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Cloud-Based Design, Engineering Analysis, and Manufacturing: A Cost-Benefit Analysis

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Abstract
From a business perspective, cloud computing has revolutionized the information and communication technology (ICT) industry by offering scalable and on-demand ICT services as well as innovative pricing plans such as pay-per-use and subscription. Considering the economic benefits of cloud computing, cloud-based design and manufacturing (CBDM) has been proposed as a new paradigm in digital manufacturing and design innovation. Although CBDM has the potential to reduce costs associated with high performance computing (HPC) and maintaining ICT infrastructures in the context of engineering design and manufacturing, it is challenging to justify the potential cost savings associated with HPC in the cloud because of the complexity in the cost-benefit analysis of migrating to CBDM. In response, this paper provides important insights into the economics of CBDM by identifying key cost factors and potential pricing models that can influence decision making on whether migrating to the cloud is economically justifiable. Specifically, the cost breakdown of adopting CBDM is presented. The general key benefits are demonstrated using real case studies. In addition, a hypothetical application example is presented to compare costs in CBDM with that of traditional in-house design and manufacturing. Finally, some of the key issues and road blocks are outlined.

Keywords: Cloud-based design and manufacturing, Cloud-based engineering analysis, Cloud computing, High performance computing, Cost-benefit analysis

1 Introduction

The well-known Pareto's principle, also referred to as the 80-20 rule or the law of the vital few, can be used to illustrate the distribution of wealth in a country. The original Pareto's principle states that 20% of the population in Italy owned 80% of the wealth in 1906. Subsequently, Pareto's principle has been observed in many other areas. The generalized Pareto's principle suggests that, for many events, roughly 80% of the effects come from 20% of the causes. For example, it has been observed that many companies in the information and communication technology (ICT) industry have been

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faced with the same phenomenon in which 80% of their budget was spent on maintaining existing ICT services and infrastructures, while only 20% on their core business functions. As a result, a limited amount of computing resources and capital can be used to improve the core competences of small- and medium-sized manufacturers (SMMs), including the development of new products and the improvement of existing products.

Because cloud computing enables ubiquitous and on-demand network access to a shared pool of configurable computing resources, the ICT industry has been promoting cloud computing since the 2000s as a profound paradigm shift. Similar to the ICT industry, product design and manufacturing industries are also undergoing a seismic paradigm shift from traditional web-based distributed and collaborative design and manufacturing to cloud-based design and manufacturing (CBDM) by migrating increasing amounts of core manufacturing functions into the cloud. For example, in the broad computer aided technology (CAx) fields such as computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), major CAx vendors have been developing or developed cloud-based CAx tools. For example, in the field of CAE, the UberCloud has launched an initiative to help SMMs apply HPC-based modeling and simulation into engineering analysis such as finite element analysis (FEA), computational fluid dynamics (CFD), and multi-body dynamics (Gentzsch & Yenier, 2013). The UberCloud brings industry end-users, computing resource providers, software providers, and HPC and cloud computing experts together, helping SMMs explore how to integrate HPC and cloud computing with CAx vendors such as Autodesk and ANSYS (UberCloud, 2014). Consequently, we envision that cloud computing has the potential to transform the way in which both large-scale manufacturers and SMMs leverage advanced data analytics, modeling and simulation tools in product design and manufacturing.

With the increasing levels of attention paid to CBDM, high-level management leaders will face a number of important decisions, including what design and manufacturing services to move and when to move those services into the cloud, how to structure the relationship with the cloud service provider, and how to manage risks while operating in a cloud computing environment. As expected, different applications and organizations will have varying decisions associated with addressing the above issues. Therefore, answering these questions requires an in-depth understanding of the cost implications of all the possible decisions specific to different circumstances. In response, the purpose of this paper is to provide decision makers with insights into the economic impacts of CBDM, including cost breakdown and potential benefits. Specifically, we identify an initial set of key factors affecting the costs of implementing CBDM and perform a cost-benefit analysis through case studies. The remainder of this paper is organized as follows: Section 2 introduces the background of CBDM. Section 3 presents some of the most commonly used pricing plans. Section 4 presents cost breakdown in the adoption of CBDM. Section 5 discusses the key benefits of migrating to CBDM using application examples and experiments. Section 6 provides recommendations that are drawn from the investigation.

