providers to rapidly scale up

and down their manufacturing capacity. With respect to the electronic components such as navigation board and main board can be outsourced through cloud-based e-commerce companies such as MFG.com and Alibaba.com.

(1) Propeller (2) Brushless motor

(3) Leg (4) Arm



(5) Frame body (6) Frame body top

(7) Frame body bottom (8) Brushless gimbal for the camera

Figure 6-9 The mechanical parts of the drone

(1) Navigation Board (2) Main board

(3) Optical Flow Smart Camera (4) Flight Control Board

(5) Battery

Figure 6-10 The electronic components of the drone [219, 220]

(4) A generic cloud-based AM process is proposed as follows:

Step 1: Submit RFQs for a product or product components to design service providers in the cloud

Step 2: Submit RFQs to AM service providers in the cloud

Step 3: Find qualified AM service providers for each product component (i.e., parts and sub-assemblies)

Step 4: Send CAD models to the service providers and build the product or product components

Step 5: Ship the product or product components to the service consumer and assemble

(5) Construct a hypothetic CBM system using existing cloud-based services with which the delivery drone can be built. First, create the bill of materials (BOM) (i.e., a list of the raw

materials, parts, sub-assembly, intermediate assemblies) for the drone. Table 6-1 summarizes some of the key mechanical and electronic components of the delivery drone.

Table 6-1 A list of key delivery drone components

Drone Part ID	Drone Part Name	Number of Parts
1	Propeller	4
2	Brushless motor	4
3	Leg	4
4	Arm	4
5	Frame body	1
6	Frame body top	1
7	Frame body bottom	1
8	Brushless gimbal for the camera	1
9	Navigation Board	1
10	Main Board	1
11	Optical Flow Smart Camera	1
12	Flight Control Board	1
13	Battery	1

Second, determine alternative AM service providers who are capable of building individual items in the BOM. The alternative service providers and their service offerings can be found by submitting RFQs on 3D Hubs, Quickparts, and Shapeways.

(6) Define the cloud-based 3D printing network for producing the delivery drone. A simple example material flow in a cloud-based 3D printing network is illustrated in Figure 6-11.

(7) Construct the SPN model for the material flow in the CBM system. As mentioned in the problem formulation, first, a set of manufacturing resources where the parts and sub-assemblies can be built are specified; second, the CBM system configuration and information about the set of tasks and functions to be performed in each manufacturing resource are specified. The build time of a 3D printing process can be estimated using an

online open source tool, Willit 3D Print [221], which allows for analyzing STL files and estimating the build time.

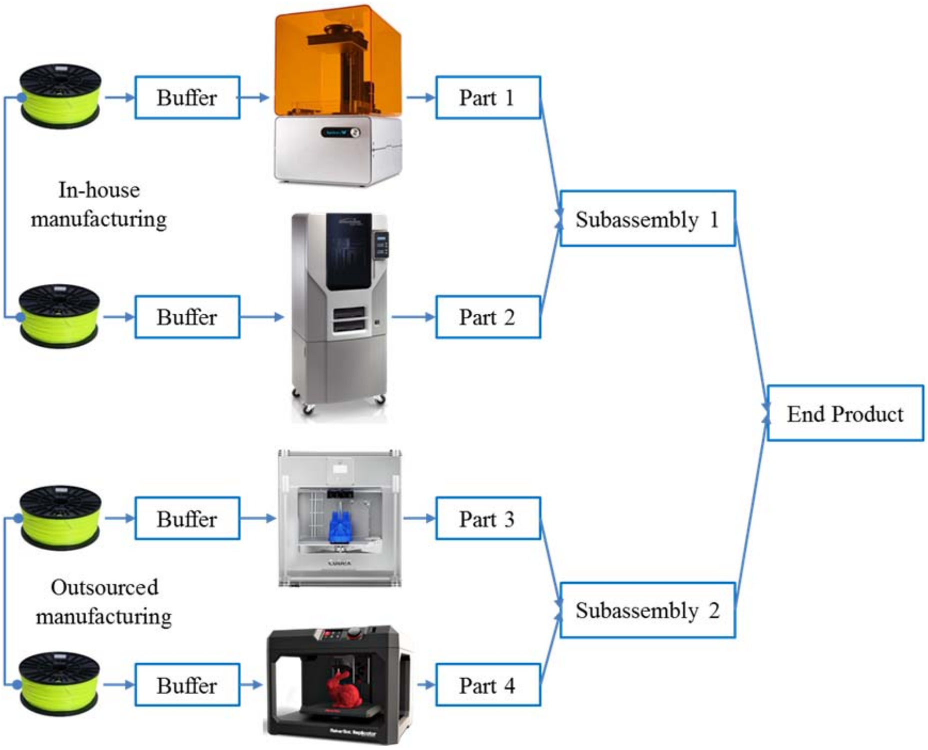


Figure 6-11 Example material flow in a cloud-based manufacturing network

(8) Perform both qualitative and quantitative analysis for the CAM system. The qualitative approach includes the analysis of the behavioral and structural properties (e.g., boundedness, liveness, and deadlock) of the SPN model. The quantitative approach includes evaluating KPIs of the CBM system.

(9) Specify one of the KPIs as a metric that determines manufacturing bottlenecks and identify bottlenecks of the CBM system. Based on the fact that if the manufacturing capacity scalability of a bottleneck improves, the capacity scalability of the entire CBM system will also improves, manufacturers can plan manufacturing capacity scalability by reconfiguring the existing material flow of the manufacturing system.

6.4.2 Description of the Delivery Drone Example

As described in Section 6.4.1, the delivery drone consists of mechanical and electronic components as shown in Figures 6-9 and 6-10, respectively. A brief specification about the drone is presented in Table 6-2.

Table 6-2 A brief specification for a delivery drone

Category	**Specification**
Height	450 millimeters
Weight	1500 grams
Payload capacity	500 grams
Battery	11.1 volts and 1500mAh lithium polymer
Propeller diameter	200 millimeters
Motors	28,000 revolutions per minute (RPM)

The propellers, frame body, frame body top, frame body bottom, legs, and arms are all made of ABS. The main board includes a 1GHz ARM Cortex A8 central CPU with 8GHz video DSP. The main board is used to auto pilot the drone. The navigation board includes an ultrasonic sensor to measure altitude changes, an altimeter sensor for improved accuracy, a 3-axis digital accelerometer onboard. The flight control board is powered by a 168MHz 32bit ARM process including a CPU internal boot loader for flashing from USB, a 8 PWM receiver inputs and motor outputs, pre-soldered and pre-loaded with flight software board. The optical flow smart camera has a native resolution of 752×480 pixels. The camera also includes a 168 MHz Cortex M4F CPU and a 752×480 image sensor.

Figure 6-12 shows the schematic diagram of the material flow in the existing manufacturing system. In the existing manufacturing network, in-house manufacturing and outsourcing are combined to produce the delivery drone. For instance, with respect to the mechanical components (e.g., the propellers, legs, arms, gimbal, frame body, frame body top, and frame body bottom), they are built in house (New York) using additive manufacturing processes. If market demand increases, the existing manufacturing capacity can be increased by outsourcing manufacturing tasks to cloud-based 3D printing service providers in the local 3D printer community in New York through 3D Hubs.

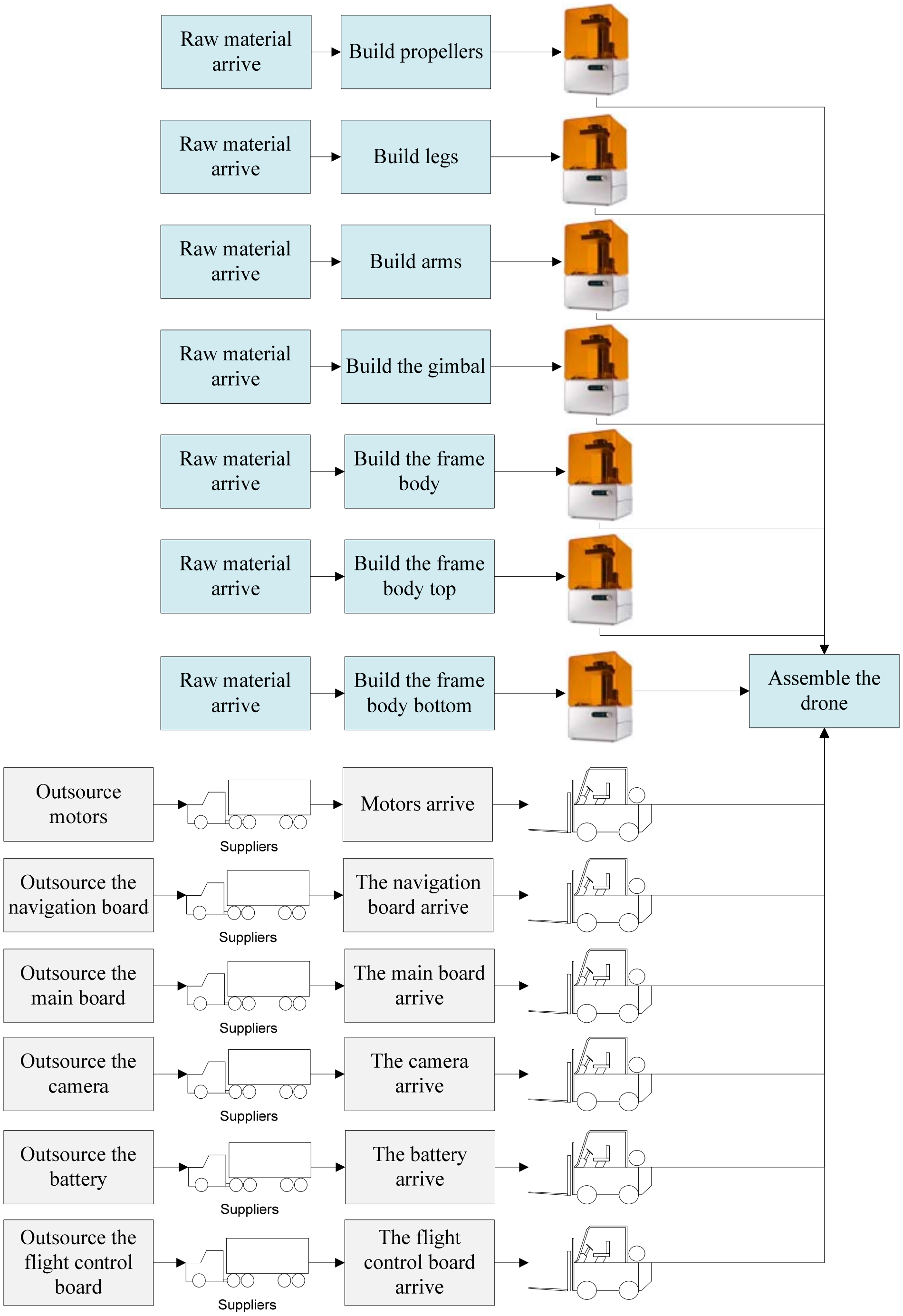
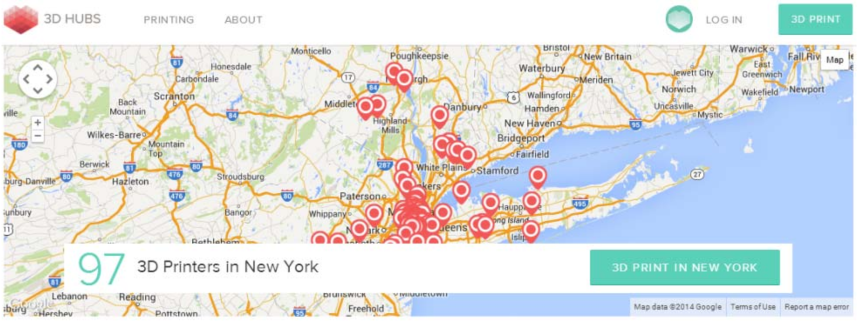


