Fall 2015

Design and implementation of a broker for cloud additive manufacturing services

Venkata Prashant Modekurthy

DESIGN AND IMPLEMENTATION OF A BROKER FOR CLOUD ADDITIVE MANUFACTURING SERVICES

by

VENKATA PRASHANT MODEKURTHY

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN COMPUTER SCIENCE

2015

Approved by

Dr. Xiaoqing (Frank) Liu, Advisor
Dr. Ming C. Leu
Dr. Wei Jiang

ABSTRACT

The growing number of cloud Additive Manufacturing (AM) services, offered by different providers over the Internet, makes it challenging for consumers to compare these cloud AM services to select a service of their choice. In addition, it is even more challenging for consumers to compare these cloud AM services against their personal preferences. This is because, consumers personal preferences on multiple service attributes such as price, material, accuracy, and schedule, should be considered for cloud AM service selection. The decentralized nature of these cloud AM services coupled by the need to consider consumers personal preferences during cloud AM service selection, requires a system that will serve as a broker between cloud AM services and consumers. But, existing frameworks of cloud manufacturing either do not have brokers between cloud manufacturing service providers and consumers or do not support personalized preference and trade-off based brokerage. To address these issues, we propose a cloud additive manufacturing framework which consists of a service broker system for cloud AM services that provides consumers with a single point of access to a large number of cloud AM services from many additive manufacturing service providers. This broker system also incorporates the first real application of service selection with fuzzy logic based personalized preferences and trade-off. We also develop a method to generate fuzzy membership functions for each service attribute. This makes it easy for consumers to specify their fuzzy membership functions. We present an application case study to demonstrate the feasibility of brokerage in cloud AM services and finally evaluate our method in terms of performance.

ACKNOWLEDGMENTS

I would like to express my gratitude to all those who have helped me during this research. Firstly, I would like to thank my advisor Dr. Xiaoqing (Frank) Liu for giving me the opportunity to work on this project, his valuable insights and suggestions have helped me to overcome many hurdles during this work. I am grateful to him for the advice and guidance he gave me throughout my Master's program. Further, I thank the Intelligent Systems Center for funding my Master's research. I would also like to thank Dr. Ming C. Leu and Dr. Wei Jiang for being part of my thesis committee and taking time to review this work. A special thanks to my friends and family whose constant support and encouragement has always been crucial for me.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

1. INTRODUCTION

Cloud services in cloud computing are usually delivered as web services [1]. Similarly, cloud manufacturing services for production, management, design, and engineering capabilities are and will be delivered to consumers as web services [2] [3] [1]. Selection of these cloud manufacturing services is a very time-consuming manual process without a broker, since numerous cloud manufacturing services are offered from many providers. Cloud manufacturing would not succeed if consumers cannot find cloud manufacturing services to their satisfaction. This problem is not addressed adequately by many existing cloud manufacturing frameworks and systems and if not addressed, it will pose a greater challenge to consumers especially with increasing number of cloud manufacturing services available from many service providers.

Additive manufacturing (AM) has found rapid growth for part fabrication in recent years [4]. This rapid growth in AM has led to several cloud AM services which are offered to consumers as web services, similar to the cloud services and cloud manufacturing services. These cloud AM services offered by different providers are similar in functionality. For instance, Shapeways [2] offers a cloud AM service to fabricate an iPhone 5 case using polyamide material and I.Materialise [3] also offers a similar cloud AM service in polyamide material. The number of similar cloud AM services offered by different service providers is expected to grow significantly in the future as more cloud AM services are provided over the Internet. Therefore, identifying and comparing these cloud AM services offered by different service providers is a cumbersome process [5] and most of the existing cloud manufacturing frameworks fail to address this issue as their frameworks do not contain a broker component.

Cloud AM services are characterized by service attributes like price, accuracy, schedule and material. These service attributes distinguish competing cloud AM services

[6]. For instance, Table 1.1 shows similar cloud AM services with different service attribute values. However, different consumers have different personal preferences for the same service attribute. In addition, different consumer's have different trade-off strategies on these service attributes. But, capturing these personal preferences and trade-off strategy is a challenging task.

Table 1.1. Cloud AM services from different providers with similar functionality showing differences in service attributes

Cloud AM Service Provider	Functionality	Material	Price ($)	Accuracy (%)	Schedule (days)
Shapeways	iPhone 5 Case	polyamide	7.56	0.15	12
I.Materialise	iPhone 5 Case	polyamide	15.66	0.3	8

A fuzzy logic approach is used to capture consumer's personal preference by a membership function. Reason for choosing fuzzy logic approach is, it supports crisp/elastic match on a service attribute and also trade-off between service attributes. But, generating a fuzzy membership function for a service attribute is a tedious task. This is because, membership functions have to capture the rate of change of degree of satisfaction between different values of the service attribute. In addition, different membership functions can be constructed for the same attribute variable. For example, consider two consumers, consumer #1 and consumer #2, who wish to manufacture some part. Consumer #1 wishes to produce the part for a price less than $20 whereas consumer #2 wishes to manufacture the same part for a best price of $20 or less and a highest acceptable price of $30. The degree of satisfaction of consumer #1 from $0 to $20 is 1. Any service with price more than $20 will have a degree of satisfaction of 0. On the other hand, the degree of satisfaction of consumer #2 from $0 to $20 is 1. Whiles the price of a service increase from $20 to $30, the degree of satisfaction gradually decreases from 1 to 0. Any service with price more than $30 will have a degree of satisfaction of 0.

This document addresses the above issues by designing and implementing a brokerage of Cloud AM services in a cloud AM framework. The broker allows service providers to register their cloud AM services in a single cloud AM platform and also register the allowed interactions between the cloud AM service and the broker, as web services. It provides consumers with a single-point access to a large number of cloud AM services. The framework includes two major engines: cloud AM service selection engine and cloud AM service registration engine. The cloud AM service registration engine provides a platform for AM service providers in a cloud platform to register their cloud AM services. The cloud AM Service selection and ranking engine incorporates the first real implementation of personalized preferences and trade-off. It uses a fuzzy logic approach, based on fuzzy membership functions, to select and rank services. Another noted contribution of this work is a simple method of capturing fuzzy membership functions of service attributes, such as material, accuracy, price and schedule, which are used in additive manufacturing. The brokerage for AM services in a cloud AM platform is implemented. An application example is used to show the feasibility of cloud AM brokerage and effectiveness of personalized preference based cloud AM service search and ranking.

The rest of this document is organized as follows. Related works is presented in section 2. Cloud manufacturing framework is presented in section 3. A framework for the proposed cloud AM service broker is presented in section 4. Fuzzy membership function generation for service attributes used in AM, such as material, accuracy, price, and schedule is presented in section 5. Service selection and ranking method is presented in section 6. An application example is presented in section 7. Performance evaluation is presented in section 8 and conclusion in section 9.

2. RELATED WORK

Cloud manufacturing is a broad paradigm which includes research in the field of virtualization, perception of devices, and general architectures of cloud manufacturing. This document focuses exclusively on a broker application, hence the scope is limited to cloud manufacturing architectures.

Cloud manufacturing makes manufacturing resources and services available over the Internet [7] [8]. Several architectures of cloud manufacturing have been proposed by applying cloud computing to manufacturing [7] [8] [9] [10]. Wu et al. [11] reviewed a few cloud manufacturing architectures in their paper. The architectures they discussed so far focus on virtualization of manufacturing resources and services and offer them as on-line services to consumers. Wu et al. [12] [13] proposed a method of cloud based design and manufacturing (CBDM) which enables sharing of manufacturing resources as cloud services, similar to Infrastructure as a Service (IaaS) or Software as a Service (SaaS). Wang [14] proposed a tiered architecture to service oriented manufacturing and connected it to a shop-floor environment to enable real time availability and monitoring. Rauschecker et al. [15] addressed the issue of manufacturing resource and services presentation by proposing a uniform representation across multiple service providers in cloud manufacturing. All the above frameworks of cloud manufacturing do not contain a cloud manufacturing service broker between service providers and consumers.

Several manufacturers provide cloud Additive Manufacturing (AM) services over the Internet. Shapeways [2] is a 3D printing marketplace that offers 3D printing services of producing parts in plastics, resin, stainless steel, gold and many other materials [2] over the internet. It allows consumers to upload a 3D model of a part they want to fabricate and also select their preferred material. Ponoko [16], Sculpteo [17], I.Materialise [3], RedProto [18], RedEye [19]] and Core [20] also offer 3D printing services online. All the above cloud

AM services limit their on-line offerings to their own 3D printing machines. Comparing cloud AM services offered by these companies for producing a specific part requested by a consumer is a cumbersome manual process. A consumer needs to upload a 3D model of the part he/she wants to fabricate on each company's site, search for cloud AM services on all websites of these companies individually, and compares the list of cloud AM services to identify a cloud AM service to their satisfaction. It may require multiple iterations of searches. Therefore, there is the need for a broker between consumers and cloud AM service providers to automate this cumbersome manual process.