2 Background

In this section, a brief overview of CBDM is provided. 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" (Wu et al., 2012; Wu et al., 2013; Wu et al., 2014; Wu et al., 2015). In the IaaS model, cloud service providers offer on-demand access to computing resources such as virtual machines and cloud storage. Examples of IaaS providers include Rackspace, Amazon, and Google. In the PaaS model, cloud service providers deliver computing platforms such as social collaboration platforms, programming and execution environments for cloud computing. Examples of

PaaS providers include Google, Microsoft, Amazon, and Salesforce. In the HaaS model, cloud service providers and consumers are allowed to rent and lease manufacturing equipment such as milling machines and 3D printers without permanently purchasing and owning them. Examples of HaaS providers include Shapeways, 3D Hubs, and MFG.com. In the SaaS model, cloud service consumers are enabled to run computationally intensive application software such as AutoCAD remotely without installing and running the software on their local computers. Examples of SaaS providers include ANSYS, Autodesk, Dassault Systemes, Sabalcore, and UberCloud.

3 Pricing Plans

In addition to the service models and deployment models presented in previous section, one of the essential characteristics of cloud computing is its pricing model or plan. A pricing plan, describing how products or services should be charged, is a critical factor for most organizations. A pricing plan will have a significant impact on the profit margins of a business. Developing and choosing an optimized pricing plan depends on the overall long-term business strategy of a company. Cloud computing service providers have developed and employed a variety of well-established pricing plans (Al-Roomi et al., 2013). The most commonly employed pricing plans include: (1) pay-per-use (also referred to as utility-based pricing plan), (2) subscription, (3) auction-based pricing (also referred to as dynamic pricing plan), and (4) advertising-based pricing, as shown in Table 1.

Pricing plan	**Description**
Pay-per-use	Price is set by a service provider based on per unit of usage.
Subscription	Price is set by a service provider and is paid in advance by a service consumer for a fixed or dynamic amount of usage and for a predefined period of time.
Auction-based	Price is set by a service consumer through virtual auctions via the Internet for a fixed or dynamic amount of usage and for a fixed or dynamic amount of time.
Advertising-based	Service consumers receive services at no charge or heavy discounts. Service providers gain profits from advertising.

Table 1: Pricing plans in the cloud computing market

More specifically, pay-per-use is a pricing plan in which a customer has access to potentially unlimited resources but only pays for what they actually use. Amazon EC2, Google App Engine, and Windows Azure, three of the market leaders in cloud computing, have employed the pay-per-use pricing plan. For example, Amazon utilizes the pricing plan by charging a fixed price for each hour of virtual machine usage. However, for start-ups, it might be very risky to employ the pay-per-use model without carefully monitoring the usage of cloud computing services. Consequently, the subscription pricing plan was introduced. In this plan, cloud computing services are not charged based on the amount of usage but for a fixed period of time, typically on a monthly or yearly basis. For example, IBM has implemented the subscription pricing plan referred to as the IBM SmartCloud for Social Business. Specifically, IBM offers four pricing options for the subscription fee for a minimum of one month up to a maximum of sixty months, including (1) entire commitment amount upfront, (2) monthly, (3) quarterly, and (4) annually. In the auction-based pricing plans, depending on market dynamics, in particular, supply and demand, service prices will vary. The mechanism of auction-based pricing is simply built upon the basic laws of supply and demand. That is, if demand increases and supply remains unchanged, a shortage occurs, leading to a higher equilibrium price. In the auction-based pricing, service consumers make a bid to use cloud computing services at a lower price. If the bid matches the market price, the requested service is activated. Amazon EC2 Spot Instances are an example of auction-based pricing. Another pricing model is advertising-based pricing which has been implemented by Alibaba Group, net2TV, Facebook, and Google Plus. As shown in Tables 2-5, there are a growing number of service providers with varying pricing plans currently in use.