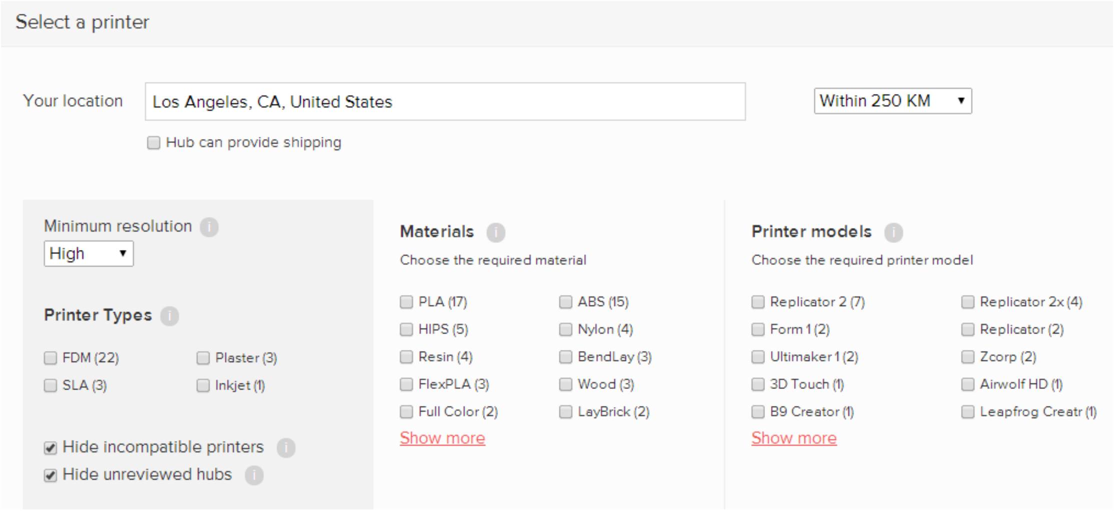
Figure 6-12 Material flow of the existing manufacturing system

(a) A snapshot of 3D printing service communities in the world [149]



97 3D Printers in New York

(b) A snapshot of the 3D printer community in New York



Select a printer

Your location: Los Angeles, CA, United States

Within 250 KM ▾

☐ Hub can provide shipping

Minimum resolution: High ▾

Printer Types

☐ FDM (22) ☐ Plaster (3)
☐ SLA (3) ☐ Inkjet (1)

☑ Hide incompatible printers
☑ Hide unreviewed hubs

Materials

Choose the required material

☐ PLA (17) ☐ ABS (15)
☐ HIPS (5) ☐ Nylon (4)
☐ Resin (4) ☐ BendLay (3)
☐ FlexPLA (3) ☐ Wood (3)
☐ Full Color (2) ☐ LayBrick (2)

Show more

Printer models

Choose the required printer model

☐ Replicator 2 (7) ☐ Replicator 2x (4)
☐ Form 1 (2) ☐ Replicator (2)
☐ Ultimaker 1 (2) ☐ Zcorp (2)
☐ 3D Touch (1) ☐ Airwolf HD (1)
☐ B9 Creator (1) ☐ Leapfrog Creatr (1)

Show more

(c) Search for a printer in 3D Hubs

Figure 6-13 A snapshot of 3D printing service communities in the world

Figure 6-13 (a) and (b) show the largest 3D printer network worldwide and the local 3D printer community in New York, respectively. Users can easily search for 3D printers based on distances, manufacturing resolutions, printer types and models, materials, and delivery modes in a local community as shown in Figure 6-13 (c). With respect to the electronic components, they are outsourced to drone electronic component suppliers. These electronic components suppliers can be easily found through Alibaba.com and MFG.com. For instance, Alibaba.com help manufacturers search for global electronic components suppliers who can provide main boards, controller boards, sensors, cameras and so on. Once the electronic components are delivered to the final assembly line, all of the drone components will be assembled.

6.4.3 The SPN Model

In this section, a bottom-up modeling approach is used to construct the complete SPNs for the existing material flow as shown in Figure 6-12. Specifically, first, sub-SPNs for system components are created. Second, all of these sub-SPNs are aggregated into a complete SPN model. For example, Figure 6-14 shows two simplified schematic diagrams of the material flows for building the propeller and motor, respectively. Figure 6-15 shows the corresponding two sub-SPNs for modeling the two material flows.

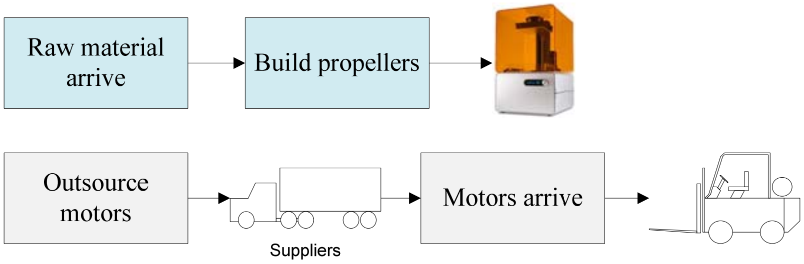


Figure 6-14 Simplified schematic diagrams for building the propeller and motor

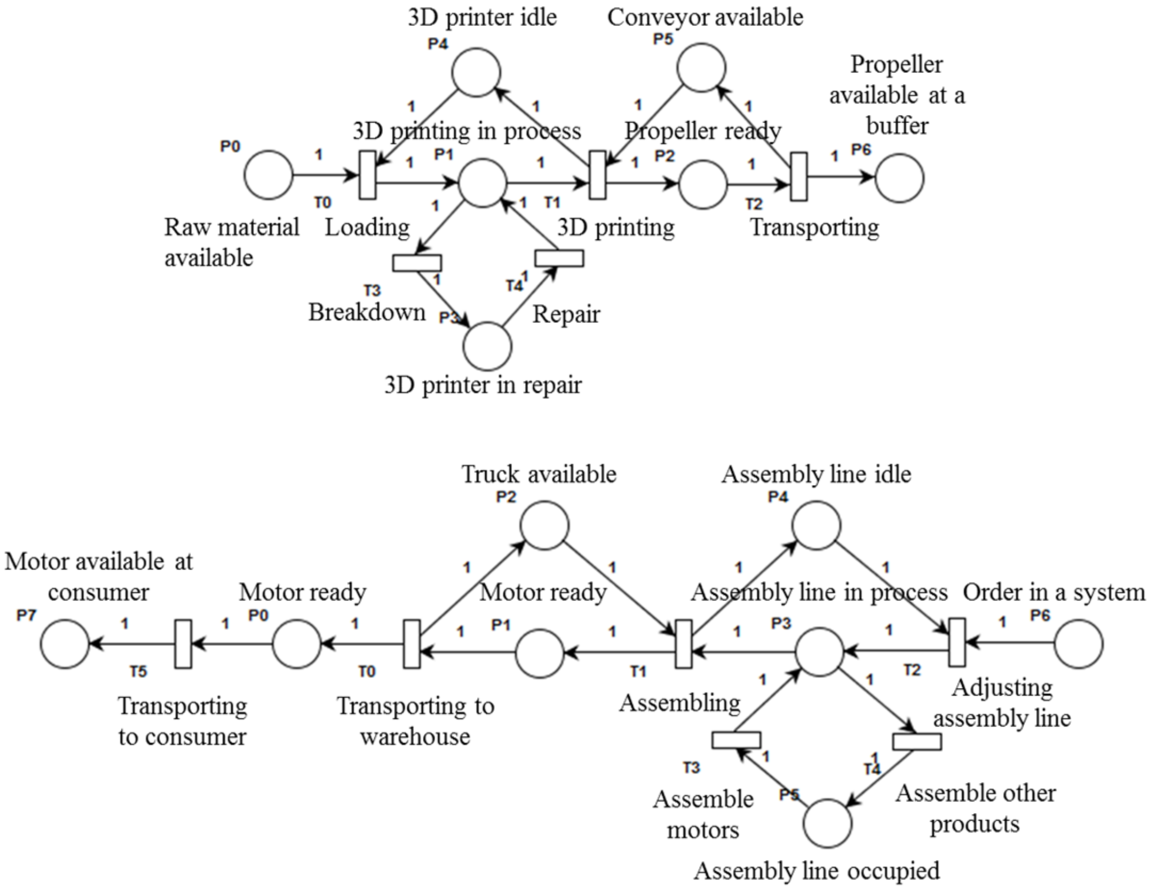


Figure 6-15 Sub-SPNs for modeling material flow in building the propeller and motor

Similarly, material flows for building other drone components can be constructed. Built upon these sub-SPNs, the SPN for modeling the material flow in the entire manufacturing system is constructed as shown in Figure 6-16.

