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ORIGINAL ARTICLE

An ontology-based product design framework for manufacturability verification and knowledge reuse

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Abstract

To achieve efficient development of high-quality product, manufacturing constraints must be fully taken into account at the early design stage. However, designers lack in-depth knowledge of manufacturing and production. Many time-consuming iterations of design changes are required between designers and manufacturing engineers. In order to minimize this knowledge gap, this paper presents an ontology-based product design framework for manufacturability verification and knowledge reuse to support the sharing and reuse of design and manufacturing knowledge. It aims at providing advices and feedback of restraints of manufacturing processes to the designers during the design process. The proposed framework consists of three major layers which include a foundation layer, a domain layer, and an instance layer. We use the Web Ontology Language (OWL), a standard of ontology representation language, to formalize the foundation layer. It contains the core product model and the standard ISO 10303 AP224 application protocol. The domain layer comprises extensional concepts and relationships for design and manufacturing integration and a rule base for manufacturability verification, which is represented in Semantic Web Rule Language (SWRL). In the instance layer, an inference engine is developed based on ontology and rule inference. It provides recommendations of manufacturability. Two case studies are provided as application examples to demonstrate the effectiveness of the framework.

Keywords Ontology · Manufacturability verification · Product design · Manufacturing knowledge · Computer-aided design (CAD) · Knowledge management

1 Introduction

With the increasing pressure of competition in new product development, a successful enterprise needs to provide rapid response to the dynamic market. In order to shorten the entire production life cycle to maintain the enterprise's competitive advantage, one of the effective methods is to reduce the time of product design process. However, design process intensely involves deep knowledge and massive information from different domains, such as design, manufacturing, and production, which requires multi-disciplinary cooperation among different departments [1]. The designers may only consider the feasibility of the design, but not take the actual situation of manufacturing into account. On the other hand, the manufacturing engineers may only focus on the manufacturing and production constraints, but do not take the aesthetic and design concepts into consideration. The knowledge and information exists in diverse formats and perceptions among different domains, in which people may get confused and have bias based on their own domain expertise [2]. This causes serious communication problems to teamwork that is based on knowledge exchange. Much design rework is due to the fact that the designed products could not be manufactured as specified, or because they could be manufactured in a much more rational way if they were changed [3]. Many time-consuming iterations of redesigns are required between the processes of design and production, which cannot meet the

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This paper is an extension of a paper presented in Faim2016.

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needs of rapid product development. Therefore, a unified product design framework, which enables effective knowledge sharing and reuse, is essential to minimize the number of iterations. There are two main challenges of this study. First, it is necessary to develop a rational and clear knowledge representation for heterogeneous design and manufacturability knowledge so that the knowledge can be acquired and shared easily. Secondly, the acquired knowledge can be easily retrieved and applied so that it can be effectively reused for assisting product designers during the design process.

In the past decades, Ontology and the Semantic Web are commonly adopted in the manufacturing domain to support design knowledge representation and application [4]. Ontology is one of the most popular technologies in the field of information science. It is a domain-specific specification of conceptualization with a formal representation of a set of classes, relations, functions, and object constants [5]. It supports domain knowledge structure analysis and knowledge sharing activities based on well-structured domain knowledge. There is research related to ontologies of products [6], particular components and features [7], customer needs [8], assembly knowledge [1], and other manufacturing processes (e.g., [9]). In particular, Web Ontology Language (OWL) is an ontology description language that has gained widespread adoption in many different industries [10]. On the other hand, Semantic Web technologies provide methods to make ontology to be easily shared and reused across different applications and domains [11]. There are also use cases in proposing different emerging Semantic Web technologies for knowledge reasoning in the manufacturing domain [4]. In particular, Semantic Web Rule Language (SWRL) has been developed for rule-based systems from the Semantic Web perspective [12]. The combination of SWRL and OWL provides high inference capabilities based on description logics [13, 14].

