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CONCEPTUAL MODELING OF COLLABORATIVE INTELLIGENT MANUFACTURING FOR CUSTOMIZED PRODUCTS: AN ONTOGICAL APPORACH

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Abstract

Mass customization is implemented to provide outstanding service to customers with diverse tastes and preferences. However, mass customization has limitations in the traditional value chain and production paradigm. Taking advantage of advanced information technology, such as manufacturing grid and virtual enterprise, to facilitate mass customization and improve the customer perceived valued of mass customization raises a challenge issue. To achieve an ideal mass customization, the customer's needs should be identified and met by the collaborative manufacturing from several manufacturers. Comprehensive conceptual models corresponding to the collaborative manufacturing for customized products are essential to understand how the collaborative process can apply in customized production, and facilitate early detection and correction of system development errors. In this paper, an ontology is described via a customized bicycle buying scenario to describe how to use an ontology for collaborative manufacturing. This ontological approach provides understanding of the domain, which can be used as a unifying framework to represent the selected phenomena for conceptual model.

Keywords: Collaborative intelligent manufacturing, Mass customization, Conceptual Model, Ontology.

1 INTRODUCTION

Today's market environment is characterized by diverse customer tastes and preferences. People are no longer willing to sacrifice their preferences but are looking for exactly what they want and need (Pine 1993). Advanced manufacturing systems are evolving towards a more agile environment that can make quick responses to the changing market environment and customer requirements.

Mass customization, relating to the ability to provide tremendous variety and individual customization (Pine 1993), is implemented by many companies to gain a significant competitive advantage (Kotha 1995). Some researchers argue that mass customization should provide customers with whatever they want, whenever they want it, wherever they want it and however they want it. However, as customers and their needs grow increasingly diverse, the degree of product variety is controlled prudently in industry practice (Moozakis 2002). This phenomenon is caused by the limitations of traditional value chain and production paradigm of mass customization (Zipkin 2001). Researches have suggested that the problems lie in both the supply side (i.e. the concerns of scale economies and costs mentioned in Randall & Ulrich 2001) and the demand side (i.e. the problem of variants cannibalization stated in Hui 2004, Moorthy 1984). And also, transformations and revolutions by adopting advanced information technologies are carried out to improve mass customization (i.e. Frutos & Borenstein 2004, Turowski 2002).

With the development of manufacturing systems, some advanced manufacturing systems and concepts are introduced, such as manufacturing grid, virtual enterprise, holonic manufacturing (Camarinha-Matos & Afsannanesh 1999, van Brussel et al 1998, Ding & Tao & Sheng & Zhou 2008). These technologies are improving the manufacturing efficiency to the changing market environment and customer requirements. Taking advantage of these advanced technologies to facilitate mass customization and improve the customer-perceived value of mass customization raises a challenge issue. Having many common and even complementary characteristics, these concepts are not necessarily contradictory. Combinations of these approaches are possible, and may help to achieve a collaborative intelligent manufacturing for a more successful mass customization.

However, little attention has been paid to how such collaborative manufacturing can better solve the problem of product variety to improve the mass customization. In this paper, we will first describe a collaborative manufacturing process for customized production. And then the corresponding conceptual model of collaborative intelligent manufacturing for customized product is presented via ontological approach. After describing the unifying ontological framework, the entities' attributes and interrelationships in this ontology, which are embedded in process of service customization and service composition, will be discussed in detail. Description and conceptual modelling of such collaborative process could provide deeper understanding of the application of collaborative manufacturing in personalized production, and facilitate early detection and correction of system development errors.

After a brief review of the related literature, the collaborative process for customized product is presented in section 3. And we will give the ontology in section 4. Conclusions and future work are presented in section 5.

2 RELATED WORK

Manufacturing systems are evolving towards a more agile environment that can make quick responses to the rapidly changing customer requirements and market environment. More and more manufacturers today focus only on their core competencies, while depending on other firms to provide the complementary expertise and resources. In collaborative manufacturing, designated individuals and organizations, both internal to the manufacturing enterprise and extended to its suppliers, customers, and partners, work together for mutual gain[1]. The concept of virtual enterprise is defined to describe such a temporary alliance of independent organizations and enterprises that come together to share skills and resources to better provide a product or service (Camarinha-Matos & Afsannanesh 1999). Also, a highly distributed control paradigm, the Holonic Manufacturing Systems (HMS), was proposed in 1994 by the HMS consortium[2]. The HMS architecture enables self-configuration, extension and modification of the system, and allows more flexibility and a larger decision space for higher control levels (van Brussel et al 1998). The concept of grid computing brought about a new manufacturing model – Manufacturing grid. The aim of the manufacturing grid is to effectively utilize resources distributed in heterogeneous systems and different places. Through the services provided by the manufacturing grid, users can obtain various manufacturing services as conveniently as obtaining information from the internet (Ding & Tao & Sheng & Zhou 2008).