Existing broker solutions are usually not AM [21] [22]. This is a primary reason to develop a brokerage for cloud AM services. Wang and Xu [23] [24] developed an interoperable cloud based manufacturing system (ICMS) which offers manufacturing services as cloud services to consumers. The proposed system integrates services from multiple service providers. It has a broker agent to find services based on exact match of service attributes with consumer's request, which often leads to search results containing no services with perfect match and consumers need to modify their requests numerous times before they can find services to their satisfaction. This problem exists mainly because the system does not take personalized preferences of consumers into consideration. Jonas Neubert developed a 3D Printing Price Check application to address the issue [5]. His application provides consumers with price estimates of many 3D printing services with multiple material options from many cloud AM service providers over the Internet [5]. However, it does not consider many AM service attributes, such as accuracy and schedule, and personal preferences of consumers on service attributes. In addition, it compares and ranks cloud AM services based on a single service attribute of price. Price is not the only service attribute consumers take into consideration when comparing and selecting cloud AM services. For instance, a consumer in the aerospace industry who wants to fabricate a turbine blade will care more about accuracy and material than price in selection of cloud AM services. In addition, it does not consider trade-offs on cloud AM services.

Similar works on service selection were developed in web service selection. Li et al. [25] developed a fuzzy logic based approach to bridge gaps between providers and consumers in terms of QoS (Quality of Service) factors of Web services. Masri and Mahmoud [26] [27] developed a method which computes the normalized difference for each QoS factor of all Web services. The summation of the normalized differences for all QoS factors of a service is used for ranking web services in a decreasing order. Similarly, K. Benouaret and D. Benslimane [28] developed an σ-skyline and α-skyline approach which improves the existing concept of ranking services based on skyline. However, the above methods do not consider the preferences of consumers on QoS values.

Benouaret et al. [29] developed a majority rule based web service selection algorithm which first calculates the similarity between consumer's preference on a QoS factor and QoS value of a service using jaccard coefficient. This coefficient is aggregated for the entire list of QoS factors through a unanimous skyline operator and then services are ranked based on the results of skyline operator. Similarly, Wang [30] developed an approach for service selection for imprecise preferences of consumers on QoS factors using fuzzy sets. Wang et al. [31] developed an approach using fuzzy linear programming for service selection and ranking. Xiuqin et al. [32] developed a method using interval valued fuzzy sets for selecting services based on QoS factors. Almulla et al. [33] suggest a fuzzy representation of constraints on QoS factors and also provide a ranking model based on the representation. Li et al. [34] developed a multidimensional class based representation of QoS values and developed a selection and ranking model based on their representation. Zhao et al. [35] developed a ranking method based on aggregating ranked lists, where each list is ranked on a QoS value. Mobedpour and Ding [36] developed a method of computing the optimal service based on the Integer optimization problem. They consider the constraints of the optimization problem to be consumer preferences. Sun et al. [37] proposed a personalized web service recommendation method based on a collaborative filtering approach. They use service attribute information from similar users with similar experience to predict values on the same service attribute values. Chen et al. [38] also proposed a location-based collaborative filtering based recommendation method to predict service attribute values of services. However, these methods do not support trade-off strategy specification. In addition, these methods do not allow consumers to choose between crisp and elastic specification for each service attribute, an approach developed by Liu et al. [6] [39]and Fletcher et al. [40].

In summary, the existing systems and efforts in cloud additive manufacturing either do not have a broker or they do not consider many AM service attributes and personalized preferences on the AM service attributes. This document addresses this issue by presenting a design and implementation of a broker for a cloud additive manufacturing system. The broker considers multiple AM service attributes and incorporates personalized preferences on these attributes from consumers to select and rank cloud AM services over the Internet. This document also talks about a simple method to develop a fuzzy membership function based service selection and ranking for cloud AM services inspired by Fletcher et al. [40]. In addition, a fuzzy membership generation method is developed to generate a membership function for a consumer. This is discussed in detail in section 5 and 6 with a running example, using hypothetical data, to explain the method step by step.

3. CLOUD ADDITIVE MANUFACTURING

Proposed cloud additive manufacturing framework for additive manufacturing is shown in Figure 3.1. The cloud manufacturing architecture consists of four (4) major layers: resource layer, virtualization and perception layer, application layer and broker layer. Of the four layer broker layer is independent to the AM service provider whereas resource layer, virtualization and perception layer, and application layer are specific to an AM service provider.

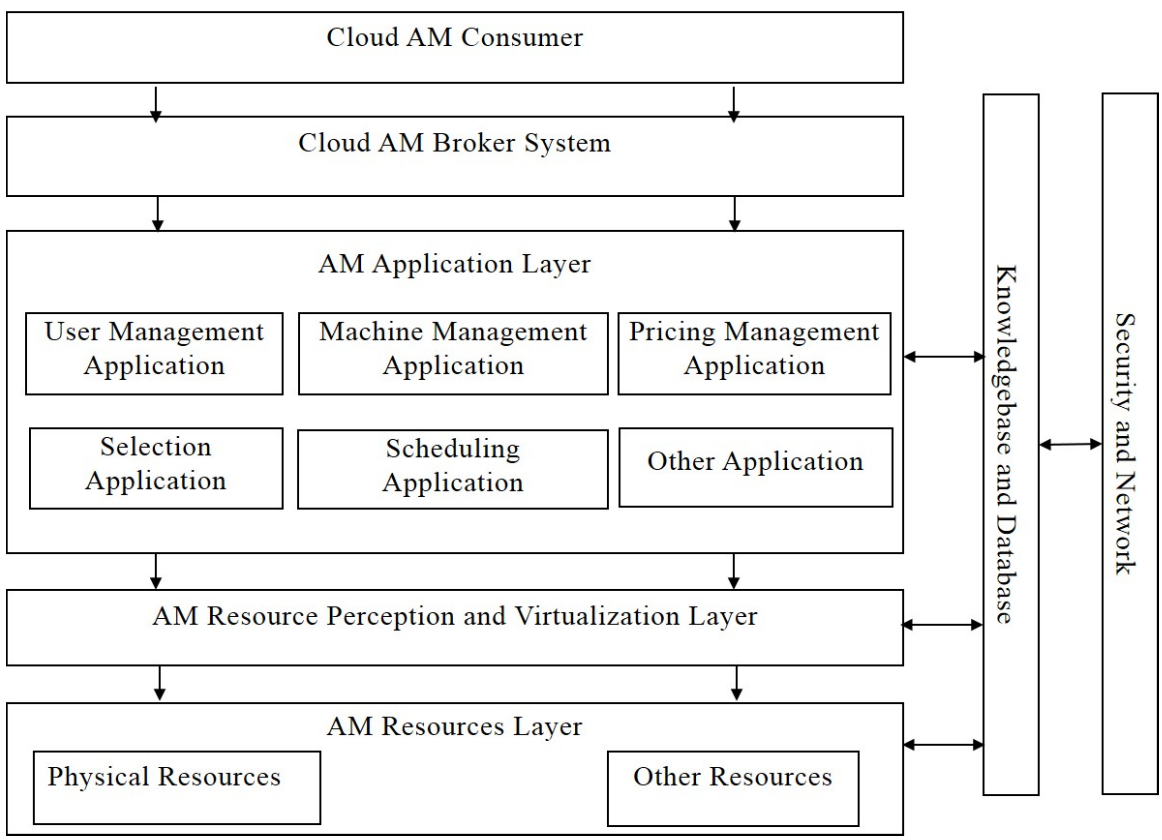

Figure 3.1. The proposed cloud AM hierarchical architecture

3.1. RESOURCE LAYER

Resource layer forms the backbone of the Cloud Additive manufacturing architecture. This layer consists of the AM machines and the computational resources that are to be offered as cloud services.

3.2. VIRTUALIZATION AND PERCEPTION LAYER

This layer is responsible for virtualizing AM machines as cloud AM services. Virtualization in this work refers to representation of a machine by its characteristics and capabilities. Here, characteristics refer to machine properties like manufacturing process, and machine location, whiles machine capabilities are max bounding box, material, accuracy, minimum wall thickness etc. An assumption here is, one machine to be virtualized as a cloud AM service. In the future, investigation will be carried out on techniques to aggregate multiple AM machines into a virtual machine and also possibility of dividing an AM machine into multiple virtual machines.

3.3. AM APPLICATION LAYER

The AM application layer provides computational and control applications required by the cloud AM services. Examples of control applications are choosing a machine for the job and monitoring the state of the machine while it is performing its task. Similarly, some computational application are maintaining a database of consumers and their respective jobs that are to be provided and provides an estimate on cost and schedule for new consumers based on their manufacturing requirements. In addition, applications can also be used to provide interactions between companies and broker. These applications are specific to a company and hence can be built on a private cloud where advanced concepts of Software as a Service (SaaS) and Infrastructure as a Service (IaaS) can be used.