The pioneering studies have made great contributions to product design. However, most researches focus on expressing the knowledge in the process of design and manufacturing separately [15] and concentrate on operating in semantic level [3]. They focus on modeling and organization of knowledge, but there is lack of consideration of reuse of knowledge [9]. In this study, we proposed to combine OWL and SWRL to develop an ontology-based product design (OBPD) framework for manufacturability verification and knowledge reuse. We represent the design and manufacturing knowledge into ontologies by OWL. We then incorporate the ontologies with SWRL so that the knowledge of design and manufacturing can be mapped and combined in terms of constraint rules and inference rules. Hence, the framework can provide clear and timely design recommendations to designers during the design process as well as facilitate the manufacturing process planning. Compared with other manufacturability verification methods, such as XML-based method and supporting software tool, ontology-based method considers manufacturability in the design process and achieves reasoning process from manufacturing to design.

This paper has three key contributions. First, it proposes an ontology-based product design framework for manufacturability verification. Contrast to the existing frameworks, the proposed framework use standardized and formal ontology language which facilitate the computation, sharing and maintenance of knowledge. Comparing to the existing frameworks that divide engineering design and manufacturing system separately, the proposed framework aims to make use of the existing manufacturing knowledge to assist design to minimize the iteration during the design and manufacturing stages. Second, by using SWRL, a rule base of manufacturability verification is established. Contrast to the existing framework, the proposed framework allows the maintenance of the rule base by the users rather than fixed rules provided by the software providers. It enables customization as well as continuous update of the rule base. Third, the applicability and flexibility of the framework are demonstrated through a prototype system.

The paper is organized as follows. Section 2 provides a quick overview of related work. Section 3 presents a three-layer ontology framework to verify manufacturability. Two design cases, which exploit the configuration provided by the proposed framework to validate the applicability of the ontology-based product design framework, are provided in Sect. 4. Conclusions and possible further research are discussed in Sect. 5.

2 Literature review

2.1 Design systems

Product design is a process in which products are designed by teams of people in single or multiple companies [16]. There are two basic design models. One is proposed by Pahl and Beitz [17], which present a systematic design approach including four core design phases: product planning, conceptual design, embodiment design, and detail design. The other one is proposed by Ulrich and Eppinger [18], which incorporate prototype testing, refinement, and production ramp-up into the Pahl and Beitz approach. Many researchers have proposed different incremental variations or modifications based on these two models.

Designers use computers to design products since the 1960s [19]. They are standalone systems, which operate on large and expensive computers and generate 2D drawings. Later on, due to the advancement of computing technology, the design systems can be operate on affordable personal desktop computers and perform 3D modeling. In 1980s and 1990s, with the advancement of Internet, web-based design systems are available [20]. Distributed system and sharing of decentralized computing resources became possible. The system provider can provide easy update of the design systems. Collaborative concurrent product design is available [21]. In the last decade, cloud technology emerges, it enables cloud-based design by using cloud computing, software-as-a-service, and pay-per-use business model [22].

2.2 Manufacturing systems

For manufacturing systems, similar evolvement happens due to the emerging technologies. It changes from assembly line from 1900s to flexible manufacturing systems in 1980s, to web-based and agent-based manufacturing systems in 2000s, and to cloud-based manufacturing systems in the last decade [16]. It is worth to note that the manufacturing systems also changed from centralized manufacturing to distributed manufacturing. In centralized manufacturing, it requires significant changes in machine tools, manufacturing plant layouts, and business models, which is usually costly. For web-based systems and cloud-based systems, they allow users to collaborate and share data instantly. Data is stored, maintained, and synchronized automatically [16].

2.3 Applications of ontology in manufacturing

The research applying Ontology and the Semantic Web for knowledge management in manufacturing industry can be divided into the development of domain ontologies, the proposal of ontological modeling and frameworks, and the development of specific applications.

The development of domain ontologies helps to explicitly represent the domain knowledge in a computational format, which enhance the ability to create, share and exchange knowledge between different applications and domains [23]. Štorga et al. [24] provided a detailed methodology on how to build a design ontology for the more efficient product development. In [1], they investigated the knowledge activities on design and assembly process planning domains. They developed a mechanism to formulate multi-perspective assembly knowledge into formal ontologies so as to support concept knowledge acquisition and sharing across the domains. In the paper of [7], they study the knowledge of a particular feature. They proposed an ontology to represent the knowledge of composite positional tolerance for patterns of holes by using OWL and SWRL. They expressed constraint knowledge with rules, and described individual knowledge using description logic. In [3], they investigated shape features of components for knowledge sharing. They built ontologies by analyzing the associated manufacturability knowledge with the shape features.