Tables 6-3 and 6-4 describe some of the places and transitions in the SPN. The firing rates associated with individual transitions such as building and transporting parts are estimated using the open source tool, Willit 3D Print, and Google map. For example, the average time for building a propeller is 1/3 time units such as hours. Thus, the firing rate λ_2 associated with the corresponding transition (T2) is 3, which is the inverse of the build time. Similarly, the average time for transporting motors to the drone manufacturer is 10 time units based on the Google map. The firing rate λ_{42} associated with the corresponding transition (T42) is 1/10, which is the inverse of the transportation time. Detailed descriptions about the places and transitions can be found in Appendix C.1 and Appendix C.2.

Figure 6-16 SPN for modeling the entire manufacturing system

Table 6-3 Places in building propellers and crowdsourcing motors

Place	Description
P1	Raw material for building propellers is available
P2	3D printing propellers is in process
P3	Propellers are ready to be transported
P4	3D printer for building propellers is in repair
P5	3D printer for building propellers is idle
P6	Conveyor for transporting propellers is available
P43	Propellers are available to be assembled
P50	Order for motors is placed in the system
P51	Assembly line for producing motors is in process
P52	Motors are ready to be transported to warehouse
P53	Assembly line for producing motors is occupied
P54	Assembly line for producing motors is idle
P55	Truck for transporting motors is available
P56	Motors are ready to be transported to consumers
P57	Motors are available to be assembled

Table 6-4 Transitions in building propellers and crowdsourcing motors

Transition	Description	Parameter (λ_i)
T1	Load raw material for building propellers	$\lambda_1 = 12$
T2	Build propellers	$\lambda_2 = 3$
T3	Transport propellers to the final assembly line	$\lambda_3 = 6$
T4	3D printer for building propellers breaks down	$\lambda_4 = 2$
T5	Repair the 3D printer for building propellers	$\lambda_5 = 4$
T37	Transport motors to warehouse	$\lambda_{37} = 4$
T38	Assemble motors	$\lambda_{38} = 8$
T39	Adjust the assembly line for motors	$\lambda_{39} = 4$
T40	Switch back to assemble motors	$\lambda_{40} = 4$
T41	Assemble other products	$\lambda_{41} = 1/12$
T42	Transport motors to consumers	$\lambda_{42} = 1/10$

As stated in Section 6.1, the objective of Chapter 6 is to understand how CBM can help the drone manufacturer plan manufacturing scalability by modeling and analyzing material flow using SPN, identifying manufacturing bottlenecks, and crowdsourcing manufacturing tasks over a cloud-based manufacturing network. Section 6.5 presents both qualitative and quantitative analysis of the SPN model.

6.5 Performance Analysis of the SPN Model

6.5.1 Performance Analysis Based on Qualitative Properties

With respect to the qualitative analysis, SPNs allow for verifying structural and behavioral properties of the manufacturing system, including deadlocks, boundedness, and safeness. The purpose of verifying boundedness and safeness is to examine whether the overflow of materials exists and availability of each manufacturing resource in the manufacturing system. If the manufacturing system is bounded, then the overflow of material does not exist. The purpose of verifying liveness is to examine whether deadlocks exist in the manufacturing system. If the manufacturing system is live, then deadlocks do not exist.

Table 6-5 Boundedness, safeness, and liveness

Property	**Value**
Bounded	True
Safe	True
Deadlock	True

PIPE provides a set of analysis modules to perform both qualitative and quantitative analyses [217]. The qualitative analysis results for the manufacturing system are shown in Table 6-5. Based on the qualitative analysis results, the SPN model for the material flow in the manufacturing system is bounded, safe, and deadlock free. Therefore, it is verified that the overflow of materials and deadlocks do not exist in the manufacturing system.

6.5.2 Performance Analysis Based on Quantitative Properties

With respect to the quantitative analysis, SPNs allow for evaluating manufacturing system performance such as capacity by simulating SPNs. In general, discrete-event simulations fall into two categories from the time frame perspective: finite-horizon (terminating) and steady state (non-terminating) simulations. A finite-horizon simulation refers to a simulation that runs for some duration of time and stops at a specific time or when a specified event occurs, while a steady-state simulation refers to a simulation that runs continuously (technically forever) or a very long period of time. Whether a finite-horizon or steady-state simulation is more appropriate in a specific application depends on (1) the objective of the simulation study and (2) the nature of the system.

In the context of the delivery drone example, we first perform finite-horizon simulations with the run length of 30 days. The statistics that are of particular interest in the finite-horizon simulations are the expected capacities for the overall manufacturing system and individual manufacturing processes with 95% confidence intervals. In statistics, confidence interval estimation quantifies the confidence (i.e., probability) that the true but unknown statistical parameter falls within an interval whose boundaries are calculated using appropriate point estimates. The major advantage of using confidence interval estimation is that it provides a range of values with a known probability of capturing the population parameter.

The details about the finite-horizon simulations using the aforementioned SPN model are summarized as follows:

- The run length of each replication is 1 month (30 days) and 24 hours per day;
- The number of replications is 100;
- 95% two-sided confidence intervals for the expected capacities.

The finite-horizon (terminating or transient) simulation results are shown in Figure 6-17. Based on the simulation results, the initial state is identified as the transient state (i.e., warm-up period). The steady state of the manufacturing system is achieved until 6 days after the system is started because the expected system throughput remains almost constant, particularly 10 items per day. Table 6-6 shows the expected capacity for the overall manufacturing system which is 288 drones over 30 days. To detect manufacturing bottlenecks, the expected capacities for individual manufacturing processes over the 30-day time horizon are also calculated as shown in Table 6-6.

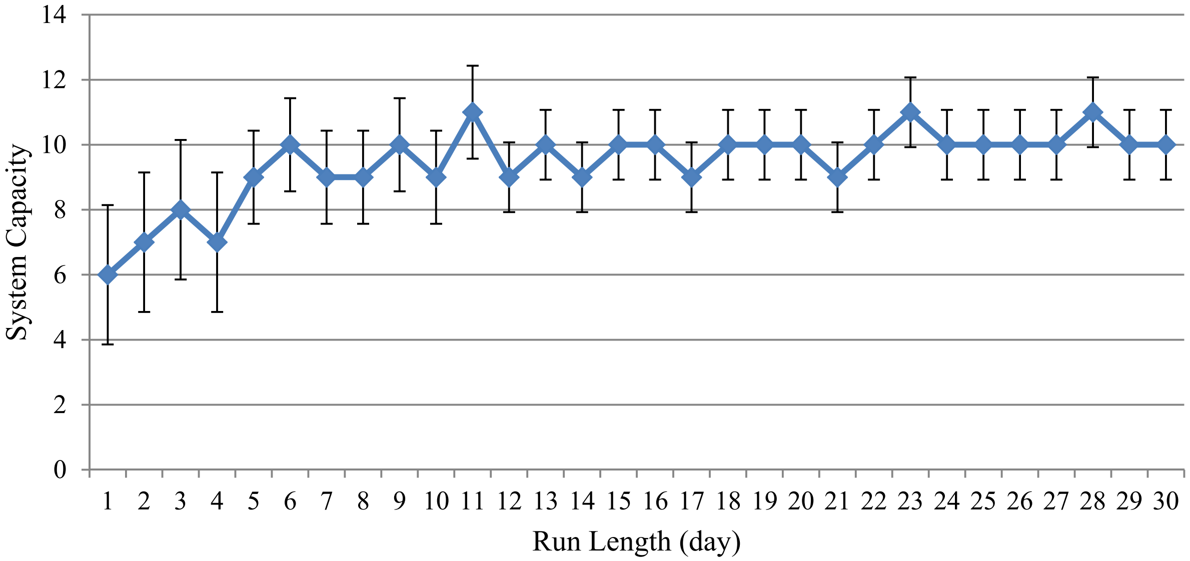


Figure 6-17 System capacity versus run length

Table 6-6 SPN simulation results

Transition	**Output Item**	**Actual Capacity (per month)**	**Required # of Items for 400 Drones (per month)**
T2	Propeller	1749	1600
T7	Leg	2304	1600
T12	Arm	2016	1600
T17	Gimbal	288	400
T22	Frame body	309	400
T27	Frame top	1944	400
T32	Frame bottom	2246	400
T42	Motors	2332	1600
T48	Navigation	885	400
T54	Main board	799	400
T60	Camera	756	400
T66	Battery	912	400
T72	Flight control	691	400
T36	Drone	288	400

Note that the delivery drone, as shown in Table 6-1, consists of 4 propellers, 4 motors, 4 legs, 4 arms, 1 frame body, 1 frame body top, 1 frame body bottom, 1 gimbal for the camera, 1 navigation board, 1 main board, 1 optical flow smart camera, 1 flight control board, and 1 battery. Suppose that the current market demand is 400 drones per month. The required number of items for each component of the drone is shown in Table 6-6. Figure 6-18 shows the composition between the current capacities for individual manufacturing processes and the corresponding required capacities. Based on the results as shown in Figure 6-18, we detect two manufacturing bottlenecks, including the 3D printing processes for building gimbals and frame bodies. The corresponding transitions in the SPN model are T17 and T22 where the overall system capacity is limited.