3.4. BROKER LAYER

The broker layer provides with consumers, who wish to manufacture a part, with a single point of access to a large database of cloud AM services offered by different cloud AM companies. It interacts with application layer of each company to obtain information about the cloud AM services requested by the consumer. This interaction between the application layer and the broker is based on a SOA framework using web services. Broker framework is discussed in detail in the following section.

4. BROKER FOR CLOUD ADDITIVE MANUFACTURING

The framework of the proposed personal preference-based cloud AM service broker system is shown in Figure 4.1. The two main components of the framework: cloud AM service registration engine and cloud AM service selection engine.

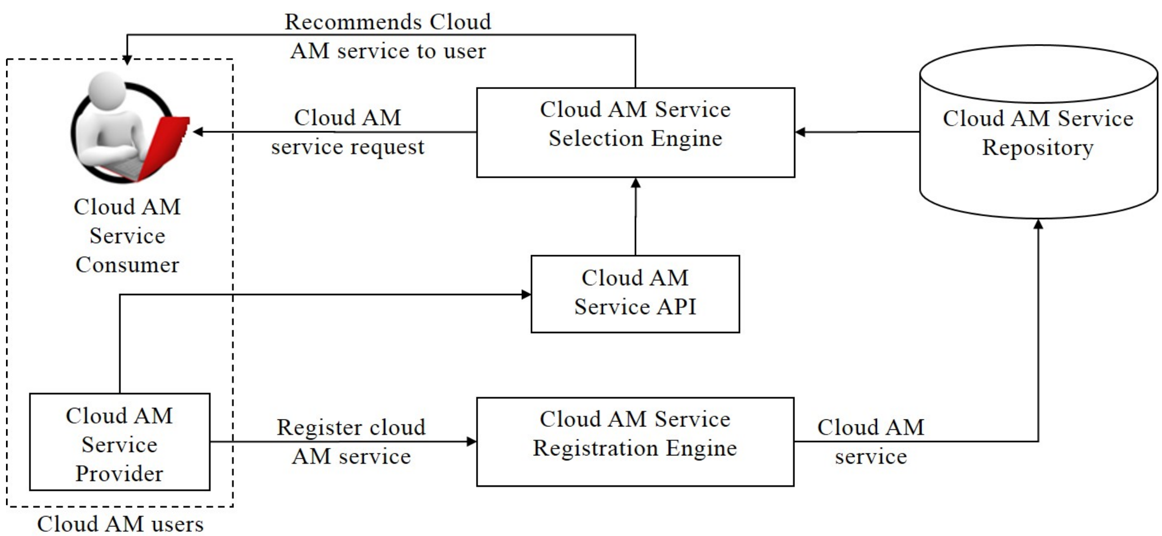

Figure 4.1. Framework of the proposed cloud AM broker system

In the proposed cloud AM service broker system, users of the system are categorized into: cloud AM service providers and cloud AM service consumers. Cloud AM service providers register their cloud AM services over the Internet using the cloud AM service registration engine. The cloud AM service registration engine creates a virtual representation of AM services of machines and stores them in cloud AM service repository based on information provided by cloud AM service providers. The virtual representation of cloud AM services offered by a machine contains static characterization of the service and its dynamic Web services, accessed by application provider interface (API).

On the other hand, cloud AM service consumers use the cloud AM service selection engine to select a cloud AM service that matches their personalized preferences and trade-off. The cloud AM service selection engine first searches the cloud AM service repository for services that can manufacture the part. It then ranks these cloud AM services, that can manufacture the part, in terms of service attributes and consumer's preferences on service attributes.

Our broker is implemented on a cloud platform using Oracle VirtualBox. Oracle VirtualBox is a cross-platform virtualization cloud platform [41]. First, a virtual machine was created using the oracle VirtualBox in this cloud platform. Next, a tomcat web application server was installed on this virtual machine and lastly the proposed web framework is deployed on the web server. Our cloud AM service broker application implements both a cloud AM service registration engine and cloud AM service selection engine. This application is developed in J2EE using the spring framework.

The major cost of the broker includes its development and infrastructure cost. Our project team spent about 18 man-months for its development. Our experimental broker is hosted in a virtual machine from a cloud platform, which costs a few thousand dollars. Both development and hosting costs of our broker are not high. The actual cost of platform hosting this type of broker in real applications depends on volumes of requests and number of cloud AM services from providers.

4.1. CLOUD AM SERVICE REGISTRATION ENGINE

This component registers all cloud AM services, supplied by cloud AM service providers, to the cloud AM service repository. The information required to register a cloud AM service include characteristics and capabilities of the machine like the number and different types of AM equipment, accuracy of each equipment, materials supported by each equipment, cost of production, and schedule. Some of these information, for instance number and different types of AM equipment and accuracy of each equipment, are static, i.e. they remain constant for each cloud AM service request. Others such as cost and schedule are dynamic because they vary with each request. Typically, each cloud AM service provider has pricing and scheduling models with which they derive the cost and schedule information. These models are confidential to the cloud AM service providers and hence are not stored in our broker system. Therefore, the cloud AM service broker stores the price and schedule information by their web service URL supplied by cloud AM service providers.

4.2. CLOUD AM SERVICE SELECTION ENGINE

This component is responsible for searching, ranking and selecting top-ranked cloud AM services to the consumer. The process used by the cloud AM service selection engine to accomplish its task is shown in Figure 4.2.

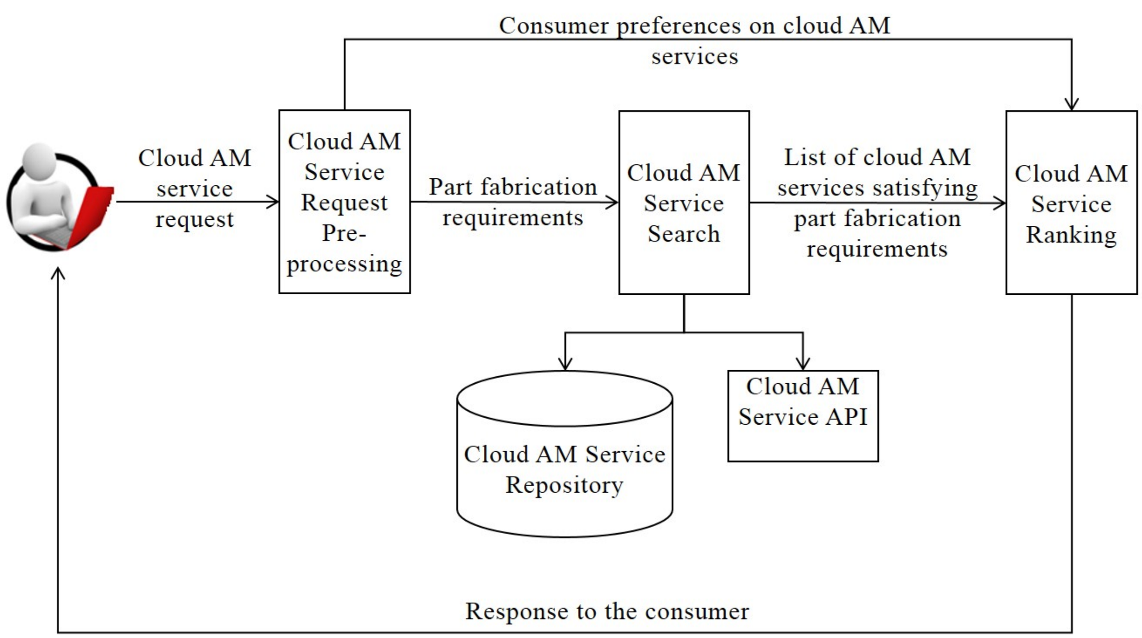

Figure 4.2. Framework of the cloud AM service selection engine

To begin with the selection process, a cloud AM service consumer submits his/her service request to the cloud AM service selection engine. Such a request usually consists of the part to be manufactured through a CAD(Computer Aided Design)/STL(STerioLithography) file which consists of a 3D model, their preference on each interested service attribute, and those service attributes they wish to trade-off. Cloud AM consumer‘s preference on a service attribute is specified as membership function which is generated from type of membership function and preferred values on the service attribute(this is discussed in detail, in section 5, how these membership functions are generated from the given inputs). For example, consumer #1 wants to manufacture the part shown in Figure 4.3 using "PLA" material, with the best accuracy at 1% or less and the lowest acceptable accuracy at 3%, with the best price at $250 or less and the highest acceptable price at $325, and with the best delivery schedule of 11 days or less and the longest acceptable delivery schedule of 15 days. Consumer #1 wants to tradeoff between price, schedule, and accuracy. Table 4.1 summarizes consumer #1‘s requests. Note that consumer #1 requests for a crisp match on material service attribute and an elastic match on other service attributes.