The above approaches for collaborative manufacturing have many common and even complementary characteristics. With the distributed and intelligent feature of collaborative manufacturing, agent technology has been recognized as a promising paradigm for collaborative intelligent manufacturing systems. A mobile agent-based ICT architecture was provided for the flexibility requirement of virtual enterprises by Aerts et al. (2002). Agent technology was also employed to the optimal-selection evaluation in manufacturing grid resources (Ding & Tao & Sheng & Zhou 2008). For the applications of agent technology to HMS, readers can refer to the work of Marik et al. (2003) and Deen (2003) for detailed reviews. Shen et al. (1998, 2006) provided thorough reviews on agent-based systems in intelligent manufacturing.

The gap in literature of collaborative manufacturing, which is also the main focus of this paper, is how collaborative manufacturing can better solve the problem of product variety and improve the mass customization. Conceptual modelling is a potential means to better understand this problem solving process. Conceptual models, which are mostly graphic representing both static phenomena and dynamic phenomena in some domain, are used to support communication between developers and users, to help analyst understand a domain, and to provide an input to systems design (Wand & Weber 2002, Xu & Wang & Wang 2005). Conceptual modelling, using the techniques from knowledge representation (KR) and KR language, is to present generic representations of domain knowledge that can be reused across a variety of enterprise, guiding the design the design, development, and investment decisions. High-quality conceptual modelling work is important because it not only provides a better understanding of the domain, but also facilitates early detection and correction of system development errors. For instance, the means of constructing a formal conceptual model of business transactions within virtual markets was studied using Telos (Wang 1997). This model is used to gain, not only a concise understanding of the key features of virtual markets on the information superhighway, but also to consider the design and implementation of such systems. Lin and Harding (2007) developed a general manufacturing system engineering knowledge representation scheme, which would facilitate communication and information exchange in inter-enterprise, multi-disciplinary engineering design teams. The grid service was also modelled in an object orientation based semantic model (Kumar & Neogi & Ram 2006). To better conceptual modelling the collaborative manufacturing for customized product, we will first give a description of the collaborative process, and then give a formal representing model by the ontological approach.

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[1] White Paper: Collaborative Manufacturing Explained from MESA Internal. http://www.mesa.org/, 2004

[2] HMS research community is organized around the international HMS consortium (http://hms.ifw.uni-hannover.de/), one of the projects under the Intelligent Manufacturing Systems program (http://www.ims.org/).

3 COLLABORATIVE MANUFACTURING PROCESS FOR CUSTOMIZED PRODUCT

In this section, a scenario will be used to demonstrate how collaborative manufacturing facilitate mass customization, and improve the customer-perceived value of mass customization.

Let us suppose a customer ("CT") is interested in acquiring a customized bicycle. Figure 1 shows a traditional value chain of mass customization. Producer provides a set of product or component variants on the web service. When consumer finishes his product configuration on the web configuration system, the manufacturers produce the product and deliver to consumer[3]. Within the traditional value train of mass customization, the consumers could do the product configuration according to their preferences. However, the producers can not provide full degree of product variety because of costs and cannibalization effects. Consumers may only choose limited set of frame types and colours for his customized bicycle. For example, CT would like his customized bicycle be made of "Titanium TY12" frame, and be painted with "ColourType32". If there are not any manufacturer providing both "Titanium TY12" and "ColourType32", CT has to sacrifice his preference and choose the other options offered by manufacturer.