Provider	Service	Pricing Plan	Price Scheme
Rackspace	Internet hosting	Pay-per-use	\$0.48/hour for 4 cores, 15 GB RAM, 40GB system disk, 150GB data disk
Amazon Elastic Compute Cloud (EC2)	Virtual machines	Pay-per-use and subscription	\$0.28/hour for 4 cores, 15 GB memory
Google Compute Engine		Pay-per-use	\$0.063/hour for 1 core, 3.75GB memory
Amazon Simple Storage Service (S3)	Online storage, file syncing	Pay-per-use	\$0.03/GB for the first 1 TB/month; \$0.0295/GB for the next 49 TB/month
Google Drive		Subscription	\$1.99/month for 100GB; \$9.99/month for 1TB;

Table 2: Examples in Infrastructure-as-a-Service

Provider	Service	Pricing Plan	Price Scheme
Google App Engine	Developing and hosting web applications	Pay-per-use	\$9/app/month
Microsoft Windows Azure		Pay-per-use	\$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	Pay-per-use	\$0.12/GB/month, limit: 2TB; \$0.035/GB, limit: 20,000 queries/day, 20TB of data processed/day
Amazon Relational Database Service		Pay-per-use	\$0.025/hour for Micro DB Instance; \$0.090/hour for Small DB Instance
Salesforce	Enterprise analytics	Subscription	\$125/user/month for Enterprise; \$250/user/month for unlimited

Table 3: Examples in Platform-as-a-Service

Provider	Service	Pricing Plan	Price Scheme
Shapeways	3D printing	Pay-per-use	Starting from \$0.21/cm3 for plastic; Starting from \$0.75/cm3 for sandstone
Cubify.com		Pay-per-use	\$1299 for 140×140×140 mm, 16 colors, plastic; \$2499-3999 for 275×265×240 mm, 18 colors, plastic

Table 4: Examples in Hardware-as-a-Service

Provider	Service	Pricing Plan	Price Scheme
Autodesk Product Design Suite 2015	Storage, 3D modeling, DWG editing, mobile viewing, rendering, design optimization, structure analysis	Subscription	\$290/month; \$2310/year
Dassault Systemes Solidworks 2015		Subscription	\$1495/year for professional; \$1295/year for standard
ANSYS		Pay-per-use	\$6,900/15,000 core hours, 512 parallel cores, 40 hours technical support
Siemens Solid Edge		Subscription	\$130/month for basic CAD;

2015			$220/month for complete CAD
TeamPlatform	Sharing and viewing CAD files, synchronize CAD files	Subscription	$25 for unlimited workspaces, guests, shared pages and forms, storage
Sabalcore	High performance computing resource	Pay-per-use	$0.20-$0.29/core-hour for premium service
Nimbix		Pay-per-use	$1.75/hour for ANSYS CFX, Fluent, Mechanical v15.0
Penguin Computing		Pay-per-use	$0.10/core-hour/GB/day
UberCloud OpenFOAM		Pay-per-use	$1,880 for up to 10,000 cores hours (CPU 24/7)
			$799 for up to 10,000 cores hours (Ohio supercomputer center)

Table 5: Examples in Software-as-a-Service

4 Cost-Benefit Analysis

According to a report from Gartner (2009), the costs of building and maintaining a data center break down into categories as shown in Figure 1.

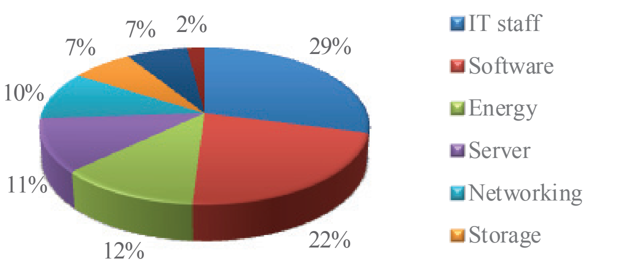

Figure 1 Data center cost portfolio (Gartner, 2009)

Similarly, the cost factors associated with CBDM are composed of software, hardware, data centers, electricity, raw material, manufacturing, supply chain, and expert consulting costs, as shown in Figure 2. Software costs refer to the costs incurred by purchasing software licenses. Based on its purpose, software can be divided into system software (e.g., operating systems and device drivers), middleware (e.g., Simple Object Access Protocol, and Oracle WebLogic server), and application software (e.g., CAD/CAE/CAM software). Hardware costs refer to the costs incurred by purchasing manufacturing equipment (e.g., CNC machines and 3D printers) and ICT devices (e.g., servers, gateways, routers, network bridges, hubs, and storage). Data center costs refer to the costs incurred by storing, managing, processing, and analyzing a large volume of datasets. Electricity costs refer to the costs incurred by power consumption in a shop floor or production plant. Raw material costs refer to the costs incurred by purchasing raw materials for producing parts. Supply chain costs refer to the costs incurred by transporting raw materials, assemblies, and end products. Expert consulting costs refer to the costs incurred by acquiring expert advice in data security, cloud computing/HPC, product design, engineering analysis, and manufacturing.