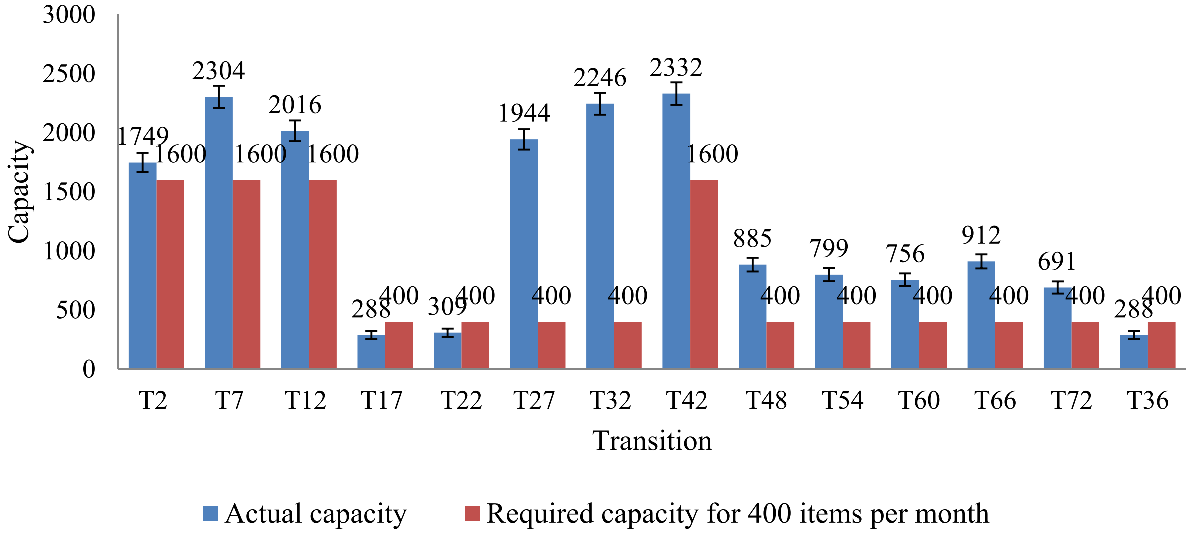


Figure 6-18 Actual capacity versus required capacity for the original manufacturing system

6.6 Planning Manufacturing Scalability

Given that the market demand is 400 drones per month and the current system capacity is 288 drones per month, the current manufacturing system cannot meet the market demand. The drone manufacturer needs to scale up the current system capacity by combining in-house manufacturing and outsourcing in the CBM setting.

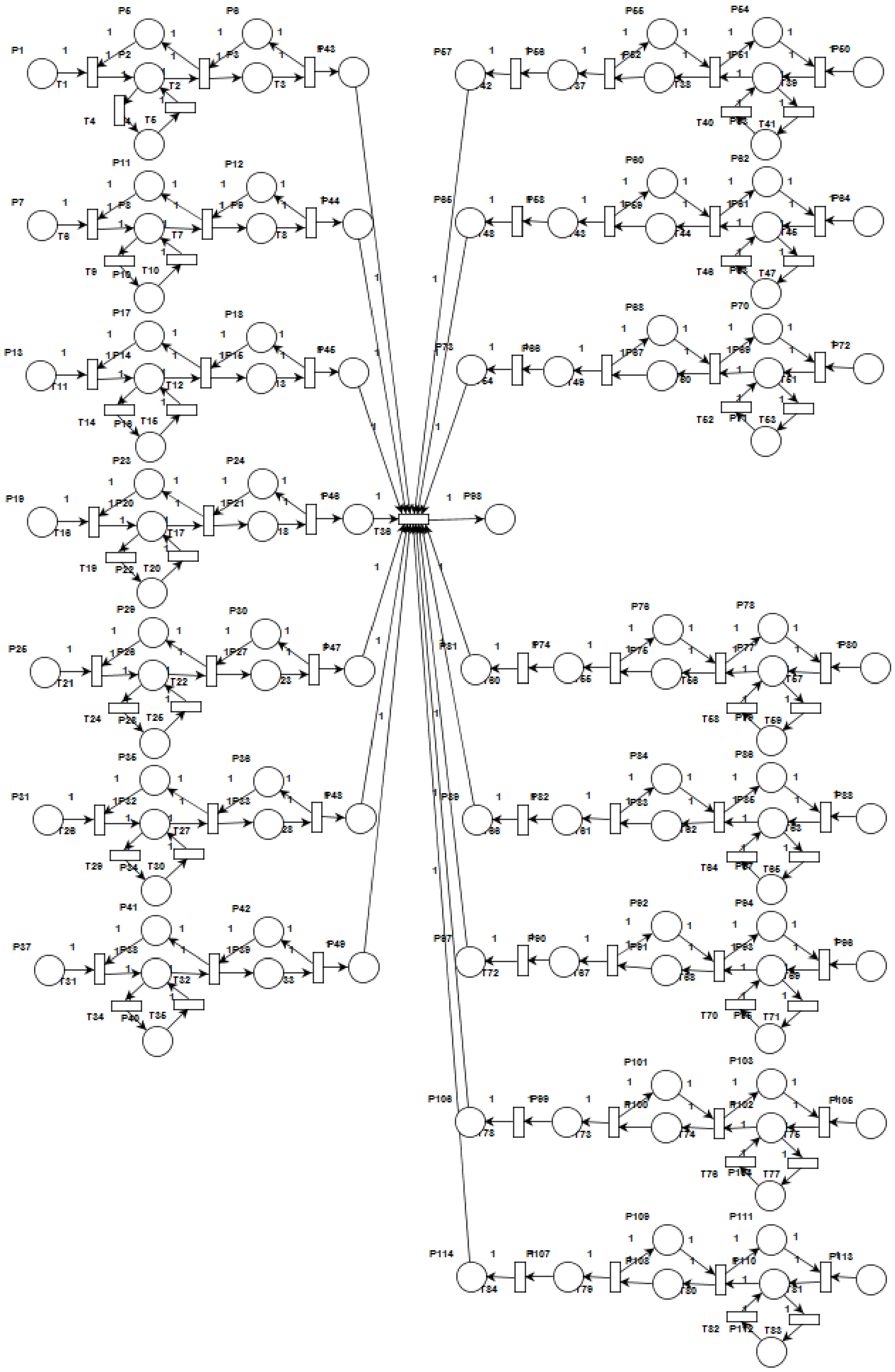


Figure 6-19 New SPN model for the new manufacturing system

As illustrated previously, 3D Hubs provide the drone manufacturer with access to a large local community of 3D printers. Based on the simulation results presented in Section 6.5, the 3D printing tasks for building gimbals and frame bodies need to be outsourced to other cloud-based 3D printing service providers. As shown in Figure 6-19, we construct a new SPN model in which two additional 3D printing processes for building gimbals and frame bodies are added into the original SPN.

Tables 6-7 and 6-8 list the new places and transitions associated with the added 3D printing processes. Based on the increasing number of 3D printers in the New York's 3D printer community, it is reasonable to assume that most of the mechanical components of the drone can be delivered within 1 to 10 hours. In this example, the transportation times are estimated as 5 hours. As a result, the firing rates associated with the transitions, transporting gimbals and frame bodies, are 1/5 as shown in Table 6-8.

Table 6-7 Places in the new SPN model

Place	Description
P105	Order for gimbals is placed in the system
P102	3D printing gimbals is in process
P100	Gimbals are ready to be transported to warehouse
P104	3D printer for building gimbals is in repair
P103	3D printer for building gimbals is idle
P101	Truck for transporting gimbals is available
P99	Gimbals are ready to be transported to consumers
P106	Gimbals are available to be assembled
P113	Order for frame bodies is placed in the system
P110	3D printing frame bodies is in process
P108	Frame bodies are ready to be transported to warehouse
P112	3D printer for building frame bodies is in repair
P111	3D printer for building frame bodies is idle
P109	Truck for transporting frame bodies is available
P107	Frame bodies are ready to be transported to consumers
P114	Frame bodies are available to be assembled

Table 6-8 Transitions in the new SPN model

Transition	Description	Parameter (λ_i)
T73	Transport gimbals to warehouse	λ_{73} =4
T74	Build gimbals	$\lambda_{74} = 1/2$
T75	Adjust 3D printer for gimbals	$\lambda_{75} = 12$
T76	Switch back to build gimbals	$\lambda_{76} = 2$
T77	Build other products	$\lambda_{77} = 1/12$
T78	Transport gimbals to consumers	λ_{78} =1/5
T79	Transport frame bodies to warehouse	λ_{79} =4
T80	Build frame bodies	$\lambda_{80} = 1/2$
T81	Adjust 3D printer for frame bodies	$\lambda_{81} = 12$
T82	Switch back to build frame bodies	$\lambda_{82} = 2$
T83	Build other products	$\lambda_{83} = 1/12$
T84	Transport frame bodies to consumers	λ_{84} =1/5

Table 6-9 SPN simulation results

Transition	Output Item	Actual Capacity (per month)	Required # of Items for 400 Drones (per month)
T2	Propeller	1728	1600
T7	Leg	2217	1600
T12	Arm	2419	1600
T17+T74	Gimbal	475	400
T22+T80	Frame body	464	400
T27	Frame top	1555	400
T32	Frame bottom	2160	400
T42	Motors	2419	1600
T48	Navigation	831	400
T54	Main board	810	400
T60	Camera	896	400
T66	Battery	1044	400
T72	Flight control	854	400
T36	Drone	464	400

Table 6-9 shows the expected capacity for the new CBM system which is 464 drones and the expected capacities for individual manufacturing processes over the 30-day time horizon. Figure 6-20 shows the composition between the new capacities for individual manufacturing processes and the corresponding required capacities to meet the market demand. Based on the simulation results, the new manufacturing system can build 464 drones per month on average, which meets the current market demand 400 drones per month, by temporarily outsourcing the 3D printing tasks in the bottlenecks to third-party cloud service providers in the CBM setting without purchasing, maintaining, and operating any new 3D printers.