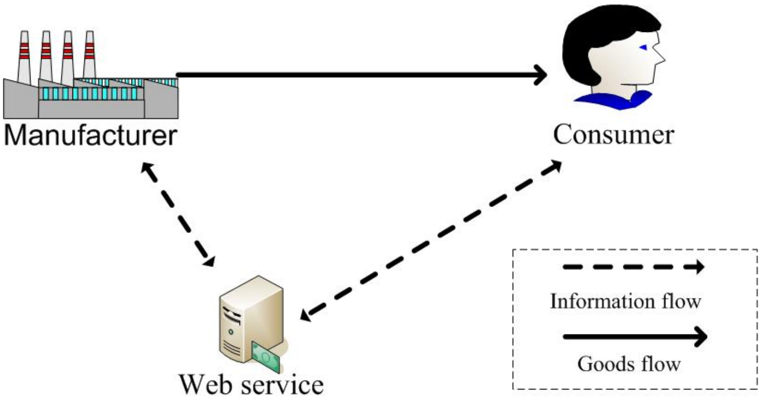

Figure 1. The traditional value train of mass customization.

In collaborative manufacturing, each producers focus on their core competence, so as to minimize their production cost and market mediating costs. A typical collaboration manufacturing for customized production is shown in figure 2.

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[3] Many companies still have the traditional chain of producer, wholesaler, retailer, and consumer. However, the application of E-commerce has become a trend in mass customization, so in this paper, we omit the wholesaler and retailer in the value chain of mass customization

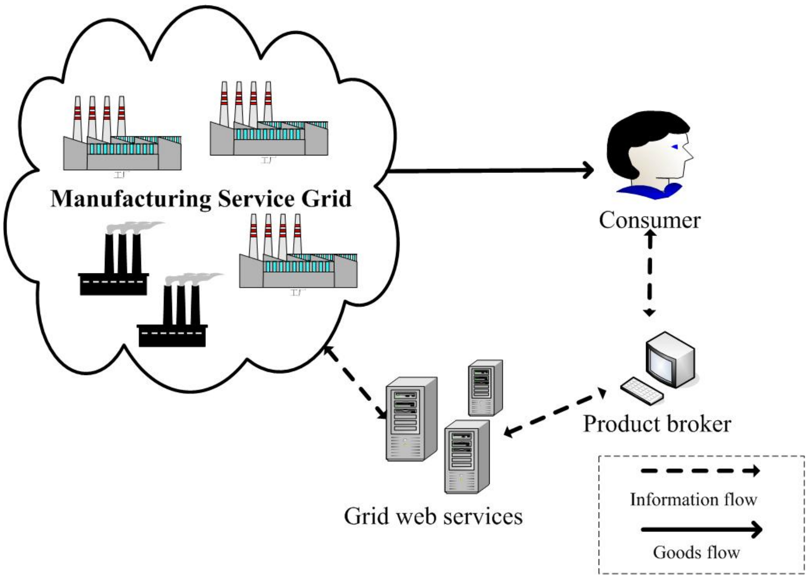

Figure 2. *Collaborative manufacturing for customized production*

The major components are manufacturing service grid, grid web services, and product broker. Manufacturing service grid is composed of manufacturers all over the world, which focuses on its core manufacturing competence and offers special manufacturing services. The information of these manufacturing services are all encapsulated in the grid web services, with well defined interface using WSDL, a standardized messaging protocol such as SOAP, and a service address that a requester can use to access the service. The grid web services can be accessed and invoked programmatically by software agents. The product broker is such a software agent that could help consumers customize their product and find the corresponding manufacturing services.

With this novel value chain, we have the scenario and transaction stated below:

Stage 1: Product development verification.

The customer "CT" wants his customized bicycle, so he asks help to the product broker. With its domain knowledge, the product broker tells CT the three generic production tasks which bicycle production requires: frame fabrication, frame painting, and bicycle assembly; these tasks must be performed in this order. Frame fabrication consists of cutting and welding tubes into unfinished frames. Frame painting consists of adding colour to frames and applying decals and a final clear finish. In assembly, components such as wheels, tires, suspension, and drive trains are attached to the finished frame. Firms need not collocate operations.

The consumers could add some additional production tasks to meet his individual needs. In this scenario, we assume the CT accepts the three production tasks and does not need any more additional production tasks.

Stage 2: Product broker self development.

After the product development verification, the product broker duplicates into 3 sub-brokers: frame broker, painting broker and assembly broker. All these 3 sub-brokers are responsible to the bicycle production broker, and will search the corresponding manufacturing services.

Stage 3: Manufacturing services verification.