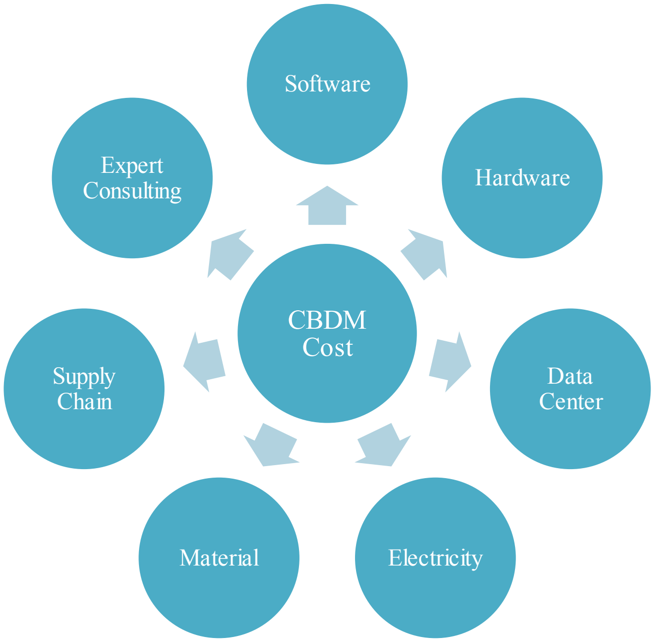

Figure 2 Cost breakdown for CBDM

The key benefits of adopting CBDM are articulated based on the experiments conducted by the Penguin HPC cloud and UberCloud in collaboration with end users from the engineering design and manufacturing sectors.

1. **Lower cost barriers**: SMMs or startups can purchase cloud-based data storage and computing resources to perform complex engineering analysis and simulation such as CFD and FEA. Without adopting CBDM, SMMs and startups can hardly afford and justify the extremely high acquisition, operation, and maintenance costs of the advanced CAD/CAE/CAM systems. Because of the inherent characteristics of CBDM such as virtualization, multi-tenancy, ubiquitous access, software-as-a-service, and pay-per-use, CBDM has the potential to significantly reduce market entry costs and democratize access to HPC and manufacturing equipment for product design and manufacturing.
2. **Shorter time to results/market**: Today's engineering workstations usually have 4 to 8 CPU cores. However, CBDM can potentially provide unlimited number of cores in parallel, typically dozens or hundreds of cores, as shown in Tables 6-12. For example, ANSYS Fluent can easily scale to several hundreds of cores, and thus running hundreds of times faster than running on a single workstation. In addition, instead of one job/task on an eight-core workstation, hundreds of 8-core jobs can be executed in parallel, which results in a speedup factor of several hundreds. Such a shorter time to result/market would not be possible without migrating into CBDM. Moreover, according to UberCloud, in the early cloud-based HPC experiments, the experiment process is as follows: (1) identifying the best suited cloud provider, (2) accessing the cloud computing resources, (3) executing the simulations, (4) collecting the results, and (5) sending them back to the end user. The entire process could easily take one month with three months on average. However, UberCloud has recently developed the new Linux Container technology with fully integrated software, hardware, and data centers which enables end users to have access to

their application software, cloud resources, and data within minutes or even seconds (Gentzsch & Yenier, 2014).