Some research focus on modeling of knowledge sharing process for manufacturing systems. In [9], the paper presented a product modeling and knowledge organization method for managing conceptual design in the early stage in the product design process. The product modeling integrated physical quantity model and feature-based representation model based on the generalized assembly model. [25] built an ontology-based design tool for universal design process in the conceptual design phase. It is developed by analyzing the knowledge processing and representation of the convergence cognitive strategies and cognitive needs of designers. In [26], they presents a model-driven architecture (MDA) to model the semantic concepts from multiple knowledge bases of product and manufacturing information platforms based on a rule-based ontology language. The development of such model helped the utilization of expressive ontology language to enable the verification of knowledge. In the paper of [27], the authors suggested that collaborative manufacturing requires integration of heterogeneous product knowledge. They hence introduced a structure of ontology schema of knowledge concept on manufacturing knowledge for a collaborative business process. They integrated the knowledge by an ontology integration method composed of ontology mapping and ontology merging based on ontology similarity between local ontology and global ontology.

In summary, the existing literature considers the establishment of the design and manufacturing ontology on the foundation ontology separately, which uses the terms in their respective fields to define a same concept. In addition, they put more emphasis on the concept of sharing, the mapping, and the reuse of knowledge of design and manufacturability is relatively less concern.

3 Ontology-based product design framework

Figure 1 illustrates the ontology-based product design framework. The purpose of the developed framework is to achieve effective integration between design knowledge and manufacturing knowledge. It aims to guide designers with reasonable design advice based on knowledge of manufacturing constraint. The framework mainly consists of three layers: (1) foundation layer, (2) domain layer, and (3) instance layer. The foundation layer is mainly composed of the core product model (CPM) and the ISO 10303 AP224 standard, which converts core design knowledge and core manufacturing knowledge into core design ontology and core manufacturing ontology. It defines general concepts, relationships, and restrictions for the entire framework. The domain layer is adapted according to different custom application areas. It consists of customized design ontology, customized manufacturing ontology, and the mapping between their common concepts. Semantic rules of both design and manufacturing are also built and stored in this layer. In the instance layer, it consists of an inference engine for performing ontology