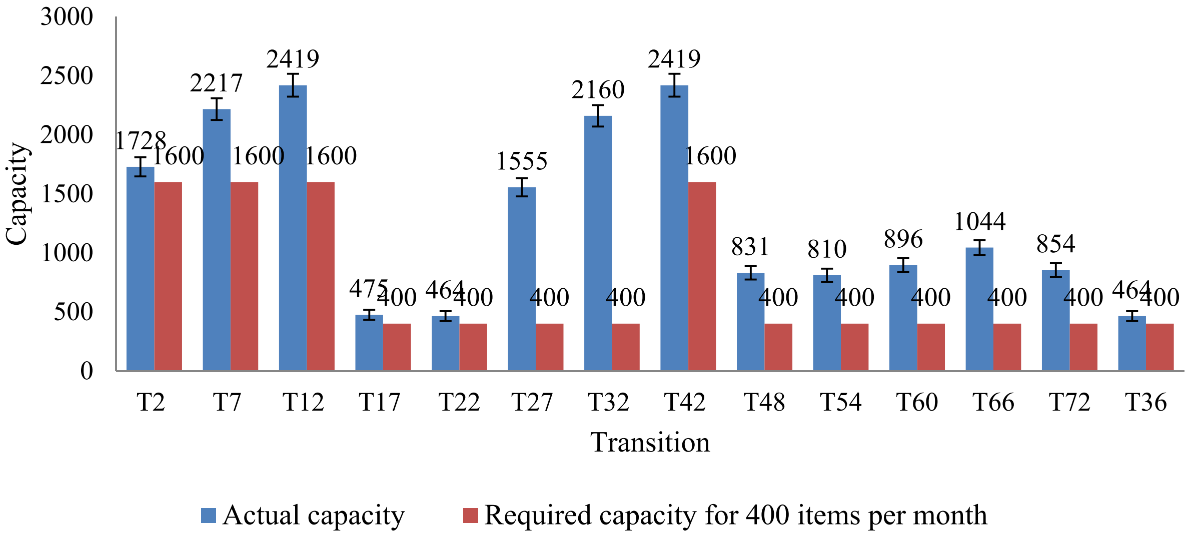


Figure 6-20 Actual capacity versus required capacity for the new CBM system

6.7 Summary

In this chapter, the modeling and analysis of cloud-based manufacturing networks is addressed. In traditional manufacturing settings, to scale up manufacturing capacity, manufacturers need to purchase more manufacturing resources such as milling machines and 3D printers to meet increasing market demand. However, if market demand decreases, these added manufacturing resources will become idle, and the utilization rate of these resources will greatly decrease. Therefore, it is challenging to achieve rapid manufacturing capacity scalability cost effectively. In this context, the objective of this chapter is to understand how CBM can help manufacturers plan manufacturing capacity scalability by identifying manufacturing bottlenecks and reconfiguring existing manufacturing systems through cloud-based manufacturing networks.

Specifically, Research Question 3 and its hypothesis were formulated as follows:

Research Question 3:

- *How should the manufacturing capacity scalability of a CBM system be planned prior to the implementation and deployment of a CBM system?*

Hypothesis 3:

- *Discrete-event simulation can be used to formally model and simulate the manufacturing network of a CBM system and to plan manufacturing capacity scalability by identifying manufacturing bottlenecks and reconfiguring a manufacturing network.*

The hypothesis was validated using a delivery drone example. Specifically, to validate the hypothesis, this chapter introduced the SPN-based approach for modeling and analyzing the material flow in the CBM system. The results have shown that the SPN-based approach can be used to perform both qualitative and quantitative analysis for the CBM system. Based on the quantitative analysis, the manufacturing bottlenecks that determine the manufacturing system capacity were identified. Further, after increasing the capacities of the bottlenecks by combining the existing manufacturing system with cloud-based 3D printing services, rapid manufacturing capacity scalability can be achieved.

CHAPTER 7

CONCLUSION

7.1 Summary of the Dissertation

Chapter 1 presented the challenges pertaining to CBDM as a whole as well as challenges related to CBD and CBM, respectively, as follows:

- Challenge 1: the systematic development of a conceptual framework that defines the computing architecture, information and communication flow, the design and manufacturing process, the programming model, data storage, and the business model of an idealized CBDM system;
- Challenge 2: the development of a new approach for visualizing distributed and collaborative design processes, and measuring tie strengths in a complex and large design team, detecting design communities with common design interests or activities in cloud-based design (CBD) settings from a social network perspective;
- Challenge 3: the development of a new approach that helps identify potential manufacturing bottlenecks that determine manufacturing scalability in cloud-based manufacturing (CBM) settings from a manufacturing network perspective.

Based on these challenges, three research questions and hypotheses were formulated. In addition to the research questions and hypotheses, the assumptions in this research and potential impacts of CBDM were also presented in Chapter 1.

Chapter 2 reviewed the literature related to the scientific foundations for CBDM, including cloud computing, collaborative design, social network analysis, distributed manufacturing systems, manufacturing scalability, and discrete event simulation. In addition, the state-of-the-art research and development related to CBDM from both academia and industry is presented.

Based on the literature review, Chapter 2 identified research gaps in CBDM, including the systematic development of a conceptual framework for future CBDM systems, the development of the SNA-based approach for modeling, analyzing, and improving distributed design collaboration networks in CBD settings, and the development of the SPN-based approach for identifying potential manufacturing bottlenecks and planning manufacturing scalability in CBM settings.

Chapter 3 presented the first definition, a reference model and key characteristics, and a holistic vision for CBDM. A requirements checklist that a future CBDM system should satisfy was defined. Moreover, CBDM was compared to web- and agent-based design and manufacturing from a number of perspectives, including computing architecture, design communication, sourcing process, information and communication, programming model, data storage, and business model. Further, a hypothetical design and manufacturing scenario in future CBDM environments based on currently existing and potentially new cloud-based service offerings was presented to clarify our vision of CBDM and demonstrate its potential value.

Chapter 4 presented a prototype system, DMCloud, collectively developed by several research groups at Georgia Tech. The prototype is currently implemented as a private cloud, but it can be easily extended to be a public DMCloud. It built upon an integrated collaborative design and distributed manufacturing infrastructure with tools such as CNC machines, 3D printers, and engineering software through a partnership constituting a network of high schools in a geographically dispersed environment. The prototype enabled users across clusters of high schools to learn modern CAD and analysis software tools to design novel devices, practice collaborative design and distributed manufacturing, utilize a distributed manufacturing infrastructure, and understand collaborative design through technical and social networking platforms.

Chapter 5 presented the SNA-based approach for modeling, analyzing, and improving design collaboration networks in the context of CBD. Specifically, the *Adamic and Adar index* was used to measure tie strengths between actors in two illustrative examples. Based on the *Adamic and Adar index* scores, implicit design collaboration networks were modeled using formal social networks. In the two illustrative examples, the information flow in the CBD setting, including transforming customer needs, to functional requirements, to design parameters, and to process variables, was visualized based on the SNA results. The social networks at both actor and system levels were analyzed, and design communities with common interests and activities were detected. Moreover, by combining the text mining technique (i.e., tag cloud), the SNA-based approach can not only model and analyze distributed design collaboration networks but also identify topical content based on key words extracted from various text documents.

Chapter 6 presented the SPN-based approach for modeling and analyzing the material flow in the CBM system and planning manufacturing scalability based on qualitative and quantitative analysis. The SPN-based approach was validated using the delivery drone example. The qualitative analysis verified the structural and behavioral properties of the CBM system, including the existence of deadlocks, boundedness, and safeness. The quantitative analysis measured the specific manufacturing system performance such as throughput by simulating the SPN model. The results have shown that the SPN-based approach can be used to detect manufacturing bottlenecks in the CBM system. Based on the process capacities of the manufacturing bottlenecks, manufacturers can scale up and down manufacturing capacity by combining in-house manufacturing and CBM, and eventually achieve rapid manufacturing scalability in CBM settings.

7.2 Hypotheses Evaluation

Chapter 1 raised three research questions to fill the research gaps between the state-of-the-art and the research objectives of this dissertation. These research questions and hypotheses are revisited and evaluated as follows:

Research Question 1.a:

- *What are the definition, characteristics, requirements, reference model, computing architecture, operational process, programming model, and business model of a Cloud-Based Design and Manufacturing (CBDM) system?*

Research Question 1.b:

- *How is a CBDM system different from a traditional collaborative design and distributed manufacturing system such as a web- and agent-based design and manufacturing system?*

Research Question 1.c:

- *What could an idealized CBDM scenario be?*

Chapters 3 and 4 answered these aforementioned research questions definitively. In Chapter 3, the first definition for CBDM was proposed and compared to other relevant definitions. The essential characteristics of CBDM were identified, including scalability, agility, high performance and affordable computing, networked environments, ubiquitous access, self-service, big data, search engine, social media, real-time quoting, pay-per-use, resource pooling, virtualization, multi-tenancy, crowdsourcing, IaaS, PaaS, HaaS, and SaaS. A systematic requirements checklist was developed to define an idealized CBDM system. The requirements checklist served as a benchmark for developing future CBDM systems. To clarify the vision of an idealized CBDM system, a high-level, systematic, conceptual reference model was proposed. The reference model defines a set of actors, activities, and functions involved in CBDM systems. Four major actors are defined in the reference model: (1) cloud consumer, (2) cloud provider, (3) cloud broker, and (4) cloud carrier. Four types of service delivery models (i.e., IaaS, PaaS, HaaS, and SaaS) were also defined. Moreover, CBDM was distinguished from web- and agent-based approaches from the perspectives of computing architecture, design communication, sourcing process, information and communication, programming model, data storage, and business model. Further, an idealized design and manufacturing scenario in a hypothetical CBDM setting based on currently existing and potentially new cloud-based service offerings was presented to clarify the conceptual framework of CBDM.