3. **Improved scalability**: Scalability refers to both computing and manufacturing scalability in the context of CBDM. Computing scalability refers to the ability of a computer system to pool a large amount of computing resources from data centers for handling unpredictable fluctuations in demand. Manufacturing scalability refers to the ability to adjust the production capacity of a manufacturing system through system reconfiguration. With respect to computing scalability, because of varying loads over the time of a project, in-house HPC servers might not always be fully loaded, and thus unused CPU cores will be wasted. Similarly, considering the entire life cycle of a manufacturing system, the time a manufacturing system operates at the full capacity in reality is usually sub-optimal, although originally optimally designed, and thus idle machines will be wasted. Migrating into CBDM can allow users to quickly scale up and down their capacities of computing and manufacturing because required computing (e.g., CPU cores and RAM) and manufacturing resources (e.g., 3D printers) can be added and removed as needed to respond to rapidly changing market demand. The case studies as shown in Tables 6-12 demonstrate how computing scalability can be achieved. Moreover, emerging cloud-based manufacturing services can help manufacturers handle transient demand and dynamic capacity planning under emergency situations incurred by unpredictable customer needs and reliability issues.

	Before	After
Task	Structure analysis and vehicle crash simulations	
Software	LS-DYNA	
Server	SGI Altix 330 with12 CPUs	Penguin HPC cloud
Time to results	4 weeks to 1 year	Shorter run times
Maximum number of concurrent jobs	2	8

Table 6: Case 1 (End User: IMMI) (Penguincomputing, 2014)

	Before	After
Task	Finite element analysis	
Software	LS-DYNA	
Server	4 node, 16 cores in-house HPC cluster	Penguin HPC cloud
Time to results	15 hours	1.5 hours
Maximum number of concurrent jobs	1	3

Table 7: Case 2 (End User: Callaway Golf) (Penguincomputing, 2014)

	Before	After
Task	Crash simulation	
Software	Pam-Crash from ESI Group	
Server	In-house HPC cluster with 2000 CPU cores	Penguin HPC cloud
Time to results	9 days	7 hours
Maximum number of concurrent jobs	1	More than 20

Table 8: Case 3 (End User: NEC Soft) (Penguincomputing, 2014)

	Before	After
Task	Computational fluid dynamics	
Software	ANSYS Fluent + in-house FEA code	
Server	2 nodes, 32 cores with dual Intel Xeon E5-2690 2.9 GHz, 16 cores, 128 GB RAM	CPU 24/7 HPC cloud and UberCloud
Time to results	5X	1X

Table 9: Case 4 (End User: Rolls-Royce) (Gentzsch & Yenier, 2013)

	Before	After
Task	Computational fluid dynamics	
Software	ANSYS	
Server	Intel Xeon X5667, 12M Cache, 3.06GHz, 6.4 GT/s, 24 GB RAM	Bull and UberCloud
Time to results	5 days	46.5 hours

Table 10: Case 5 (End User: FLSmidth) (Gentzsch & Yenier, 2013)

	Before	After
Task	Computational fluid dynamics	
Software	HYDRO_AS-2D	
Server	In-house PC 6 cores i7, 3.33GHz, 24 GB RAM	HSR Hochschule für Technik and UberCloud
Time to results	5 hours	3 hours

Table 11: Case 6 (End User: Pöyry Energy GmbH) (Gentzsch & Yenier, 2013)

	Before	After
Task	Computational fluid dynamics	
Software	Autodesk Simulation CFD 360	
Server	HP Z800 Dual 2.4 GHz Quad Core E5620 Workstation, 24 GB RAM	Autodesk cloud and UberCloud
Time to results	800 hours	24 hours

Table 12: Case 7 (End User: Lobo Engineering PLC) (Gentzsch & Yenier, 2013)

5 A Hypothetical Case Study

In this section, a hypothetical case study is performed to demonstrate potential cost saving in CBDM in comparison with traditional in-house engineering design, analysis, and manufacturing. Specifically, the application example is to design and manufacture the major mechanical components of a mini drone, as shown in Figure 3.