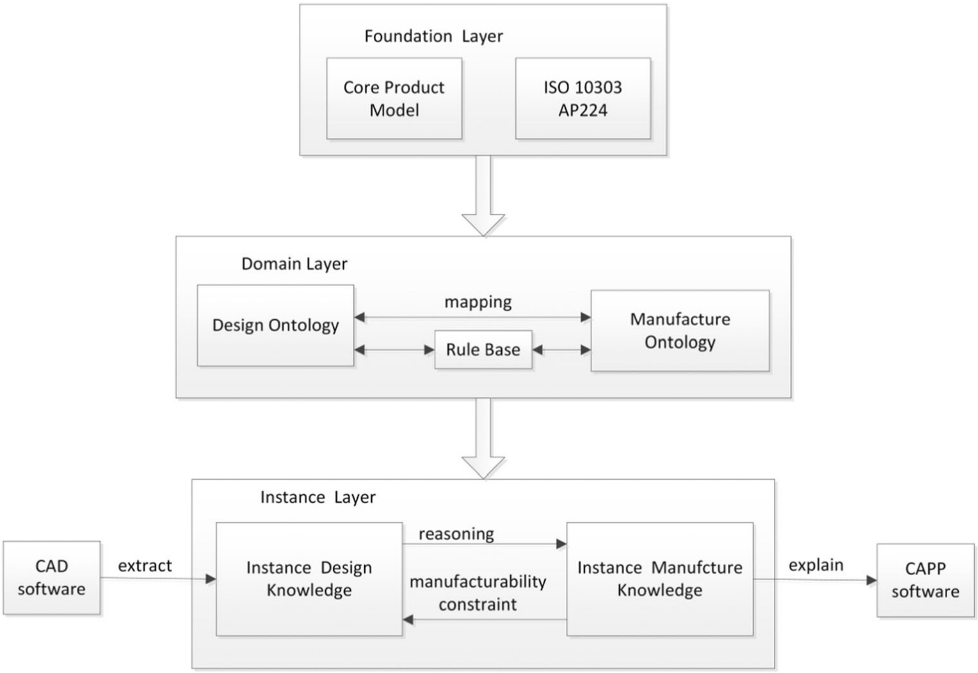


Fig. 1 Ontology-based product design framework

reasoning. When there is a new design, the features and parameters will be extracted from the CAD software. The inference engine will then make use of the semantic rules and ontologies in domain layer to infer the new design's manufacturability and provide redesign recommendations when it is necessary. The recommended results will then be converted into OWL and fed back to the CAD software. If no redesign is needed, the OWL file that consists of recommended manufacturing process will then be imported by CAPP software for further processing planning.

3.1 Foundation layer

To capture generic core design and manufacturing concepts, the foundation layer is mainly composed of the CPM, Standard for the Exchange of Product model data, (STEP) and Web Ontology Web Language (OWL) as shown in Fig. 2. The CPM is a generic and abstract model with generic semantics which describes the generic information of component features of different products about a particular domain. It was built on an earlier work of product representations described in [28]. The CPM supports the semantics of form and function of the component features [29]. STEP consists of a wide range of application protocols, such as representation of explicit drafting, mechanical design, shipbuilding, and process planning [30] In most of existing studies, there is no general international standard for defining the core concepts of design. The STEP 10303 AP224 standard (Mechanical product definition for process plans using machining features) is adopted in the present study. The STEP 10303 AP224 standard is an ISO standard for the computer-interpretable representation and exchange of product manufacturing information [31]. It defines a wide range of features and supports the integration between design and manufacturing. It can be easily linked with other existing ontologies. Therefore, it is considered as a good starting point for building customized ontologies. The core concepts from CPM and STEP 10303 AP224 are extracted, and the relations and logical axioms among the extracted core concepts are also determined in the foundation layer.

The OWL Web Ontology Language is a W3C standard, which is designed for improving machine interpretability and easing computational processing of content of different computational applications [32]. It is used to explicitly represent the meaning of terms in concepts and the relationships between those concepts. In the present study, based on the extracted concepts from CPM and STEP, OWL is used to represent the knowledge of core design and core manufacturing as core design ontology and core manufacturing ontology, respectively. These foundation ontologies help to provide global restrictions and clear definitions for the entire framework to reduce the ambiguity and confusion based on different semantic meaning of a term. Thus, the knowledge providers can build their own ontologies with a common foundation, which enhance the efficiency of communication and knowledge sharing. Figure 3 shows an example of a foundation ontology built based on OWL by an ontology editor (Protégé). It shows the relationships among the identified concepts. Figure 4 is an example of core data properties hierarchy of the foundation layer, which specifies the core design knowledge. Data property "size_dimensions" has its sub data properties, such as "diameter," "height," "hole_depth,"