Searching and finding the corresponding manufacturing services in the manufacturing grid services, the product broker will offer a set of available manufacturing services for frame fabrication, painting and assembly. The customer DL could either choose the services himself according to his preferences or delegate the product broker to choose the favourite services by the agent's negotiation. In this scenario, we assume DL chooses manufacturer M1 which is the only frame provider of "Titanium

TY12” frame to do the frame fabrication, manufacturer M2 which provides painting of ColourType32 to paint the frame, and Manufacturer M3 to do the assembly work.

Stage 4: Producing and delivery.

After the completion of the manufacturing services verification, M1, M2, M3 will carry out their manufacturing services in order. The physical distribution network (such as UPS) will be responsible for the transportation among M1, M2 and M3. After the production, the finished customized bicycle will ship to CT.

The main difference between traditional mass customization and collaboration manufacturing for customized production is that the manufacturing service the latter offered is separated into several subtasks and finished by the collaboration of corresponding manufacturing services, while the production of the former is dominated by an individual manufacturer. Such feature provides the following benefits:

- Producers could focus on their core competencies. By efficiently producing its core product, the producer could reduce the production cost and the response time.
- Without handling other aspects of business activities, the producers could reduce market mediation costs.
- The customer could control the order-to-delivery time to his need by agent’s negotiation with corresponding manufacturing services.
- Consumers, as innovators, achieve a higher free to “design” their product. Not only more product variety could be produced by collaborative manufacturing, customers could even design their products by adding new production tasks.
- The autonomous agent and services’ interaction lower co-ordination costs.

4 ONTOLOGY

Within the information systems field, the task of conceptual modelling involves building a representation of selected phenomena in the domain (Wang & Weber, 2002). Ontologies refer to the shared understanding of some domain of interest which can be used as a unifying framework to represent the selected phenomena. An ontology necessarily entails or embodies some sort of world view with respect to a given domain. The world view, referred as a conceptualisation, is often conceived as a set of concepts (e.g. entities, attributes, and processes), their definitions and their inter-relationships (Uschold & Gruninger 1996).

4.1 Concepts organization

The ontology of collaborative manufacturing for customized production has been designed to model the foundation for collaborative manufacturing applications, which have been captured in four key based classes: Consumer Class, Product Broker Class, Manufacturing Service Class, and Distribution Service Class. A portion of semantic schema of the collaborative manufacturing for customized production is shown in Figure 3. The subset of the overall collaborative manufacturing schema is sufficient to demonstrate the ontology. Because of the complexity of this figure in mind, many links, such as Is_a, Instance_of, Object_property and Dataype_property, have been omitted.