Figure 4.3. A sample cloud AM consumer request for running example

Table 4.1. A sample cloud AM consumer request for running example

Consumer	$R_{PartInfo}$	$R_{Attributes}$								R_{Tr}
		Material		Price ($)		Accuracy (%)		Schedule (Days)		
		Preference	Type	Preference	Type	Preference	Type	Preference	Type	
Consumer #1	Figure 4.3	PLA	C	250-325	E	1-3	E	11-15	E	P,A,S

4.2.1. Cloud AM Service Request Preprocessing. Based on the cloud AM consumer's request, the cloud AM service selection engine extracts the part fabrication requirements and preferences and trade-off on service attributes. This is accomplished by the cloud AM service pre-processing component as shown in Figure 4.2. The part fabrication requirements are those extracted from the 3D model representation of the part to be manufactured. The part fabrication requirements are extracted from the CAD or the STL file submitted by the consumer.

These requirements include the maximum part envelop (bounding box), surface area and volume. These information are extracted by the cloud AM broker system with the sole purpose of reducing the network overhead caused by transferring the entire 3D model file to all the different cloud AM service providers. X, Y, Z dimensions for the part envelop are computed using an algorithm in Selvi et al. [4]. The total surface area and volume of the part can be computed using Equations. 4.1 and 4.2, respectively, [42].

$$TotalSurfaceArea = \sum_{i=1}^{n} \frac{|t_{i12} \times t_{i13}|}{2} \tag{4.1}$$

$$Volume = \frac{1}{3} \sum_{i=1}^{n} t_{i1} . \frac{t_{i2} \times t_{i3}}{2} \tag{4.2}$$

where $t_{i12} = t_{i1} - t_{i2}$ is the vector subtraction, $t_{i13} = ti1 - ti3$ is the vector subtraction, $\times$ is a vector cross product, $|t_{i12} \times t_{i13}|$ is the magnitude of the cross product, t_i is the i^{th}

triangle in the STL file, t_{i1}, t_{i2}, and t_{i3} are the vector representations of the vertices of the i^{th} triangle in counter clockwise direction. For example, the computed total surface area and volume of the requested part in consumer #1's request are: Total Surface Area $= 161,205.62mm^2$ and Volume $= 530,519.52mm^3$.

4.2.2. Cloud AM Service Search. With the part fabrication requirement, the cloud AM service selection engine selects all the available cloud AM services that matches the requirements requested by the consumer. This is done by the cloud AM service search component (see Figure 4.2). The cloud AM service search component achieves its task by comparing the capabilities of registered equipment in the cloud AM service repository, with the part envelop, surface area and volume information of the consumer's request. For those cloud AM services that meet the consumer's part fabrication requirement, web service calls are made to obtain the dynamic service attribute information. Finally, the list of cloud AM services that satisfies the cloud AM consumer's part fabrication requirements are then sent over to the cloud AM services selection and ranking component. A sample list of cloud AM services for the requested part in our running example is given in Table 4.2.

4.2.3. Cloud AM Service Selection and Ranking. This component ranks the cloud AM services using the cloud AM consumer's preference on service attributes and top-ranked cloud AM services are selected to the consumer. The service selection is based on a fuzzy logic approach.

Table 4.2. Sample cloud AM services that can fabricate the requested part

Cloud AM Service	Company	Material	Price	Accuracy	Schedule
AMS_1	Company 1	PLA	343	0.1	14
AMS_2	Company 2	PLA	293	0.7	9
AMS_3	Company 3	PLA	327	0.3	7
AMS_4	Company 4	PLA	237	1.5	15
AMS_5	Company 5	PLA	286	1.5	12

In this approach, the cloud AM service selection and ranking component first constructs membership functions for each service attribute using the preference specified by the consumer. The cloud AM services selection and ranking component then computes the individual attribute satisfaction from the developed membership functions and subsequently computes the overall satisfaction on a service by aggregating the individual attribute satisfaction based on the trade-off strategy specified. This approach is discussed in detail in the following two sections.

To formally define the selection and ranking process, some notations are pre-defined, let $AMS = AMS_1, AMS_2, ...AMS_n$ be a list of cloud AM services that meet the consumer's part fabrication requirement and $SA = SA_1, SA_2, ...SA_m$ be a set of service attributes. Let $S(AMS_i)$ be the overall satisfaction of a service AMS_i on the consumer request and $S_M(AMS_i)$, $S_P(AMS_i)$, $S_A(AMS_i)$, and $S_S(AMS_i)$ be the material, price, accuracy, and schedule attribute satisfaction of service AMS_i on consumer request respectively.

5. GENERATION OF MEMBERSHIP FUNCTIONS AND TRADE-OFF STRATEGY

This section discusses membership function generation and trade-off strategy generation from consumer input.

5.1. MEMBERSHIP FUNCTIONS

As already discussed, membership functions have to capture the rate of change of degree of satisfaction between different values of the service attribute. In addition, different membership functions can be constructed for the same attribute variable because they represent the consumer's personal preference. Therefore, membership functions are classified into crisp and elastic membership functions. In addition, a template for each service attribute is developed which would describe the rate of change of degree of satisfaction between preferred values selected by the consumer. In the case of service attributes such as price, schedule, and accuracy, consumer's preferred value is usually specified as a single or range of values. However, with the material service attribute, material name is used to indicate consumer's preferred material.

In order to generate the membership function, consumers select the type of membership function and preferred values on the service attribute. Following sub-sections describe the how consumer preferred values and template of the membership function are used to generate a membership function for each service attribute. Later in this section, a discussion on personalized trade-off strategy generation used by the consumer is provided.

5.1.1. Material Service Attribute. Consumer indicate their preferred material using material name such as "Polyamide". This makes it challenging to compute similarities between materials, because different providers may represent the same material with different names. For example, Shapeways provides a cloud AM service with material as "White strong flexible plastic" whereas I.Materialize offers a cloud AM service in the same material as "Polyamide". Therefore similarity between materials is based on membership functions developed on material properties: tensile strength and elongation at break. Choice of these material properties is based on the availability of the property values in material datasheets of most of the materials used in additive manufacturing. These two material properties have the same template of membership function.

A crisp selection on a material preference by a consumer indicates that the consumer is willing to manufacture a part only in that material. Therefore the template of membership function on the material property "PR" (either tensile strength "T" or elongation at break "E") is as shown in Figure 5.1 (ii). In the figure, X-axis denotes value of property "PR" offered by the cloud AM service, Y-axis denotes degree of satisfaction of the cloud AM service on consumer preference on material property "PR" and 'PR_S' denotes the value of property "PR" selected by the consumer. The membership function describes that any material with the exact same value on the property "PR" as that of the selected material will have a satisfaction of 1. Material with any other value on the property "PR" except for the selected material property value will be 0.

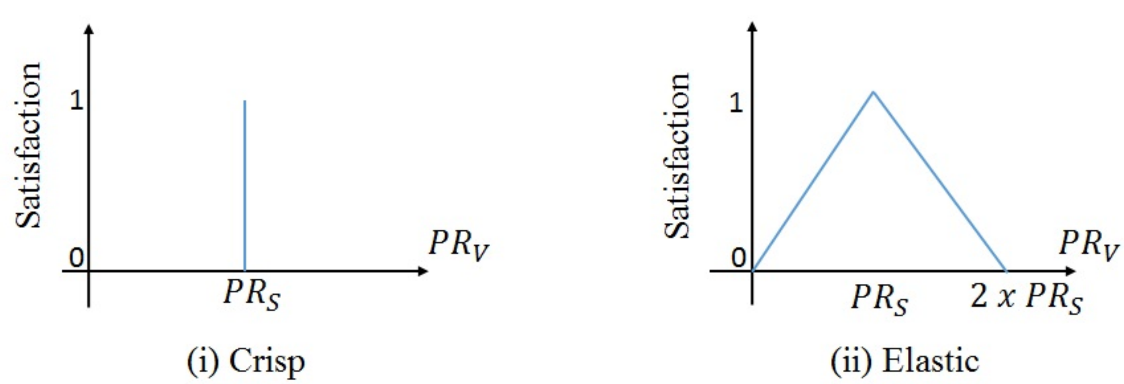

Figure 5.1. Membership functions for material service attribute

Similarly, an elastic selection on a material by a consumer indicates that the consumer is willing to manufacture a part in a material with similar property values. Here, similar means that the degree of satisfaction is 1 if the material property values are the same but the degree of satisfaction on a material decreases as the distance between its property value and selected property value increases. This is shown in Figure 5.1 (i). As shown in the figure, the degree of satisfaction reaches a 0 if the material property value "PR" reaches 0 or twice the selected material property value ('PR_S').