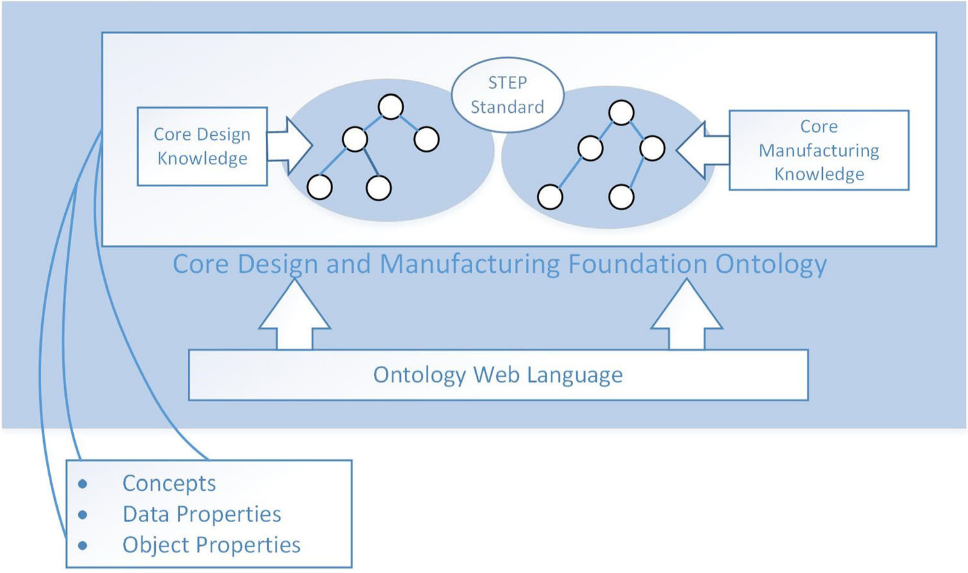


Fig. 2 Foundation layer of the OBPD framework

"length," and "width." Figure 5 shows an example of core object properties of the foundation layer, which specifies the core manufacturing knowledge. Object property "machined_by" has its sub object properties, such as "drilled_by," "welded_by," "milled_by," "planed_by," and "turned_by."

3.2 Domain layer

The domain layer consists of design ontology, manufacturing ontology, the mapping between the ontologies, and their related semantic rules.

3.2.1 Design ontology

Design ontology is specialized from the core design ontology from the foundation layer. The foundation design ontology can be considered as an abstract format that consists of abstracted classes and properties, while design ontology of domain layer is more specific which is customized based on domain knowledge and custom application. For example, as shown in Fig. 6, a component with round hole can be further divided into centered drilled hole, blind hole, counter bore hole, etc. The domain design ontology also specifies the relative positions of different features of components. There are many ways to represent the relative positions of the features. In this study, we used a common approach, absolute coordinates, to represent the position of the reference points for each feature, and use *x*-, *y*-, and *z*-axis to indicate the direction of the reference line at the reference point. So that different features can form a complete component through their reference points and reference lines. Similarly, the reference points are defined by the class of the ontology, and the subclasses of the reference points are x, y, z coordinates. The class reference lines are hence defined and the subclasses of reference lines are the *x*-axis, the *y*-axis, and the *z*-axis, respectively. Moreover, the domain design ontology specifies the data properties of features of the components. As is shown in Fig. 7, data properties are formalized by OWL. It consists of concrete value that specifying different attributes for each

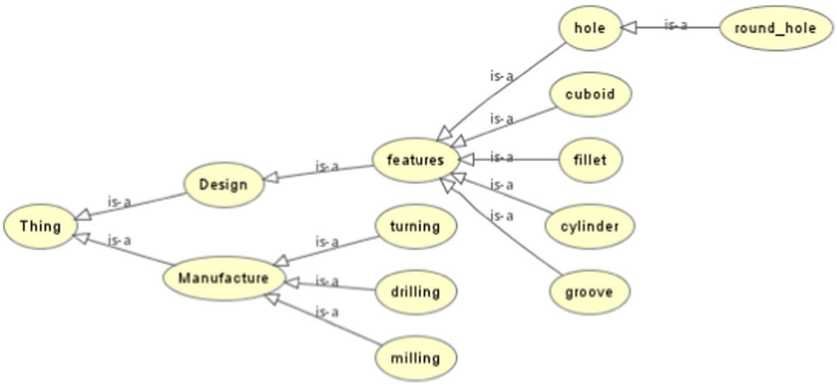
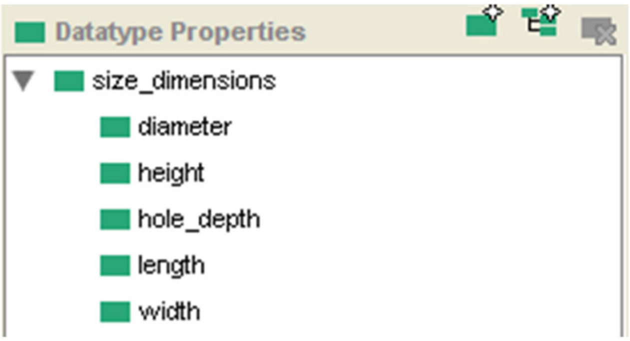