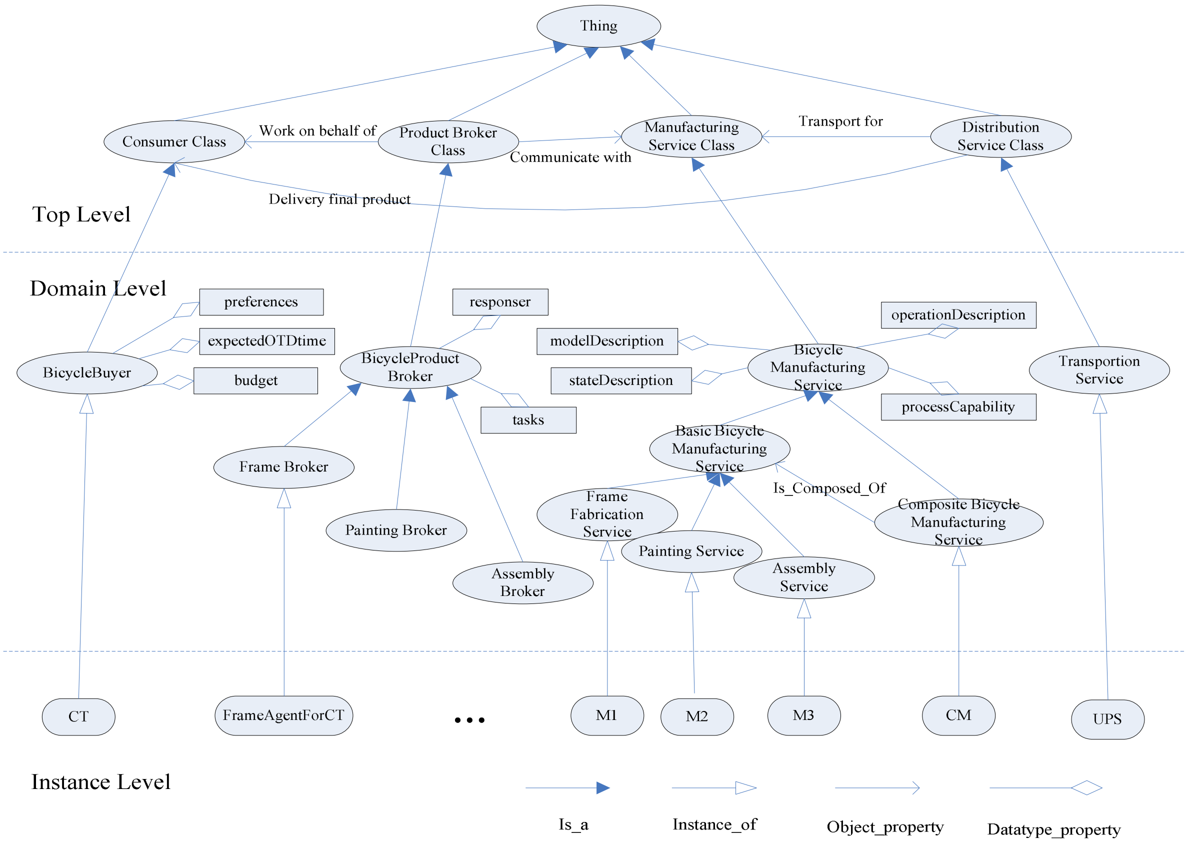

Figure 3. A partial schema

The ontology which represents the collaborative manufacturing for customized production is produced in three levels: Top Level, Domain Level, and Instance Level. The entities at the instance level correspond to the instances of domain classes, while the domain classes inherit the attributes from top level classes. For example, the object property of finalGoodDelivery (omitted in Fig. 3) at the instance level is instances of a domain level object property "delivery final product", which in turn inherits from the top level object property.

Web Ontology Language (OWL)[4] could be used to model the collaborative manufacturing from this schema. The main advantages of OWL, which has become a widely used ontology language for the semantic web, are efficient reasoning support, sufficient expressive power, and convenient expression.

In the OWL DL definition, the subClassOf keyword shows the inheritance hierarchies of domain concepts. Table 1 shows an example of OWL definition of class Manufacturing_Service_Class.

```
<!-- http://www.semanticweb.org/ontologies/2008/1/Ontology1203231410743.owl#Manufacturing_Service_Class -->

<owl:Class rdf:about="#Manufacturing_Service_Class">
   <rdfs:subClassOf rdf:resource="&owl;Thing"/>
   <owl:disjointWith rdf:resource="#Distribution_Service_Class"/>
   <owl:disjointWith rdf:resource="#Consumer_Class"/>
   </owl:Class>
```

Table 1. The OWL DL definition of class Manufacturing_Service_Class

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[4] OWL Web Ontology Language Reference, Available on line as http://www.w3.org/TR/owl-ref/

A property defines a directed relationship from a resource to a resource or literal. OWL distinguishes two types of properties: (1) an "object property" linking a resource to a resource, and (2) a "datatype property" linking a resource to a literal. Table 2 and Table 3 show the examples of the OWL DL definitions of object property and datatype property.

```
<!-- http://www.semanticweb.org/ontologies/2008/1/Ontology1203231410743.owl#communicate_with -->

<owl:ObjectProperty rdf:about="#communicate_with">
  <rdfs:range rdf:resource="#Manufacturing_Service_Class"/>
  <rdfs:domain rdf:resource="#Product_Broker_Class"/>
</owl:ObjectProperty>
```

Table 2. The OWL DL definition of ObjectProperty communicate_with

```
<!-- http://www.semanticweb.org/ontologies/2008/1/Ontology1203231410743.owl#state_description -->

<owl:DatatypeProperty rdf:about="#state_description">
  <rdfs:domain rdf:resource="#Manufacturing_Service_Class"/>
  <rdfs:range rdf:resource="&xsd;string"/>
</owl:DatatypeProperty>
```