In Chapter 4, a CBDM prototype system, referred to as DMCloud, was developed for the Defense Advanced Research Projects Agency (DARPA). DMCloud integrated cloud-based tools and infrastructure such as cloud-based CAE software and additive manufacturing equipment into one thousand high schools across the U.S. The development and implementation of the prototype serves as a pilot study and represents the first attempt at building an idealized CBDM system. Therefore, Research Questions 1.a, 1.b, and 1.c were definitively answered.

Research Question 2.a:

- *What indices can be used to measure tie strengths between engineers in CBD?*

Hypothesis 2.a:

- *The Adamic and Adar index can be used to measure tie strengths in engineering design.*

Research Question 2.b:

- *How can communication and collaboration be improved?*

Hypothesis 2.b:

- *Measures and community detection methods in social network analysis can be used to improve communication and collaboration.*

Chapter 5 presented a SNA-based approach to support design communication and collaboration while design activities are being conducted in the social media-supported CBD environment. Specifically, tie strengths were measured using four indices that satisfy all of the axioms in social network analysis. Because the Entropy in Shannon's information theory and axiomatic design is expressed in the form of common logarithm and the *Adamic and Adar index* is also defined using common logarithm, the *Adamic and Adar index* was used to measure tie strengths in two illustrative examples. Based on the *Adamic and Adar index* scores, implicit design networks were successfully transformed into explicit and formal social networks. In these examples, the process of transforming customer needs, to functional requirements, to design parameters, and to process variables was visualized using SNA. Further, the social networks were measured at both actor and systems levels using quantitative measures in SNA. Design communities with common design activities were also detected. Therefore, Hypotheses 2.a and 2.b were validated and Research Questions 2.a and 2.b were answered.

Although the SNA-based approach was validated using two examples after design activities are finished, it can be further developed as a software tool running at the back end of a CBD system in real time while design activities are being conducted. In this case, a social network (e.g., number of nodes and edges) may change as design activities are being conducted. For instance, as a design process goes from the market analysis phase to conceptual design phase, more actors will get involved in the design process and more communication and collaboration events will take place. Therefore, the number of nodes and edges will increase during this process. However, because engineering design is a cyclic process of proposing design concepts, making changes, and refining preliminary and embodiment designs, a social network will evolve and become relatively stable during engineering design processes. Consequently, a software tool developed based on the SNA-based approach can run at the back end of a CBD system while design activities are being conducted rather than after they are finished as the illustrative examples.

Research Question 3:

- *How should the manufacturing capacity scalability of a CBM system be planned prior to the implementation and deployment of a CBM system?*

Hypothesis 3:

- *Discrete-event simulation can be used to formally model and simulate the manufacturing network of a CBM system and to plan manufacturing capacity scalability by identifying manufacturing bottlenecks.*

Chapter 6 addressed the planning of manufacturing scalability in the context of CBM. In this chapter, the research problem of modeling and analyzing the material flow in CBM systems was formulated. A discrete event simulation-based approach was used to formally represent the structure of a CBM system and analyze the qualitative and quantitative properties of the system. Specifically, the delivery drone example was used to demonstrate the effectiveness of this approach. In this example, the SPN model was simulated to identify potential manufacturing bottlenecks that determine manufacturing capacity scalability. The simulation results provided the insight to system designers about the dynamics of the material flow and the reconfiguration of the existing manufacturing network that allows for rapid manufacturing capacity scalability in the CBM setting. Therefore, Hypothesis 3 was validated and Research Questions 3 was answered.

7.3 Contributions

The research described in this dissertation contributes to the current body of knowledge from the following perspectives:

1. The first definition of CBDM was proposed, and the key characteristics of CBDM were identified. A reference model was defined to illustrate the vision for a future CBDM system, including the essential system components and major activities pertaining to CBDM. A requirements checklist was developed to determine the functional needs to meet for a future CBDM system. An example of hypothetical application scenario was developed to demonstrate the benefits of CBDM.
2. The SNA-based approach was proposed to formally model and analyze information flow in distributed and complex design collaboration networks. The SNA-based approach was demonstrated to have the potential to improve communication and collaboration in CBD using quantitative measures in SNA, community detection and text mining algorithms.
3. The SPN-based approach was proposed to formally model and analyze material flow in distributed and complex manufacturing supply chain networks. The SPN-based approach was demonstrated to have the potential to identify manufacturing bottlenecks and plan manufacturing scalability in CBM using both qualitative and quantitative analysis.

7.4 Opportunities for Future Work

This dissertation has been concerned with developing a conceptual framework for idealized CBDM systems from a system engineering perspective, a SNA-based approach for supporting effective design communication and collaboration from a social network perspective, and a discrete event simulation-based approach for planning manufacturing capacity scalability from a manufacturing network perspective. Although CBDM has been systematically defined and its two counterparts, CBD and CBM, have been addressed separately in this dissertation, we believe that this dissertation is only a small step towards the fulfillment of the holistic vision for CBDM and has its limitations as follows.

With respect to assessing the economic impacts of CBDM, both SMEs and large-scale enterprises will be faced with a critical question when considering a move to CBDM: How can decision makers assess the relative benefits and costs of adopting and implementing CBDM? Answering this question requires an in-depth understanding of the cost implications of all the possible decisions specific to different circumstances. While every situation will be different, it is very worthwhile to articulate the potential areas for cost savings that CBDM can bring to design and manufacturing enterprises. The answer to this question will provide practitioners with some general economic assessment guidelines for implementing CBDM.

In addition to the economic assessment of implementing CBDM, future research could be focused on developing a cloud-based cyber-physical manufacturing system prototype based on cloud computing and Internet of Things. Building such a cloud-based cyber-physical manufacturing system is very challenging and complex because it requires integrating heterogeneous software and hardware components and understanding human interaction with coupled software and hardware. To address this research issue, a scientific methodology that combines the cyber aspects of computing and communications with the dynamics and physics of manufacturing systems needs to be developed.

Last but not least, future research could also be focused on developing a sematic search engine to allow enterprises to search for qualified service providers. Currently, most search engines in design and manufacturing systems are based on keywords. None of the existing search engines is capable of searching for design concepts, 2D and 3D sketches, and manufacturing processes. It is very worthwhile to provide a scientific answer to the questions of what metrics should be defined to measure the performance of a design and manufacturing search engine, how to crawl and index design and manufacturing solutions and produce more satisfying search results.

APPENDIX A.1: INDEX SCORES FOR EXAMPLE 1

Connections		Delta Index	Max Index	Linear Index	Adamic and Adar Index
Actor ID	Actor ID				
1	2	28.0000	0.3333	28.0000	176.0559
1	3	28.0000	0.3333	28.0000	176.0559
1	4	6.0000	0.2500	9.0000	59.7947
2	3	28.0000	0.3333	28.0000	176.0559
4	5	16.8333	0.2500	25.2500	167.7574
4	6	16.8333	0.2500	25.2500	167.7574
4	7	16.8333	0.2500	25.2500	167.7574
4	8	6.0000	0.2500	9.0000	59.7947
5	6	16.8333	0.2500	25.2500	167.7574
5	7	16.8333	0.2500	25.2500	167.7574
6	7	16.8333	0.2500	25.2500	167.7574
8	9	15.6667	0.2500	23.5000	156.1306
8	10	15.6667	0.2500	23.5000	156.1306
8	11	15.6667	0.2500	23.5000	156.1306
8	15	6.0000	0.2500	9.0000	59.7947
9	10	15.6667	0.2500	23.5000	156.1306
9	11	15.6667	0.2500	23.5000	156.1306
10	11	15.6667	0.2500	23.5000	156.1306
12	13	17.8333	0.2500	26.7500	177.7232
12	14	17.8333	0.2500	26.7500	177.7232
12	15	17.8333	0.2500	26.7500	177.7232
13	14	17.8333	0.2500	26.7500	177.7232
13	15	17.8333	0.2500	26.7500	177.7232
14	15	17.8333	0.2500	26.7500	177.7232
16	17	26.6667	0.2500	20.0000	132.8771
16	18	26.6667	0.2500	20.0000	132.8771
16	19	26.6667	0.2500	20.0000	132.8771
16	20	18.0000	0.2500	12.2500	81.3872
17	18	26.6667	0.2500	20.0000	132.8771
17	19	26.6667	0.2500	20.0000	132.8771
18	19	26.6667	0.2500	20.0000	132.8771
20	21	15.0000	0.2500	22.5000	149.4868
20	22	15.0000	0.2500	22.5000	149.4868
20	23	15.0000	0.2500	22.5000	149.4868