Fig. 3 Core concepts of the foundation layer



Datatype Properties
- size_dimensions
  - diameter
  - height
  - hole_depth
  - length
  - width

Fig. 4 Core data properties of the foundation layer

feature referring. The data type could be integer, float, or enumeration. As a formal language with description logic-based semantics, OWL can ease computation and enable automatic inference about the inconsistencies of the concepts [7]. Its XML presentation syntax as well as an RDF concrete syntax makes it simple for exchange data between different computational systems. So that the knowledge can be understood by both design application and manufacturing application. It is also used to restrict the dimensions and many other feature requirements based on custom domain setting, which helps to facilitate the verification of design during the design process by minimizing the iterations of knowledge retrieve, exchange, and application.

3.2.2 Manufacturing ontology and mapping

A component is required to be manufactured by going through many different processes, such as turning, drilling, and grinding. In the manufacturing ontology of domain layer, some abstracted manufacturing processes can be subdivided into further specified processes. For example, as shown in Fig. 6, a drilling process can be divided into ordinary drilling, reaming drilling, expanding drilling, and screwing drilling. Each processing step involves a lot of knowledge, for example, turning knowledge including speed, feed rate, cutting depth, the characteristics of the cutting tool, machines, and materials. They are formalized by OWL, which is similar to that of design ontology, in order to restrict the criteria or availability of different manufacturing processes provided by the custom domain and application.

Object properties
- machined_by
  - drilled_by
  - welded_by
  - milled_by
  - planed_by
  - turned_by

Fig. 5 Core object properties of the foundation layer

The design ontology and the manufacturing ontology are related based on a concept mapping mechanism that consists of object properties between design features and manufacturing processes. As shown in Fig. 6, the object properties are also encoded in OWL format, which specify the relations between the design features and manufacturing process. It is the center link for mapping manufacturing knowledge with design knowledge. Each feature corresponds to one or more specified processes. For example, a groove should be manufactured by milling.

3.2.3 Rule base

In order to provide design recommendations for manufacturability verification of different designs, a rule base is needed for storing expert rules that are defined based on design and manufacturing knowledge. A rule-based modeling language, semantic web rule language (SWRL), is selected in the present study. SWRL is a rule-based ontology language for the Semantic Web. It is developed based on a combination of the OWL and the Rule Markup Language [12]; hence, it can work closely with the OWL-based ontologies. SWRL enables the definition of declarative rules by invoking the concepts of the design and manufacturing ontologies and inferring knowledge of design recommendations. SWRL is used in this study because of its extensibility and expressiveness. In product design, users are usually making extensive use of rules. They may want to restrict the form or expressiveness of the rules they employ. SWRL allows high interoperability, reusability, extensibility, computational scalability, or ease of implementation [12]. Based on the classes and properties which have been defined in the design and manufacturing ontologies in the OWL, the relations between design feature parameter and manufacturing constrains are mapped and represented in SWRL. The rule base stores two major types of rules which are inference rules and constraint rules. Inference rules are used to infer design parameters and/or manufacturing processes. The rules are defined by the designers and the manufacturers based on their knowledge. For example, rule (1) means that if there is a hole with diameter less than 10 mm, then it can be machined by drilling.

- (Rule 1) hole(?x) ∧ diameter(?x,?y) ∧ swrlb:lessThan(?y,10) ∧ drilling(?z)→machined_by(?x,?z)

On the other hand, constraint rules are rules to restrict design parameters and/or manufacturing processes. They can be divided into process constraints, capacity constraints, and