These membership functions are used to compute the material degree of satisfaction for a cloud AM service on each property. i.e. $S_E(AMS_i)$ and $S_T(AMS_i)$. The material satisfaction is then given by computing the average of these values, as shown in Equation 5.1.

$$S_M(AMS_i) = \frac{S_T(AMS_i) + S_E(AMS_i)}{2} \tag{5.1}$$

For consumer #1's request from running example, membership function on material properties(Tensile Strength and Elongation at Break) are as shown in Figure 5.2.

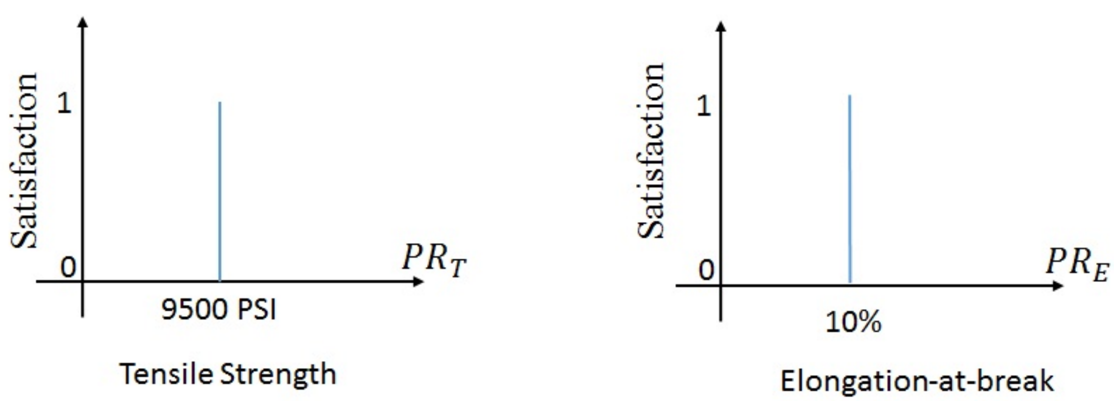

Figure 5.2. Membership functions for material service attribute

5.1.2. Accuracy, Price and Schedule Service Attributes. Price, accuracy and schedule have similar membership functions, therefore a same template definition is used for these three service attributes. For the rest of the section, a generalized notation for these three service attributes is given as $N = \{Price/Accuracy/schedule\}$. Consumer preferred value on accuracy, price and schedule service attribute for crisp type of membership function is a single value (N_S). Therefore, a crisp selection on service attribute N (price, accuracy or schedule) by a consumer indicates that the consumer is willing to manufacture the part if the service attribute value offered by the service (N_V) is less than or equal to the selected value (N_S). So, a template for the crisp membership function is developed and is shown in Figure 5.3 (ii). In the figure, Y-axis denotes the degree of satisfaction of the consumer and X-axis denotes the service attribute value offered by the service (N_V). The membership function describes that the satisfaction on service attribute N is 1 if the service offers a service attribute value less than or equal to the selected value. If the service offers a service attribute value greater than the selected value then the satisfaction on service attribute N is 0.

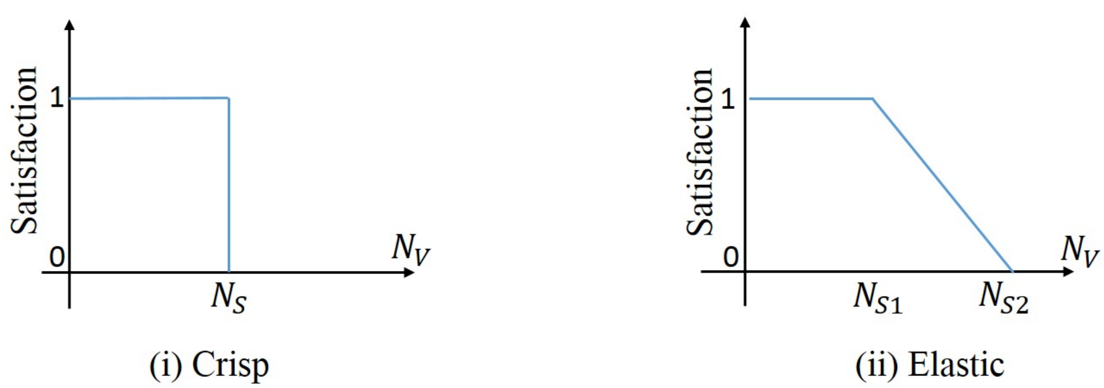

Figure 5.3. Membership functions for price, accuracy and schedule service attributes

Similarly, a consumer's preferred value on service attribute N is a range of values ($N_{S1} - N_{S2}$) for an elastic membership function. Therefore an elastic selection on service attribute N by a consumer indicates that the consumer is willing to manufacture the part if the value of N offered by the service (N_V) is less than or equal to the lower bound (N_{S1}). As the N_V increases from N_{S1} to N_{S2} the degree of satisfaction decreases from 1 to 0. If N_V is greater than the upper bound of specified range (N_{S2}) then the degree of satisfaction is 0. So, the template of membership function is developed and is shown in Figure 5.3 (i).

For consumer #1's request from running example, membership function on accuracy, price and schedule are as shown in Figure 5.4.

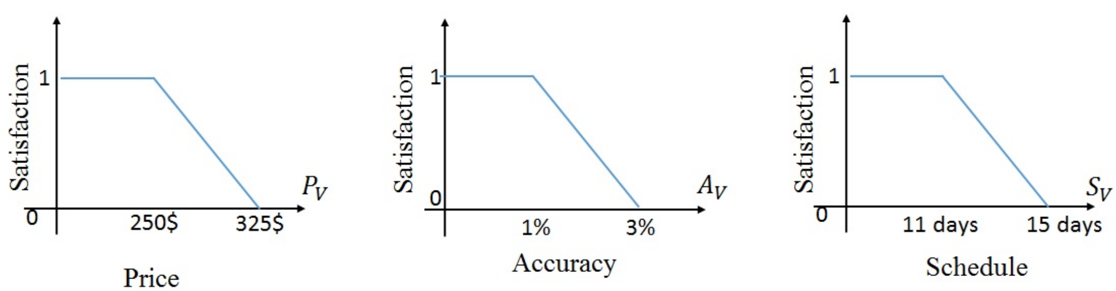

Figure 5.4. Membership functions for material service attribute

5.2. TRADE-OFF STRATEGY GENERATION

Trade-off strategy is used to compute the overall satisfaction of the service on the consumer request from individual attribute satisfaction, i.e. aggregation of individual attribute satisfaction. A "fuzzy compromise" is proposed for trade-off between conflicting service attributes and a "fuzzy And" operator for aggregating co-operating service attributes. Conflicting service attributes are attributes for which an increase in value of one attribute causes a decrease in the value of another and vice-versa, for example a decrease in the schedule delivery causes an increase in price . Co-operating service attributes are attributes for which an increase in value of one attribute causes an increase in value of the other, for example an increase in accuracy increases the price.

The consumer can choose service attributes he wishes to consider for trade-off. Service attributes selected for trade-off are formally defined as R_{Tr}. By default the other service attributes are set to service attributes not selected for trade-off. An example of a consumer request is present in Table 4.1.

6. SERVICE SELECTION AND RANKING

This section presents the service selection and ranking algorithm used by the cloud AM service broker system.

6.1. SERVICE SELECTION

The cloud AM service selection can be divided into two phases: computation of the individual degree of satisfaction on each service attribute of a service and computation of overall satisfaction on a service. Individual attribute satisfaction ($S_{SA_j}(AMS_i)$) of service attribute SA_j (where SA_j can either be material, price, accuracy or schedule) is obtained from the membership functions generated for a consumer, as described in the previous section. As an example, let us consider the first cloud AM service in Table 4.2. For consumer #1's request, individual satisfactions are,

$S_M(AMS_i) = 1$

$S_P(AMS_i) = 0$

$S_A(AMS_i) = 1$

$S_S(AMS_i) = 0.25$

The overall degree of satisfaction is computed by first aggregating the degree of satisfaction across service attributes selected for trade-off ($S_{Tr}(AMS_i)$) and aggregating the degree of satisfaction across service attributes not selected for trade-off ($S_{NTr}(AMS_i)$) individually. Aggregation of service attributes selected for trade-off is computed using a fuzzy compromise operator, i.e. an average of the satisfaction degree for all the selected service attributes. Similarly, Aggregation of service attributes not selected for trade-off is computed using a fuzzy AND operator, i.e. a minimum function of all the not selected service attributes. Then the overall degree of satisfaction ($S(AMS_i)$) is defined as the fuzzy AND of aggregation performed on trade-off service attributes ($S_{Tr}(AMS_i)$) and aggregation performed on service attributes not selected for trade-off ($S_{NTr}(AMS_i)$). This is can be explained formally as shown in the equations below:

$$S_{Tr} = \begin{cases} 1 & where R_{Tr} = \phi \\ \frac{1}{\|R_{Tr}\|} \sum_{\substack{j=1 \\ SA_j \varepsilon R_{Tr}}}^{m} S_{SA_j}(AMS_i) & where R_{Tr} \neq \phi \end{cases} \quad (6.1)$$

$$S_{NTr} = \begin{cases} 1 & where SA - R_{Tr} = \phi \\ \bigwedge_{\substack{j=1 \\ SA_j \varepsilon SA - R_{Tr}}}^{m} S_{SA_j}(AMS_i) & where SA - R_{Tr} \neq \phi \end{cases} \quad (6.2)$$

where Λ represents a MIN function [43], R_{Tr} is the set of service attributes selected for trade-off, and SA is the set of service attributes. The services with a satisfaction greater than "S_{MIN}" are selected for ranking. For this broker system "S_{MIN}" is considered to be "0.3".