Table 3. The OWL DL definition of DatatypeProperty state_description

For instance, the datatype property of a manufacturing service class consists of an optional modelDescription, a stateDescription and an operationDescription. The modelDescription describes the general information about the service type, while the stateDescription defines the internal state maintained by the manufacturing service. The operationDescription is a 4-tuple <I, O, C, E> (Kumar & Neogi & Ram 2006), I and O represent the data elements accepted by the service during invocation and made available after the invocation of this operation respectively. C is the set of conditions that should be true for this operation to be invoked. E is a set of expressions that become true after the invocation of this operation. For the painting service in the scenario, the <I, O, C, E> in simplified form would be <Frame, ColouredFrame, ColourTypeAvailable, AssemblyServiceAssigned>. The datatype property and object property of class have the features of inheritance and polymorphism, which we will further discuss in the next section.

4.2 Manufacturing service customization

The characteristics of inheritance and polymorphism in the ontology can be used to provide differentiated and customized manufacturing service to different client. As manufacturers focus on their core competences, the manufacturing services they provided would evolve to incorporate changing requirements. Interface inheritance can be effectively applied to enable different clients of same service to experience different behaviour. For instance, the manufacturer M1 in the scenario is a bicycle manufacturer. However, its core competence is its frame fabrication technology. It could provide the shape of “Titanium TY12” frame, which other bicycle manufacturers can not provide. Corresponding to the domain level, frame fabrication service is modelled with the inheritance and polymorphism from bicycle manufacturing service, which is shown in Figure 4. The frame agent for CT, which is an instance of Frame Broker, would negotiate with M1 service for the frame fabrication service.