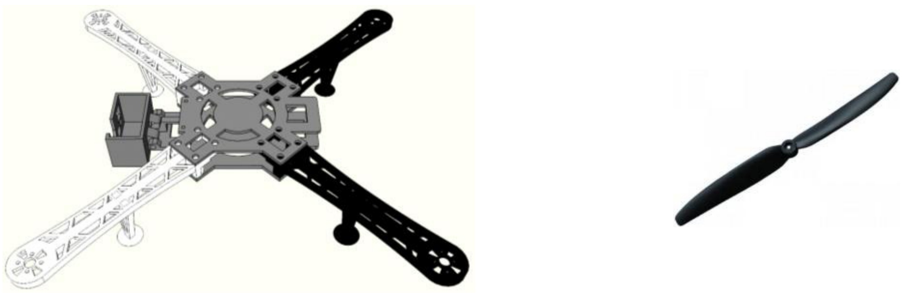

Figure 3 The main body and propeller of the mini drone (DIYDRONES, 2012)

To estimate costs associated with engineering design and manufacturing in the hypothetic case study, activity-based costing (ABC) is used to identify activities required to produce the mini drone and assign costs to the activities that consume resources. ABC states that products consume activities, it is not the products but the activities that consume resources, the activities are the cost drivers. Instead of allocating costs to cost centers such as marketing, design, and manufacturing, ABC allocates direct and indirect costs to the activities such as creating a 3D model for a part, performing structural or thermal analysis, performing a manufacturing operation, and processing an order. Specifically, ABC traces resources to activities then to cost objects for a more accurate cost distribution. A cost object refers to a product or process to which costs are assigned. An activity refers to an action or event in which the cost objects are created. Resources are objects consumed by the activities which result in costs, including software, hardware, labor, and materials. The specific steps of ABC in the case study are described as follows:

(1) Identify cost objects: Cost objects in CBDM and traditional in-house design and manufacturing are shown in Tables 13 and 14, including propellers, legs, arms, top frames, bottom frames, brushless gimbals, 3D models, and so on.
(2) Identify activities: Major activities include purchasing software licenses, creating the 3D models of the mechanical components of the mini drone, analyzing structural and fluid dynamics, and building parts using 3D printing.
(3) Identify cost drivers and estimate cost driver rates: In order to calculate the total cost, the specific cost drivers and associated resource consumption rates need to be identified. For example, the cost driver for building a propeller is build time (i.e., the number of time units). Build time can be estimated based on the 3D model, part volume, and 3D printing resolution.
(4) Estimate the cost assigned to each activity: The cost assigned to each activity can be calculated by multiplying the use of the consumed cost drivers by the cost driver rates.

Cost object	Activity	Cost driver	Cost driver consumed	Cost driver rate	Cost assigned ($)
CAD Software	Subscribe	Number of months	1	$290/month (AutoCAD)	290
3D model	Create & modify 3D models	Number of hours	8×5	$5/hour	200
Simulation	Perform FEA & CFD	Number of hours	24	$1.75/core-hour (ANSYS)	42
FEA & CFD model	Create FEA & CFD models	Number of hours	8×1	$5/hour	40
Propeller	Build propellers using 3D printing	Material volume	160×4	$0.21/cm^3 (Shapeways)	134.4
Leg	Build legs using 3D printing	Material volume	10×4	$0.21/cm^3 (Shapeways)	8.4
Arm	Build arms using 3D printing	Material volume	90×4	$0.21/cm^3 (Shapeways)	75.6
Frame body top	Build body tops using 3D printing	Material volume	35×1	$0.21/cm^3 (Shapeways)	7.35
Frame body bottom	Build body bottoms using 3D printing	Material volume	35×1	$0.21/cm^3 (Shapeways)	7.35
Brushless gimbal	Build gimbals using 3D printing	Material volume	60×1	$0.21/cm^3 (Shapeways)	12.6
				Total cost	817.7

Table 13: Activity-based costing in CBDM

Cost object	Activity	Cost driver	Cost driver consumed	Cost driver rate	Cost assigned ($)
CAD Software	Purchase software license	Number of users	1	$4,525/user (AutoCAD)	4525
3D model	Create & modify	Number of	8×5	$5/hour	200