For example, let us consider the first cloud AM service (AMS1) from Table 4.2. Consumer #1 wants to tradeoff between price, schedule, and accuracy. The degree of satisfaction across service attributes selected for trade-off is

$S_{Tr}(AMS_1) = \frac{1}{3}(S_P(AMS_1) + S_A(AMS_1) + S_S(AMS_1)) = 0.42$

Similarly, degree of satisfaction across service attributes not selected for trade-off is

$S_{NTr}(AMS_1) = S_M(AMS_1) = 1$

Therefore, overall degree of satisfaction of AMS_1 on consumer #1's request is

$S_{Tr}(AMS_1) = Min(S_{Tr}(AMS_1) + S_{NTr}(AMS_1)) = 0.42$

6.2. SERVICE RANKING

The ranking algorithm is to rank the cloud AM services based on the decreasing order of the overall satisfaction degree. If the overall satisfaction degree of two cloud AM services is the same, then the services are ranked on increasing order of price. To formally describe the ranking process, for a given satisfaction degree of cloud AM services $S(AMS_i)$ and $S(AMS_j)$, cloud AM services AMS_i and AMS_j can be ranked in terms of the satisfaction degree of consumer request, such that the following are true:

$$AMS_i \succ AMS_j \Leftrightarrow S(AMS_i) > S(AMS_j) \tag{6.3}$$

$$AMS_i \succ AMS_j \Leftrightarrow S_P(AMS_i) > S_P(AMS_j) AND S(AMS_i) = S(AMS_j) \tag{6.4}$$

Where, $\succ$ denotes the precedence operator.

For example, if AMS_2 has an overall satisfaction degree as 0.81 whereas AMS_1 has an overall satisfaction degree of 0.42. $AMS_2 \succ AMS_1$, indicating that AMS_2 is ranked higher than AMS_2 and thus is a preferred service. For the running example considered, Table 6.1 lists the ranking of the services given in Table 4.2 for consumer #1's request.

Table 6.1. Ranking of cloud AM services for consumer #1's request

Cloud AM Service	Company	Material	Price	Accuracy	Schedule	Degree of Satisfaction
AMS_2	Company 2	PLA	293	0.7	9	0.81
AMS_5	Company 5	PLA	286	1.5	12	0.67
AMS_3	Company 3	PLA	327	0.3	7	0.66
AMS_4	Company 4	PLA	237	1.5	15	0.58
AMS_1	Company 1	PLA	343	0.1	14	0.42

7. APPLICATION EXAMPLE

This section demonstrates how the proposed cloud AM service broker system works. For the purpose of illustration, services from Shapeways and I.Materialise were registered using both the static attributes provided on their website and the dynamic attributes through their API. To increase the number of cloud AM services registered with the broker, sample APIs for thirty companies were developed and registered using our AM registration engine. For registration of each company, sample data was provided for static information. For dynamic information, sample pricing and scheduling web services were developed and registered. These web services function in the same way as pricing and scheduling applications in layer 3 of the proposed cloud manufacturing architecture. These web services are implemented in Java using the RESTEasy framework [45]. Illustration is provided with two consumer requests which is similar to the request considered for the running example. Figure 7.1 shows the CAD file of the part to be manufactured and the consumer preferences are shown in Table 7.1. From the table, Consumer #1's request contains an exact match for all service attributes. This is to demonstrate how our proposed system ranks services when an exact match is requested on all service attributes and no service attribute is selected for trade-off.

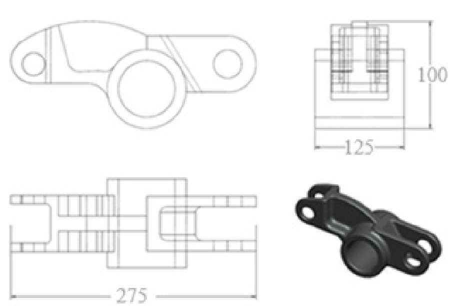

Figure 7.1. Example of a 3d model required by consumer #1

Table 7.1. Two sample cloud AM consumer requests for application example

Consumer	$R_{PartInfo}$	$R_{Attributes}$								R_{Tr}
		Material		Price ($)		Accuracy (%)		Schedule (Days)		
		Preference	Type	Preference	Type	Preference	Type	Preference	Type	
Consumer #1	Figure 7.1	PLA	C	450	C	3	C	16	C	
Consumer #2	Figure 7.1	PLA	E	350-450	E	1-3	E	12-16	E	P,A,S

On the other hand, Consumer #2's request contains varied match types on all service attributes and price, accuracy and schedule are selected for trade-off. This request shows how the proposed system handles a request with varied match types and trade-offs. Upon receiving the consumer request, our cloud AM preprocessing component extracts the part fabrication requirements and personalized preferences and trade-offs from the request. It also computes the bounding box, surface area and volume parameters from the CAD file. For the connector shown in Figure 7.1, bounding box dimensions are computed to be 275.0 mm x 125.0 mm x 100.0 mm; surface area is computed to be 113,133.09 mm2 and volume to be 727,562.97 mm3. These part fabrication requirements are sent to the cloud AM service search component, which returns available cloud AM services that meet the part fabrication requirements. The ranking of cloud AM services for the request of consumer #1 and that of consumer #2 is showed in Figure 7.2 and Figure 7.3 respectively.

Figure 7.2, since consumer #1's request is for an exact match on all service attributes, cloud AM services displayed all have a satisfaction of 1 and are ranked on price. However, it is observed from Figure 7.3 that cloud AM services with higher degrees of satisfaction on consumer #2's personalized preferences and trade-offs are ranked higher.