20	24	18.0000	0.2500	12.2500	81.3872
21	22	15.0000	0.2500	22.5000	149.4868
21	23	15.0000	0.2500	22.5000	149.4868
22	23	15.0000	0.2500	22.5000	149.4868
24	25	16.5000	0.2500	24.7500	164.4354
24	26	16.5000	0.2500	24.7500	164.4354
24	27	16.5000	0.2500	24.7500	164.4354
24	28	18.0000	0.2500	12.2500	81.3872
25	26	16.5000	0.2500	24.7500	164.4354
25	27	16.5000	0.2500	24.7500	164.4354
26	27	16.5000	0.2500	24.7500	164.4354
28	29	18.0000	0.2500	27.0000	179.3841
28	30	18.0000	0.2500	27.0000	179.3841
28	31	18.0000	0.2500	27.0000	179.3841
29	30	18.0000	0.2500	27.0000	179.3841
29	31	18.0000	0.2500	27.0000	179.3841
30	31	18.0000	0.2500	27.0000	179.3841

APPENDIX A.2: INDEX SCORES FOR EXAMPLE 2

Connections		Delta Index	Max Index	Linear Index	Adamic and Adar Index
Actor ID	Actor ID				
A	B	13.3333	0.2500	20.0000	132.8771
A	C	13.3333	0.2500	20.0000	132.8771
A	D	13.3333	0.2500	20.0000	132.8771
B	C	13.3333	0.2500	20.0000	132.8771
B	D	13.3333	0.2500	20.0000	132.8771
C	D	13.3333	0.2500	20.0000	132.8771
E	F	9.2000	0.2000	18.4000	131.6222
E	G	9.2000	0.2000	18.4000	131.6222
E	H	9.2000	0.2000	18.4000	131.6222
E	I	9.2000	0.2000	18.4000	131.6222
F	G	9.2000	0.2000	18.4000	131.6222
F	H	9.2000	0.2000	18.4000	131.6222
F	I	9.2000	0.2000	18.4000	131.6222
G	H	9.2000	0.2000	18.4000	131.6222
G	I	9.2000	0.2000	18.4000	131.6222
H	I	9.2000	0.2000	18.4000	131.6222
J	K	6.1333	0.1667	15.3333	118.2289
J	L	6.1333	0.1667	15.3333	118.2289
J	M	6.1333	0.1667	15.3333	118.2289
J	N	6.1333	0.1667	15.3333	118.2289
J	O	6.1333	0.1667	15.3333	118.2289
K	L	6.1333	0.1667	15.3333	118.2289
K	M	6.1333	0.1667	15.3333	118.2289
K	N	6.1333	0.1667	15.3333	118.2289
K	O	6.1333	0.1667	15.3333	118.2289
L	M	6.1333	0.1667	15.3333	118.2289
L	N	6.1333	0.1667	15.3333	118.2289
L	O	6.1333	0.1667	15.3333	118.2289
M	N	6.1333	0.1667	15.3333	118.2289
M	O	6.1333	0.1667	15.3333	118.2289
N	O	6.1333	0.1667	15.3333	118.2289
P	Q	17.3333	0.2500	26.0000	172.7403
P	R	17.3333	0.2500	26.0000	172.7403
P	S	17.3333	0.2500	26.0000	172.7403

Q	R	17.3333	0.2500	26.0000	172.7403
Q	S	17.3333	0.2500	26.0000	172.7403
R	S	17.3333	0.2500	26.0000	172.7403
A1	B1	5.6667	0.1667	14.1667	109.2333
A1	C1	5.6667	0.1667	14.1667	109.2333
A1	D1	5.6667	0.1667	14.1667	109.2333
A1	E1	5.6667	0.1667	14.1667	109.2333
A1	F1	5.6667	0.1667	14.1667	109.2333
B1	C1	5.6667	0.1667	14.1667	109.2333
B1	D1	5.6667	0.1667	14.1667	109.2333
B1	E1	5.6667	0.1667	14.1667	109.2333
B1	F1	5.6667	0.1667	14.1667	109.2333
C1	D1	5.6667	0.1667	14.1667	109.2333
C1	E1	5.6667	0.1667	14.1667	109.2333
C1	F1	5.6667	0.1667	14.1667	109.2333
D1	E1	5.6667	0.1667	14.1667	109.2333
D1	F1	5.6667	0.1667	14.1667	109.2333
E1	F1	5.6667	0.1667	14.1667	109.2333
G1	H1	9.3000	0.2000	18.6000	133.0529
G1	I1	9.3000	0.2000	18.6000	133.0529
G1	J1	9.3000	0.2000	18.6000	133.0529
G1	K1	9.3000	0.2000	18.6000	133.0529
H1	I1	9.3000	0.2000	18.6000	133.0529
H1	J1	9.3000	0.2000	18.6000	133.0529
H1	K1	9.3000	0.2000	18.6000	133.0529
I1	J1	9.3000	0.2000	18.6000	133.0529
I1	K1	9.3000	0.2000	18.6000	133.0529
J1	K1	9.3000	0.2000	18.6000	133.0529
L1	M1	14.6667	0.2500	22.0000	146.1648
L1	N1	14.6667	0.2500	22.0000	146.1648
L1	O1	14.6667	0.2500	22.0000	146.1648
M1	N1	14.6667	0.2500	22.0000	146.1648
M1	O1	14.6667	0.2500	22.0000	146.1648
N1	O1	14.6667	0.2500	22.0000	146.1648
P1	T1	9.4000	0.2000	18.8000	134.4836
P1	Q1	9.4000	0.2000	18.8000	134.4836
P1	R1	9.4000	0.2000	18.8000	134.4836
P1	S1	9.4000	0.2000	18.8000	134.4836
Q1	R1	9.4000	0.2000	18.8000	134.4836

Q1	S1	9.4000	0.2000	18.8000	134.4836
Q1	T1	9.4000	0.2000	18.8000	134.4836
R1	S1	9.4000	0.2000	18.8000	134.4836
R1	T1	9.4000	0.2000	18.8000	134.4836
S1	T1	9.4000	0.2000	18.8000	134.4836
A1	G1	6.3333	0.2500	9.5000	63.1166
A1	L1	6.3333	0.2500	9.5000	63.1166
A1	P1	6.3333	0.2500	9.5000	63.1166
G1	L1	6.3333	0.2500	9.5000	63.1166
G1	P1	6.3333	0.2500	9.5000	63.1166
L1	P1	6.3333	0.2500	9.5000	63.1166
A	E	6.3333	0.2500	9.5000	63.1166
A	J	6.3333	0.2500	9.5000	63.1166
A	P	6.3333	0.2500	9.5000	63.1166
E	J	6.3333	0.2500	9.5000	63.1166
E	P	6.3333	0.2500	9.5000	63.1166
J	P	6.3333	0.2500	9.5000	63.1166
A	A1	6.3333	0.2500	9.5000	63.1166
A	G1	6.3333	0.2500	9.5000	63.1166
A	L1	6.3333	0.2500	9.5000	63.1166
A	P1	6.3333	0.2500	9.5000	63.1166
E	A1	6.3333	0.2500	9.5000	63.1166
E	G1	6.3333	0.2500	9.5000	63.1166
E	L1	6.3333	0.2500	9.5000	63.1166
E	P1	6.3333	0.2500	9.5000	63.1166
J	A1	6.3333	0.2500	9.5000	63.1166
J	G1	6.3333	0.2500	9.5000	63.1166
J	L1	6.3333	0.2500	9.5000	63.1166
J	P1	6.3333	0.2500	9.5000	63.1166
P	A1	6.3333	0.2500	9.5000	63.1166
P	G1	6.3333	0.2500	9.5000	63.1166
P	L1	6.3333	0.2500	9.5000	63.1166
P	P1	6.3333	0.2500	9.5000	63.1166

APPENDIX B.1: NETWORK MEASURES FOR EXAMPLE 1

Vertex	Degree	Betweenness	Cluster Coefficient
1	3	24.000	0.333
2	2	0.000	1.000
3	2	0.000	1.000
4	5	57.000	0.300
5	3	0.000	1.000
6	3	0.000	1.000
7	3	0.000	1.000
8	5	61.000	0.300
9	3	0.000	1.000
10	3	0.000	1.000
11	3	0.000	1.000
12	3	0.000	1.000
13	3	0.000	1.000
14	3	0.000	1.000
15	4	33.000	0.500
16	4	36.000	0.500
17	3	0.000	1.000
18	3	0.000	1.000
19	3	0.000	1.000
20	5	68.000	0.300
21	3	0.000	1.000
22	3	0.000	1.000
23	3	0.000	1.000
24	5	68.000	0.300
25	3	0.000	1.000
26	3	0.000	1.000
27	3	0.000	1.000
28	4	36.000	0.500
29	3	0.000	1.000
30	3	0.000	1.000
31	3	0.000	1.000

APPENDIX B.2: NETWORK MEASURES FOR EXAMPLE 2

Vertex	Degree	Betweenness	Cluster Coefficient
A	10	105.000	0.533
B	3	0.000	1.000
C	3	0.000	1.000
D	3	0.000	1.000
E	11	136.000	0.491
F	4	0.000	1.000
G	4	0.000	1.000
H	4	0.000	1.000
I	4	0.000	1.000
J	12	165.000	0.470
K	5	0.000	1.000
L	5	0.000	1.000
M	5	0.000	1.000
N	5	0.000	1.000
O	5	0.000	1.000
P	10	105.000	0.533
Q	3	0.000	1.000
R	3	0.000	1.000
S	3	0.000	1.000
A1	12	165.000	0.470
B1	5	0.000	1.000
C1	5	0.000	1.000
D1	5	0.000	1.000
E1	5	0.000	1.000
F1	5	0.000	1.000
G1	11	136.000	0.491
H1	4	0.000	1.000
I1	4	0.000	1.000
J1	4	0.000	1.000
K1	4	0.000	1.000
L1	10	105.000	0.533
M1	3	0.000	1.000
N1	3	0.000	1.000
O1	3	0.000	1.000
P1	11	136.000	0.491