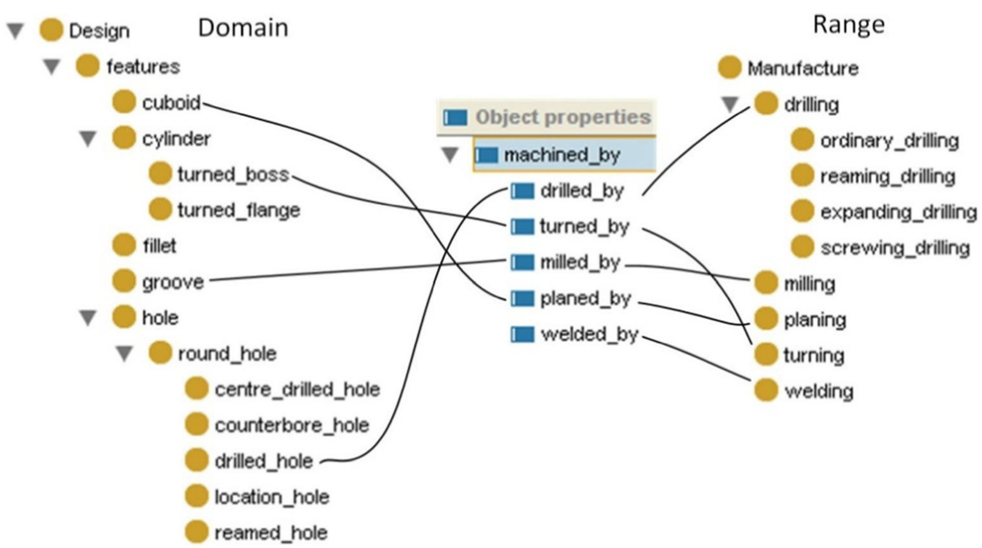


Fig. 6 Mapping between design and manufacture ontologies through object properties

process constraints. For example, rule (2) means that if there is a hole with diameter larger than 70 mm and it is going to use drilling, then the hole is oversized.

- (Rule 2) hole(?x) ∧ diameter(?x,?y) ∧ ordinary_drilling(?z) ∧ drilled_by(?x,?z) ∧ swrlb:greaterThan(?y, 70) → has_irrationnality(?x, "oversize")

3.3 Instance layer

As shown in Fig. 8, the instance layer is the application tier which mainly consists of an extraction module of parameters from CAD software, an instantiation module of design knowledge, a instantiation module of manufacturing, an inference engine, and a recommendation module for redesign and suggested manufacturing processes.

During the instantiation process, the feature parameters and process parameters are extracted from CAD and assigned with definite values. At the same time, the instance of product design knowledge and manufacturing knowledge are instantiated with domain ontology class. The parameter values will then be bound by the ontologies of domain ontologies to consider manufacturability. When there is a conflict with domain ontologies, an alert will be prompted for redesign of the related feature. As is shown in Fig. 9, the turned_boss class has instance turned_boss_A and instance turned_boss_B. The diameter and height of turned_boss_A is 80.0 and 20.0, respectively. And the diameter and height of turned_boss_A is 75.0 and 20.0, respectively.