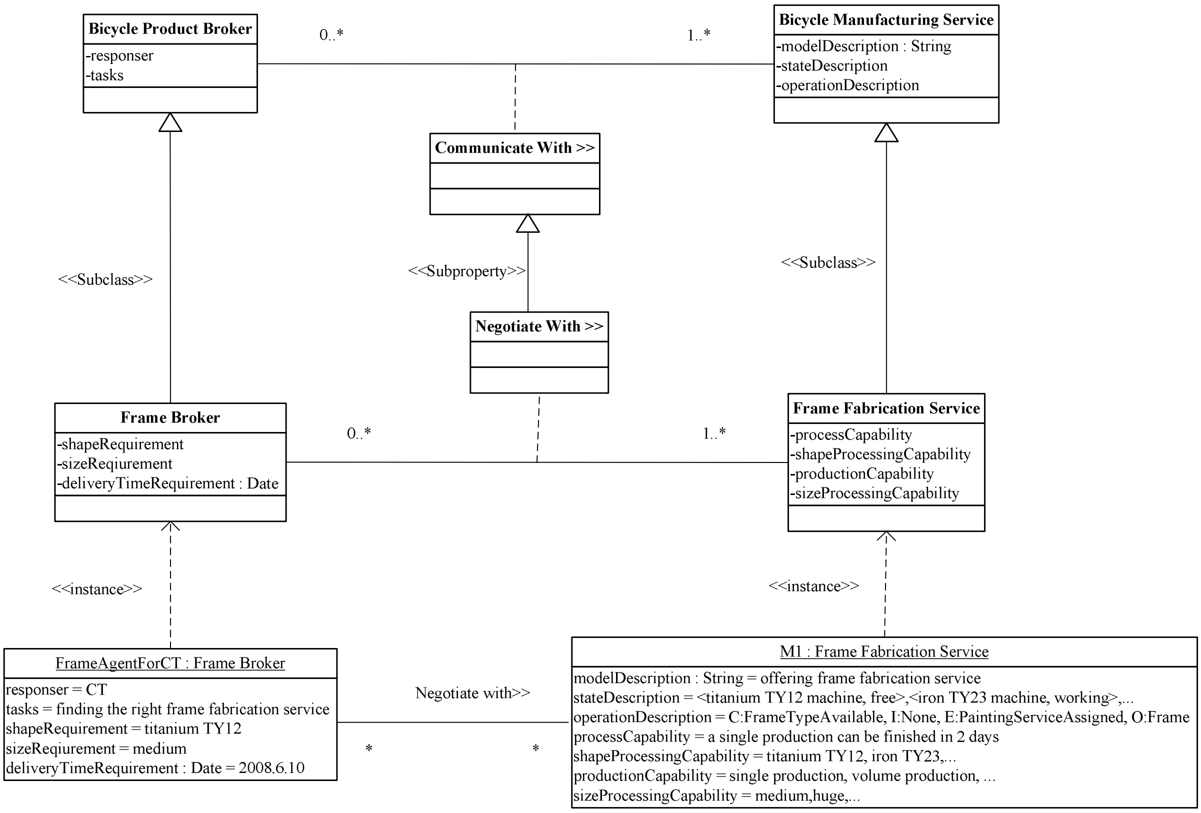

Figure 4. Inheritance and polymorphism of the manufacturing services

Given a base Manufacturing Service MS_{base} and the derived Manufacturing Service $MS_{derived}$., $MS_{derived}$ may add new properties to the set of properties inherited from MS_{base}. For instance, in Figure 4, there are new properties of processCability, shapeProcessingCapability, productionCapability, sizeProcessingCapability in the Frame Fabrication Service. On another hand, the derived service can maintain additional state elements (such as the specific machine working state), apart from the state inherited from the base service.

4.3 Manufacturing service composition

Collaborative manufacturing is achieved by manufacturing service composition. In Figure 3, the class of Composite_Bicycle_Manufacturing_Service has an ObjectProperty of “is_composed_of” to the class of “Basic_Bicycle_Manufacturing_Service”, which demonstrates the service composition. In the former scenario, given a set of Manufacturing Services, M_1, M_2, M_3, a composite manufacturing service CM can be composed using the following axioms:

- The state of a composite manufacturing service is a union of the state maintained by its component services. SDCM = SD1□SD2□SD3, where SDCM = stateDescription (CM) and SDi = stateDescription (Mi).
- The operationDescription ODCM of the composite manufacturing service is composed from those operationsDescription ODi of Mi, i=1,2,3. The workflow is ODCM = OD1⊕OD2⊕OD3, where “⊕” stands for composition. <I, O, C, E> of ODCM are composed as below:
    - ICM = {e | e □ Ij □ e ∉ Ok, j,k = M1, M2, M3}, where (Ij □ ODj) □(Ik □ ODk) □(k≺j). This means that the set of input elements of ODCM consists of input elements of all the operations involved minus those which occur as output elements of a preceding operation in the workflow.

- OCM = {e | e □ Oj □ e ∉ Ik, j,k = M1, M2, M3}, where (Ij □ ODj) □(Ik □ ODk) □ (j ≺ k). This means that the set of output elements of ODCM consists of output elements that become available through all the operations involved minus those which occur as input elements of a preceding operation.
- CCM = {p | (p □ Cj) □ (¬∃ s, (s => p) □ (s □ Ek)), j, k = M1, M2, M3}, where (Cj□ ODj) □ (Ek□ ODk)□(k ≺ j). This means the set of preconditions of ODCM consists of all the preconditions of the operations involved minus those which get satisfied by effects of a preceding operation involved.
- ECM = {t | (t □Ej) □ (¬∃ s, (s = ¬ t) □ (s □ Ek)), j, k = M1, M2, M3}.This means the set of effects of ODCM consists of all the effects of operations involved after canceling out those that negate each other.

5 CONCLUSION

In this paper, an ontology is described via a customized bicycle buying scenario to describe how to use an ontology for collaborative manufacturing. This ontological approach provides understanding of the domain which can be used as a unifying framework to represent the selected phenomena for conceptual model. The collaborative manufacturing process for customized product has the following features benefiting both producers and customers:

- Separation of production tasks facilitates producers to focus on their core competencies and efficient production, reducing the production and operating cost, market mediation costs and response time.
- The degree of product variety is enlarged by collaborative manufacturing, and the customer has the greater freedom to customize their product.
- Mediated by autonomous agent and services, the co-ordination costs of the transaction are reduced. Furthermore, customer could have a more satisfied order-to-delivery time by the agent's negotiation.

The conceptual model of the collaborative manufacturing is important, which not only provides a better understanding of how collaborative manufacturing could improve mass customization, but also facilitate early detection and correction of system development errors, and could be further developed to serve as a foundation for an architecture enabling information integration of collaborative manufacturing. The development of such a formal conceptual model provides the basis for formal study of collaborative manufacturing for customized products. In future work, the implicit schedule problem contained in the manufacturing process will be considered, and the system building of manufacturing grid and product broker will be considered.

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