	3D models	hours			
Simulation	Perform FEA & CFD	Number of workstations	1	\$1300/unit (Dell XPS)	1300
FEA & CFD model	Create FEA & CFD models	Number of hours	8×1	\$5/hour	40
3D printer	Purchase 3D printer	Number of 3D printer	1	\$34,900/unit (Dimension 1200es)	34900
Propeller	Build propellers using 3D printing	Material volume	160×4	\$0.15/cm^3	96
Leg	Build legs using 3D printing	Material volume	10×4	\$0.15/cm^3	6
Arm	Build arms using 3D printing	Material volume	90×4	\$0.15/cm^3	54
Frame body top	Build body tops using 3D printing	Material volume	35×1	\$0.15/cm^3	5.25
Frame body bottom	Build body bottoms using 3D printing	Material volume	35×1	\$0.15/cm^3	5.25
Brushless gimbal	Build gimbals using 3D printing	Material volume	60×1	\$0.15/cm^3	9
				Total cost	41,140.5

Table 14: Activity-based costing in traditional in-house design and manufacturing

As shown in Tables 13 and 14, the total cost associated with designing and manufacturing one mini drone in CBDM is \$817.7 which is significantly lower than that of traditional in-house design and manufacturing, \$41,140.5.

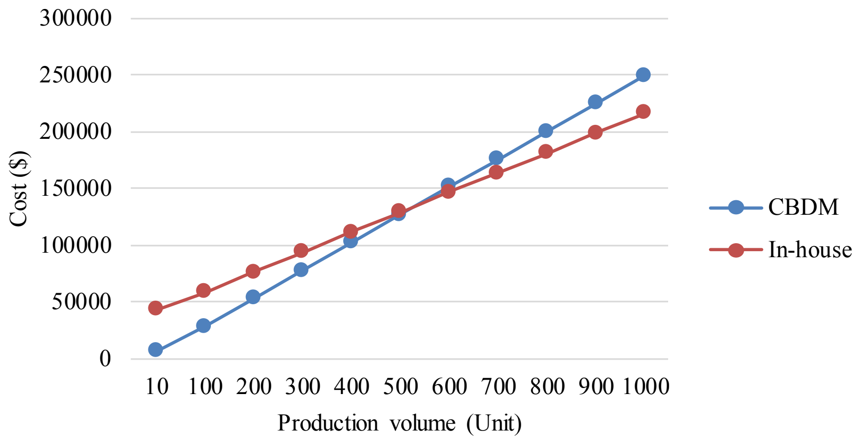

Figure 4 Break-even analysis for cost

Moreover, Figure 4 shows the break-even analysis for the costs. The break-even point in Figure 4 is the one with production volume of 600 units. In other words, when the production volume is lower than 600 units, the total cost in CBDM is lower than that of in-house design and manufacturing. When the production volume is greater than 600 units, the total cost in CBDM is greater than that of in-house design and manufacturing. Therefore, in this case study, adopting CBDM is more profitable when the production volume is less than 600 units.

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.

In general, 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. Furthermore, 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, 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 from the perspective of HaaS. 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, manufacturers in the aerospace and automotive industries such as Boeing, BMW, and GE could benefit from CBDM by implementing IaaS, PaaS, and SaaS.

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. Although the pay-per-use pricing model is widely implemented, 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 pricing model that can be applied to all circumstances.

6 Conclusion and Future Work

In this paper, some of the important insights into the economics of CBDM were presented. Specifically, most common pricing models deployed by CBDM service providers are reviewed. In addition, the key cost factors and benefits are demonstrated using several real case studies. Furthermore, a hypothetical application example was presented. Our results have shown that migrating to the cloud has the potential to significantly reduce costs associated with engineering design and manufacturing in small- and medium-volume production. The contribution of the research is that the case studies provide service providers and consumers with comparative benchmarks to assess the costs and benefits of adopting CBDM both qualitatively and quantitatively.

Future research will be focused on creating a multi-criteria decision support model for studying strategic trade-offs in engineering design and manufacturing (e.g., pay-per-use or subscription, make or buy) in the adoption of CBDM. A cost estimation model is essential to determine the costs associated with software, hardware, data center, electricity, material, supply chain, and expert consulting when migrating to the cloud. Incorporating the cost estimation model, the multi-criteria decision support model will take complex economic factors, including return-on-investment (ROI), net-present-value (NPV), payback-period, and benefit-to-cost ratio, into account for both service providers and consumers. These measures are critical to decide when and under which conditions it is better to adopt CBDM, thereby helping both SMEs and large-scale manufacturers access the economic benefits of CBDM by performing a quantitative cost-benefit analysis.

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