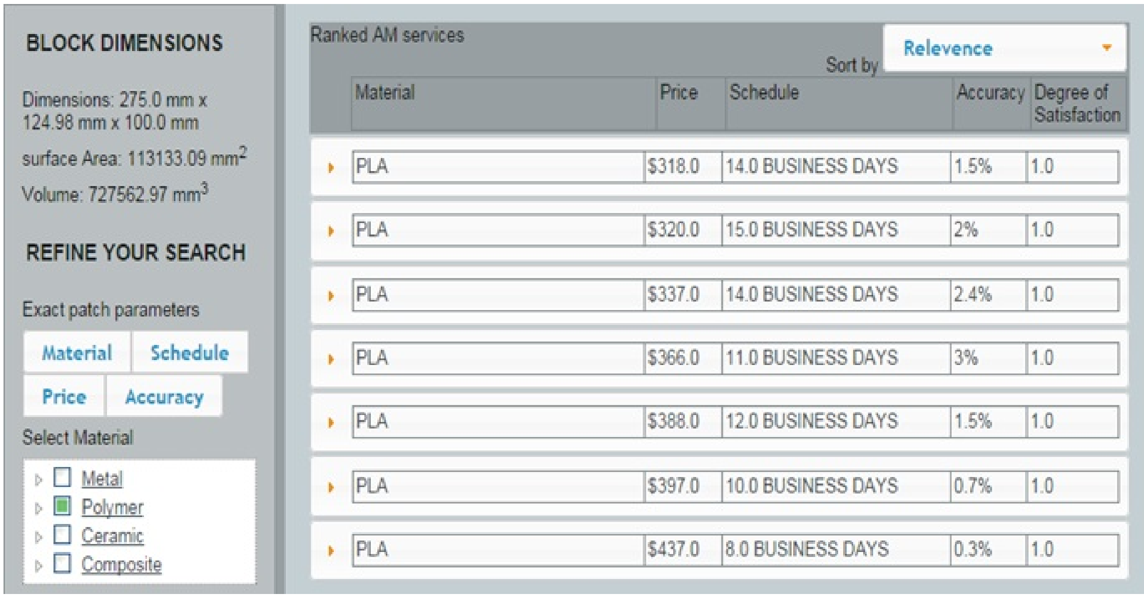

Figure 7.2. Application result for consumer #1's request

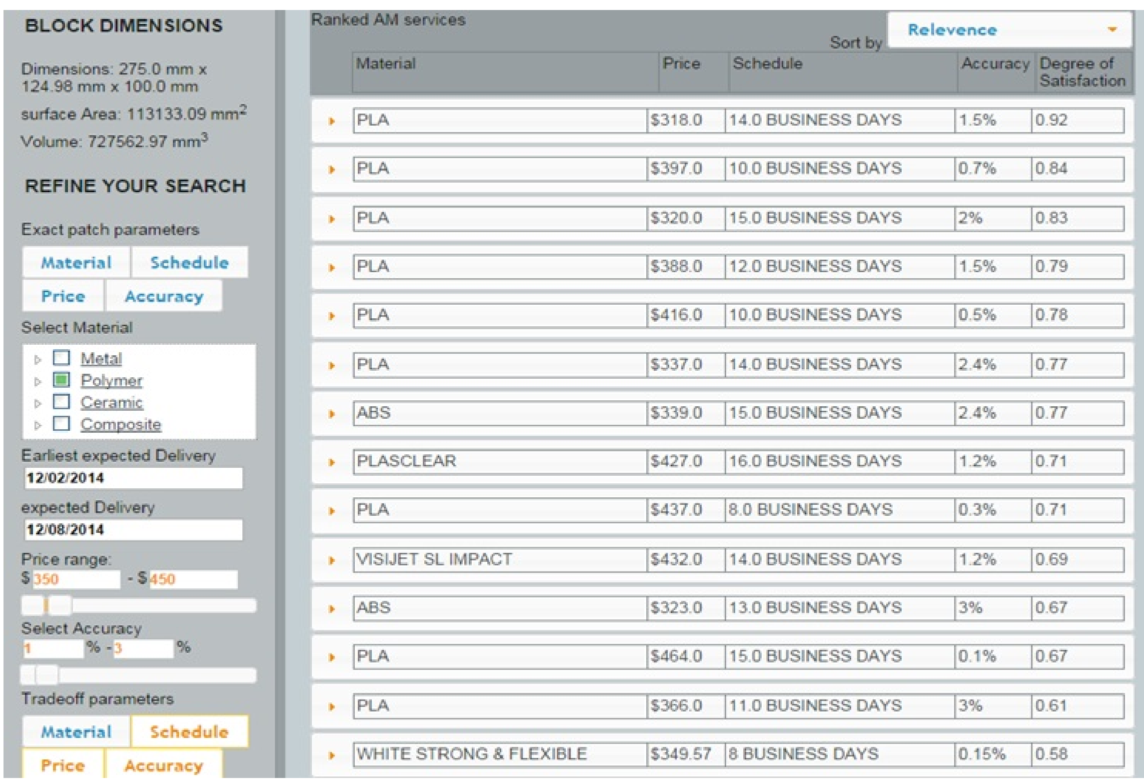

Figure 7.3. Application result for consumer #2's request

8. PERFORMANCE EVALUATION

This section firstly, discusses computational complexity of our algorithm and later presents experimental result to validate the performance of the system.

8.1. THEORETICAL ANALYSIS

Overall complexity of the ranking process can be computed by dividing service selection and ranking section into two phases: 1) computation of overall degree of satisfaction and 2) ranking. In the computation of overall degree of satisfaction phase, for each service the overall degree of satisfaction is computed by first computing the degree of satisfaction of each attribute and followed by a aggregating the individual degree of satisfaction using the personalized trade-off strategy generated by the consumer. Computation of individual degree of satisfaction is carried out from the membership function and would take 1 operation each. Aggregating the individual degree of satisfaction based on consumer's trade-off strategy, is carried out by comparing if each service attribute is selected for trade-off or not and then using the appropriate formula for aggregation. This would be carried out in 8 steps and computing overall degree of satisfaction would take 1 operation. Therefore, aggregating the individual degree of satisfaction based on consumer's trade-off strategy would be completed in 9 steps for each cloud AM service. Complexity involved in the first phase is linear hence is of the order 'O(n)', where n is the number of cloud AM services that are selected and in a worst case scenario it is equal to the number of available cloud AM services. The ranking phase involves ranking of the services based on the overall degree of satisfaction obtained. The use of merge sort algorithm to rank the services, gives an average complexity of 'O(n log n)'. Since both the phases are sequential, the overall complexity of the system can be defined as 'O(n log n)', as lower order terms can be ignored.

8.2. EXPERIMENTAL ANALYSIS

Here, performance evaluation of the service broker system under varying number of cloud AM services is discussed. An experiment was carried out in 10 iterations, where in each iteration, 10 cloud AM service providers with 100 cloud AM services were added. Response time for both selection using a single attribute (Price) and selection using all attributes and trade-off was measured for each iteration.

Figure 8.1 shows the average response time taken by the broker to respond to consumers' request at various load. In this case we consider that consumers' request contains a preference on a single attribute. Similarly, Figure 8.2 shows the average response time taken for responding to a consumer's request, considering preference on all attributes. When response time from both the graphs are compared, it is observed that the difference in response time values for both cases has a maximum of 350ms. Therefore it can be concluded that the effect of our service selection and ranking method on response time is very less. While the reason for the increase in response time is due to the number of web services the broker has to interact to obtain dynamic attribute information.

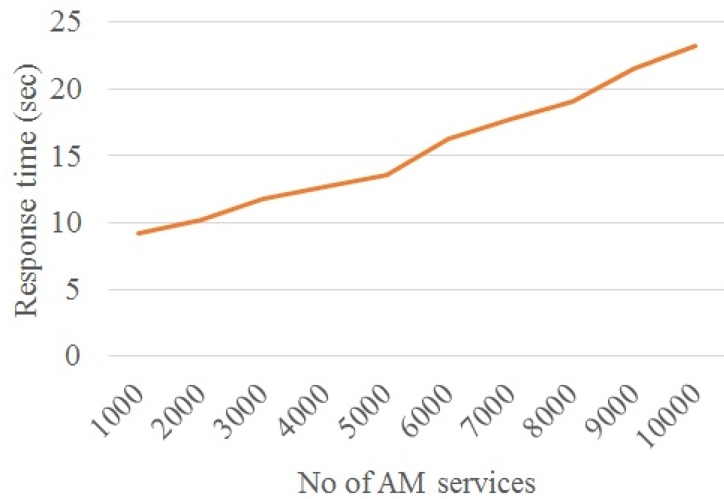

Figure 8.1. Experimental result on response time at varying loads for a consumer request on single attribute

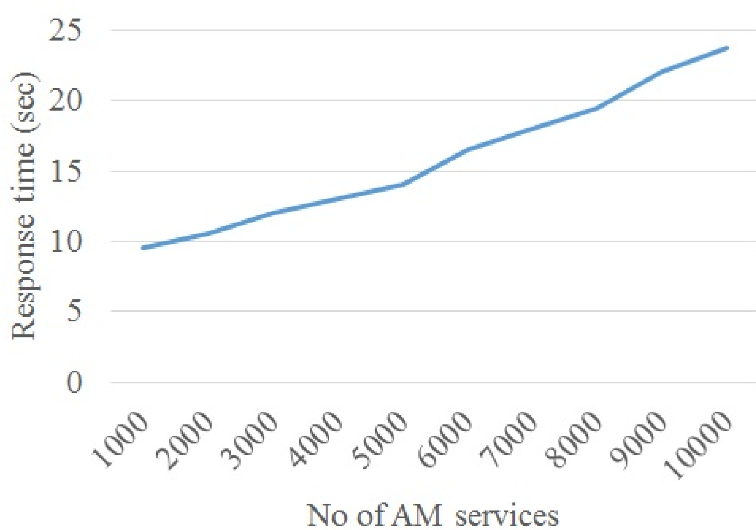

Figure 8.2. Experimental result on response time at varying loads for a consumer request on all attributes and trade-off

9. CONCLUSION

This document presents a service oriented architecture based framework of a broker for cloud additive manufacturing services. A software prototype has been developed based on the framework using web services. Our broker software system allows many cloud AM service providers to offer their cloud AM services to a large number of consumers, and it also helps consumers find their cloud AM services to meet their needs over the Internet. Cloud AM services, requested by consumers, are ranked in the order of the closest match on their personalized preferences and trade-offs. A consumer request consists of a CAD model, part material, price range, part accuracy, part schedule, and preferences of search criteria (exact or trade-off for each search criterion). A method for ranking cloud AM services in terms of AM service attributes and their trade-offs was developed. Application examples demonstrated its feasibility and applicability in cloud additive manufacturing.

BIBLIOGRAPHY

[1] Lizhe Wang, Gregor Von Laszewski, Andrew Younge, Xi He, Marcel Kunze, Jie Tao, and Cheng Fu. Cloud computing: a perspective study. *New Generation Computing*, 28(2):137–146, 2010.

[2] Shapeways. http://www.shapeways.com/, 2015. [Online; Accessed, June 12 2015].