Q1	4	0.000	1.000
R1	4	0.000	1.000
S1	4	0.000	1.000
T1	4	0.000	1.000

APPENDIX C.1: THE DESCRIPTION OF PLACES

Place	Description
P1	Raw material for building propellers is available
P2	3D printing propellers is in process
P3	Propellers are ready to be transported
P4	3D printer for building propellers is in repair
P5	3D printer for building propellers is idle
P6	Conveyor for transporting propellers is available
P43	Propellers are available to be assembled
P50	Order for motors is placed in the system
P51	Assembly line for producing motors is in process
P52	Motors are ready to be transported to warehouse
P53	Assembly line for producing motors is occupied
P54	Assembly line for producing motors is idle
P55	Truck for transporting motors is available
P56	Motors are ready to be transported to consumers
P57	Motors are available to be assembled
P7	Raw material for building legs is available
P8	3D printing legs is in process
P9	Legs are ready to be transported
P10	3D printer for building legs is in repair
P11	3D printer for building legs is idle
P12	Conveyor for transporting legs is available
P44	Legs are available to be assembled
P64	Order for navigation boards is placed in the system
P61	Assembly line for producing navigation boards is in process
P59	Navigation boards are ready to be transported to warehouse
P63	Assembly line for producing navigation boards is occupied
P62	Assembly line for producing navigation boards is idle
P60	Truck for transporting navigation boards is available
P58	Navigation boards are ready to be transported to consumers
P65	Navigation boards are available to be assembled
P13	Raw material for building arms is available
P14	3D printing arms is in process
P15	Arms are ready to be transported
P16	3D printer for building arms is in repair
P17	3D printer for building arms is idle

P18	Conveyor for transporting arms is available
P45	Arms are available to be assembled
P72	Order for main boards is placed in the system
P69	Assembly line for producing main boards is in process
P67	Main boards are ready to be transported to warehouse
P71	Assembly line for producing main boards is occupied
P70	Assembly line for producing main boards is idle
P68	Truck for transporting main boards is available
P66	Main boards are ready to be transported to consumers
P73	Main boards are available to be assembled
P19	Raw material for building gimbals is available
P20	3D printing gimbals is in process
P21	Gimbals are ready to be transported
P22	3D printer for building gimbals is in repair
P23	3D printer for building gimbals is idle
P24	Conveyor for transporting gimbals is available
P46	Gimbals are available to be assembled
P80	Order for cameras is placed in the system
P77	Assembly line for producing cameras is in process
P75	Cameras are ready to be transported to warehouse
P79	Assembly line for producing cameras is occupied
P78	Assembly line for producing cameras is idle
P76	Truck for transporting cameras is available
P74	Cameras are ready to be transported to consumers
P81	Cameras are available to be assembled
P25	Raw material for building frame bodies is available
P26	3D printing frame bodies is in process
P27	Frame bodies are ready to be transported
P28	3D printer for building frame bodies is in repair
P29	3D printer for building frame bodies is idle
P30	Conveyor for transporting frame bodies is available
P47	Frame bodies are available to be assembled
P88	Order for batteries is placed in the system
P85	Assembly line for producing batteries is in process
P83	Batteries are ready to be transported to warehouse
P87	Assembly line for producing batteries is occupied
P86	Assembly line for producing batteries is idle
P84	Truck for transporting batteries is available
P82	Batteries are ready to be transported to consumers

P89	Batteries are available to be assembled
P31	Raw material for building frame body tops is available
P32	3D printing frame body tops is in process
P33	Frame body tops are ready to be transported
P34	3D printer for building frame body tops is in repair
P35	3D printer for building frame body tops is idle
P36	Conveyor for transporting frame body tops is available
P48	Frame body tops are available to be assembled
P96	Order for flight control boards is placed in the system
P93	Assembly line for producing flight control boards is in process
P91	Flight control boards are ready to be transported to warehouse
P95	Assembly line for producing flight control boards is occupied
P94	Assembly line for producing flight control boards is idle
P92	Truck for transporting flight control boards is available
P90	Flight control boards are ready to be transported to consumers
P97	Flight control boards are available to be assembled
P37	Raw material for building frame body bottoms is available
P38	3D printing frame body bottoms is in process
P39	Frame body bottoms are ready to be transported
P40	3D printer for building frame body bottoms is in repair
P41	3D printer for building frame body bottoms is idle
P42	Conveyor for transporting frame body bottoms is available
P49	Frame body bottoms are available to be assembled
P98	Final products (i.e., drones) are available

APPENDIX C.2: THE DESCRIPTION OF TRANSITIONS

Transition	Description	Parameter (λ_i)
T1	Load raw material for building propellers	$\lambda_1 = 12$
T2	Build propellers	$\lambda_2 = 3$
T3	Transport propellers to the final assembly line	$\lambda_3 = 6$
T4	3D printer for building propellers breaks down	$\lambda_4 = 2$
T5	Repair the 3D printer for building propellers	$\lambda_5 = 4$
T37	Transport motors to warehouse	$\lambda_{37} = 4$
T38	Assemble motors	$\lambda_{38} = 8$
T39	Adjust the assembly line for motors	$\lambda_{39} = 4$
T40	Switch back to assemble motors	$\lambda_{40} = 4$
T41	Assemble other products	$\lambda_{41} = 1/12$
T42	Transport motors to consumers	$\lambda_{42} = 1/10$
T6	Load raw material for building legs	$\lambda_6 = 12$
T7	Build legs	$\lambda_7 = 4$
T8	Transport legs to the final assembly line	$\lambda_8 = 6$
T9	3D printer for building legs breaks down	$\lambda_9 = 2$
T10	Repair the 3D printer for building legs	$\lambda_{10} = 4$
T43	Transport navigation boards to warehouse	$\lambda_{43} = 4$
T44	Assemble navigation boards	$\lambda_{44} = 6$
T45	Adjust the assembly line for navigation boards	$\lambda_{45} = 4$
T46	Switch back to assemble navigation boards	$\lambda_{46} = 4$
T47	Assemble other products	$\lambda_{47} = 1/18$
T48	Transport navigation boards to consumers	$\lambda_{48} = 1/10$
T11	Load raw material for building arms	$\lambda_{11} = 12$
T12	Build arms	$\lambda_{12} = 4$
T13	Transport arms to the final assembly line	$\lambda_{13} = 6$
T14	3D printer for building arms breaks down	$\lambda_{14} = 2$
T15	Repair the 3D printer for building arms	$\lambda_{15} = 4$
T49	Transport main boards to warehouse	$\lambda_{49} = 4$
T50	Assemble main boards	$\lambda_{50} = 6$
T51	Adjust the assembly line for main boards	$\lambda_{51} = 4$
T52	Switch back to assemble main boards	$\lambda_{52} = 4$
T53	Assemble other products	$\lambda_{53} = 1/18$
T54	Transport main boards to consumers	$\lambda_{54} = 1/10$

T16	Load raw material for building gimbals	$\lambda_{16} = 12$
T17	Build gimbals	$\lambda_{17} = 0.5$
T18	Transport gimbals to the final assembly line	$\lambda_{18} = 6$
T19	3D printer for building gimbals breaks down	$\lambda_{19} = 2$
T20	Repair the 3D printer for building gimbals	$\lambda_{20} = 4$
T55	Transport cameras to warehouse	$\lambda_{55} = 4$
T56	Assemble cameras	$\lambda_{56} = 6$
T57	Adjust the assembly line for cameras	$\lambda_{57} = 4$
T58	Switch back to assemble cameras	$\lambda_{58} = 4$
T59	Assemble other products	$\lambda_{59} = 1/18$
T60	Transport cameras to consumers	$\lambda_{60} = 1/10$
T21	Load raw material for building frame bodies	$\lambda_{21} = 12$
T22	Build frame bodies	$\lambda_{22} = 0.5$
T23	Transport frame bodies to the final assembly line	$\lambda_{23} = 6$
T24	3D printer for building frame bodies breaks down	$\lambda_{24} = 2$
T25	Repair the 3D printer for building frame bodies	$\lambda_{25} = 4$
T61	Transport batteries to warehouse	$\lambda_{61} = 4$
T62	Assemble batteries	$\lambda_{62} = 10$
T63	Adjust the assembly line for batteries	$\lambda_{63} = 4$
T64	Switch back to assemble batteries	$\lambda_{64} = 4$
T65	Assemble other products	$\lambda_{65} = 1/20$
T66	Transport batteries to consumers	$\lambda_{66} = 1/10$
T26	Load raw material for building frame body tops	$\lambda_{26} = 12$
T27	Build frame body tops	$\lambda_{27} = 3$
T28	Transport frame body tops to the final assembly line	$\lambda_{28} = 6$
T29	3D printer for building frame body tops breaks down	$\lambda_{29} = 2$
T30	Repair the 3D printer for building frame body tops	$\lambda_{30} = 4$
T67	Transport flight control boards to warehouse	$\lambda_{67} = 4$
T68	Assemble flight control boards	$\lambda_{68} = 8$
T69	Adjust the assembly line for flight control boards	$\lambda_{69} = 4$
T70	Switch back to assemble flight control boards	$\lambda_{70} = 4$
T71	Assemble other products	$\lambda_{71} = 1/20$
T72	Transport flight control boards to consumers	$\lambda_{72} = 1/10$
T31	Load raw material for building frame body bottoms	$\lambda_{31} = 12$
T32	Build frame body bottoms	$\lambda_{32} = 4$
T33	Transport frame body bottoms to the final assembly line	$\lambda_{33} = 6$
T34	3D printer for building frame body bottoms breaks down	$\lambda_{34} = 2$
T35	Repair the 3D printer for building frame body bottoms	$\lambda_{35} = 4$

T36	Assemble drones at the final assemble line	$\lambda_{36} = 3$

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