[3] I.Materialise. http://i.materialise.com/, 2015. [Online; Accessed, June 12 2015].

[4] I. H. Selvi, T. O. Ozcelik, K. K. Fletcher, O. Iyibilgin, M. C. Leu, and X. F. Liu. A framework and prototype system for cloud-based additive manufacturing. In *International Symposium on Flexible Automation*, 2014.

[5] 3D printing price check. http://3dprintingpricecheck.com/, 2015. [Online; Accessed, June 12 2015].

[6] Xiaoqing Liu, Kenneth Kofi Fletcher, and Mingdong Tang. Service selection based on personalized preference and trade-offs among qos factors and price. In *Services Economics (SE), 2012 IEEE First International Conference on*, pages 32–39. IEEE, 2012.

[7] Xun Xu. From cloud computing to cloud manufacturing. *Robotics and computer-integrated manufacturing*, 28(1):75–86, 2012.

[8] F Tao, L Zhang, VC Venkatesh, Y Luo, and Y Cheng. Cloud manufacturing: a computing and service-oriented manufacturing model. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, page 0954405411405575, 2011.

[9] Philipp Holtewert, Rolf Wutzke, Joachim Seidelmann, and Thomas Bauernhansl. Virtual fort knox federative, secure and cloud-based platform for manufacturing. *Procedia CIRP*, 7:527–532, 2013.

[10] Yong Liang Luo, Lin Zhang, Dong Jing He, Lei Ren, and Fei Tao. Study on multi-view model for cloud manufacturing. In *Advanced Materials Research*, volume 201, pages 685–688. Trans Tech Publ, 2011.

[11] Dazhong Wu, Matthew John Greer, David W Rosen, and Dirk Schaefer. Cloud manufacturing: Strategic vision and state-of-the-art. *Journal of Manufacturing Systems*, 32(4):564–579, 2013.

[12] Dazhong Wu, David W Rosen, Lihui Wang, and Dirk Schaefer. Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation. *Computer-Aided Design*, 59:1–14, 2015.

[13] Dazhong Wu, J Lane Thames, David W Rosen, and Dirk Schaefer. Towards a cloud-based design and manufacturing paradigm: looking backward, looking forward. In *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pages 315–328. American Society of Mechanical Engineers, 2012.

[14] Lihui Wang. Machine availability monitoring and machining process planning towards cloud manufacturing. *CIRP Journal of Manufacturing Science and Technology*, 6(4):263–273, 2013.

[15] Ursula Rauschecker, Matthias Meier, Ralf Muckenhirn, Arthur Lan Kuan Yip, Ananda Prasanna Jagadeesan, and Jonathan Corney. Cloud-based manufacturing-as-a-service environment for customized products. 2011.

[16] Ponoko. https://www.ponoko.com/, 2015. [Online; Accessed, June 12 2015].

[17] Sculpteo. http://www.sculpteo.com/en/, 2015. [Online; Accessed, June 12 2015].

[18] RedProto. http://redproto.com/, 2015. [Online; Accessed, June 12 2015].

[19] RedEye. http://www.redeyeondemand.com/, 2015. [Online; Accessed, June 12 2015].

[20] Core. http://core-usa.com/rapid-prototyping/, 2015. [Online; Accessed, June 12 2015].

[21] Stella Gatziu Grivas, Tripathi Uttam Kumar, and Holger Wache. Cloud broker: Bringing intelligence into the cloud. In *Cloud Computing (CLOUD), 2010 IEEE 3rd International Conference on*, pages 544–545. IEEE, 2010.

[22] Przemyslaw Pawluk, Bradley Simmons, Michael Smit, Marin Litoiu, and Serge Mankovski. Introducing stratos: A cloud broker service. In *IEEE CLOUD*, pages 891–898, 2012.

[23] Xi Vincent Wang and Xun W Xu. Icms: a cloud-based manufacturing system. In *Cloud manufacturing*, pages 1–22. Springer, 2013.

[24] Xi Vincent Wang and Xun W Xu. An interoperable solution for cloud manufacturing. *Robotics and computer-integrated manufacturing*, 29(4):232–247, 2013.

[25] Wei-Li Lin, Chi-Chun Lo, Kuo-Ming Chao, and Muhammad Younas. Fuzzy consensus on qos in web services discovery. In *Advanced Information Networking and Applications, 2006. AINA 2006. 20th International Conference on*, volume 1, pages 791–798. IEEE, 2006.

[26] Eyhab Al-Masri and Qusay H Mahmoud. Discovering the best web service. In *Proceedings of the 16th international conference on World Wide Web*, pages 1257–1258. ACM, 2007.

[27] Eyhab Al-Masri and Qusay H Mahmoud. Qos-based discovery and ranking of web services. In *Computer Communications and Networks, 2007. ICCCN 2007. Proceedings of 16th International Conference on*, pages 529–534. IEEE, 2007.

[28] Karim Benouaret, Djamal Benslimane, and Allel Hadjali. Ws-sky: An efficient and flexible framework for qos-aware web service selection. In *Services Computing (SCC), 2012 IEEE Ninth International Conference on*, pages 146–153. IEEE, 2012.

[29] Karim Benouaret, Dimitris Sacharidis, Djamal Benslimane, and Allel Hadjali. Majority-rule-based web service selection. In *Web Information Systems Engineering-WISE 2012*, pages 689–695. Springer, 2012.

[30] Ping Wang. Qos-aware web services selection with intuitionistic fuzzy set under consumerâĂŹs vague perception. *Expert Systems with Applications*, 36(3):4460–4466, 2009.

[31] Ping Wang, Kuo-Ming Chao, and Chi-Chun Lo. On optimal decision for qos-aware composite service selection. *Expert Systems with Applications*, 37(1):440–449, 2010.

[32] M Xiuqin, S Norrozila, and R Mamta. Qos-aware web services selection with interval-valued intuitionistic fuzzy soft sets. In *Proceedings of the 2nd International Conference on Software Engineering and Computer Systems (ICSECSâĂŹ11)*, 2011.

[33] Mohammed Almulla, Kawthar Almatori, and Hamdi Yahyaoui. A qos-based fuzzy model for ranking real world web services. In *Web Services (ICWS), 2011 IEEE International Conference on*, pages 203–210. IEEE, 2011.

[34] Fei Li, Yanxiang He, Wensheng Hu, Libing Wu, and Peng Wen. Web service selection based on fuzzy qos attributes. *Journal of Computational Information Systems*, 7(1):198–205, 2011.

[35] Laiping Zhao, Yizhi Ren, Mingchu Li, and Kouichi Sakurai. Flexible service selection with user-specific qos support in service-oriented architecture. *Journal of Network and Computer Applications*, 35(3):962–973, 2012.

[36] Delnavaz Mobedpour and Chen Ding. User-centered design of a qos-based web service selection system. *Service Oriented Computing and Applications*, 7(2):117–127, 2013.

[37] Huifeng Sun, Zibin Zheng, Junliang Chen, and Michael R Lyu. Personalized web service recommendation via normal recovery collaborative filtering. *Services Computing, IEEE Transactions on*, 6(4):573–579, 2013.

[38] Xi Chen, Zibin Zheng, Xudong Liu, Zicheng Huang, and Hailong Sun. Personalized qos-aware web service recommendation and visualization. *Services Computing, IEEE Transactions on*, 6(1):35–47, 2013.

[39] Xiaoqing Liu, Manooch Azmoodeh, and Nektarios Georgalas. Specification of non-functional requirements for contract specification in the ngoss framework for quality management and product evaluation. In *Software Quality, 2007. WoSQ'07: ICSE Workshops 2007. Fifth International Workshop on*. IEEE, 2007.

[40] Kenneth K Fletcher, Xiaoqing F Liu, and Mingdong Tang. Elastic personalized non-functional attribute preference and trade-off based service selection. *ACM Transactions on the Web (TWEB)*, 9(1):1, 2015.

[41] Oracle VirtualBox Manual. https://www.virtualbox.org/manual/ch01.html, 2015. [Online; Accessed, June 12 2015].

[42] Ronald N Goldman. Area of planar polygons and volume of polyhedra. *Graphics gems II*, 2:170–171, 1991.

[43] Hans-Jürgen Zimmermann. *Fuzzy set theory and its applications*. Springer Science & Business Media, 2001.

VITA

Venkata Prashant Modekurthy earned his Bachelor degree in Electronics and Communication Engineering from Raghu Engineering College, India in 2011. After completion of his bachelor, he worked as a Test Engineer at Infosys Limited, Hyderabad, India for 2 years (till January 2014). He was a graduate student in the Computer Science Department at Missouri University of Science and Technology from January 2014, and worked as a Graduate Research assistant under Dr. Xiaoqing (Frank) Liu from March 2014, to the current date. He received his Master in Computer Science at Missouri University of Science and Technology in December 2015.