Fig. 7 Data properties formalized by OWL

```
<owl:DatatypeProperty rdf:ID="length">
  <rdfs:subPropertyOf>
    <owl:DatatypeProperty rdf:ID="size_dimensions"/>
  </rdfs:subPropertyOf>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="depth">
  <rdfs:subPropertyOf rdf:resource="#size_dimensions"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="diameter">
  <rdfs:subPropertyOf rdf:resource="#size_dimensions"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="height">|
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
  <rdfs:subPropertyOf rdf:resource="#size_dimensions"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="irrationnality"/>
<owl:DatatypeProperty rdf:ID="size_irrationnality">
  <rdfs:subPropertyOf rdf:resource="#irrationnality"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="roughness_irrationnality">
  <rdfs:subPropertyOf rdf:resource="#irrationnality"/>
</owl:DatatypeProperty>
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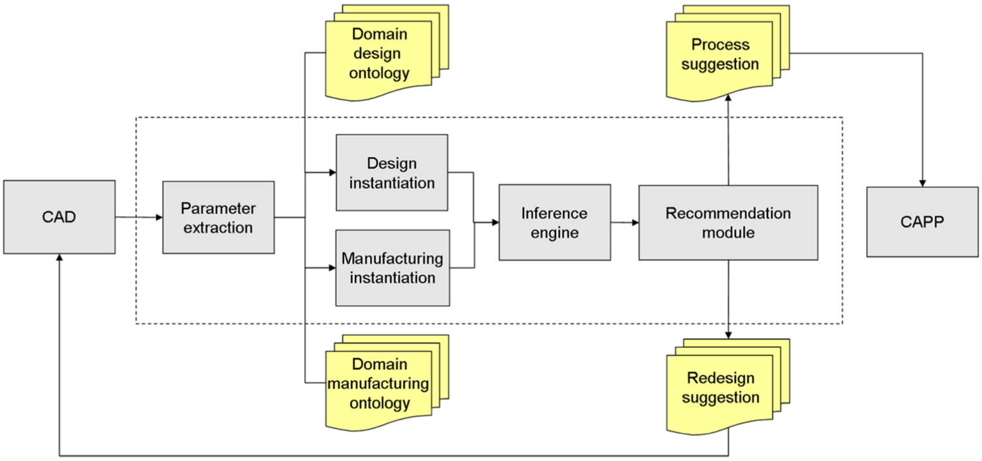


Fig. 8 Instance layer of the OBPD framework

In order to realize the inference of expert rules for manufacturability verification, the Java Expert System Shell (JESS) is employed in this work to perform reasoning process. JESS is a popular rule-based expert system shell written entirely in Java, which is tightly coupled with the powerful and portable Java language [33]. It has been adopted in many different applications for the development of rule-based expert system [34]. After the instantiation process, the parameters and the SWRL rules are transformed into the JESS's format for inference. The inferred results will then be converted back to OWL. Based on the design recommendation, it will be either feedback to the CAD for redesign, or it will be passed to the specified CAPP software interface for further processing.

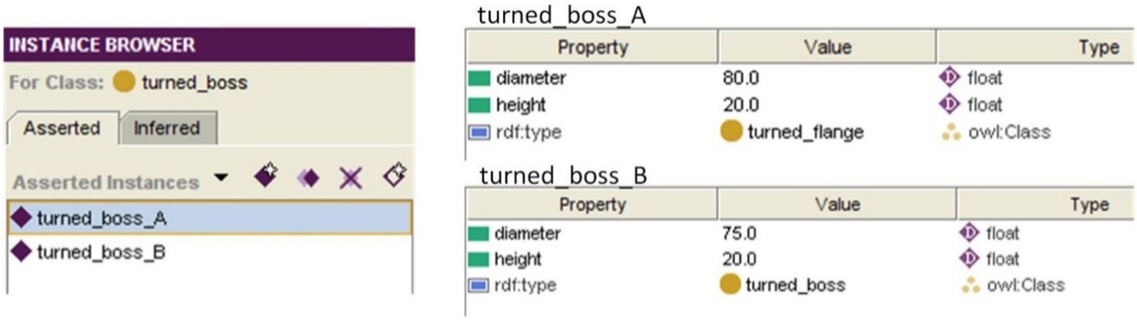
4 Case studies

In order to demonstrate the effectiveness of the OBPD framework, two case studies are provided.

4.1 Case study 1

Case study 1 presents a design of a bearing block. It is mechanical component that requires going through a series of manufacturing processes after casting. The drawing of the component is shown in Fig. 10. There are four drilled holes, two counter bore holes, one fillet, one bearing hole, and one groove required machining. The drilled holes and counter bore holes should be drilled by drilling machine; the fillet should be machined by turning machine; and the bearing hole and groove need to be fine machined by milling machine in order to reach the required roughness.

We extract the related core design knowledge and core manufacturing knowledge into core design ontology and core manufacturing ontology from the core product model (CPM) and the ISO 10303 AP224 standard as described in Sect. 3. We construct the core concepts, core data properties, and core object properties of the foundation layer. We then formulae and map the design ontology and manufacturing ontology in the domain layer. Lastly, we construct the constraint rules based on the manufacturing knowledge. Based on the OBPD, there



For Class: turned_boss

turned_boss_A
turned_boss_B

turned_boss_A

Property	Value	Type
diameter	80.0	float
height	20.0	float
rdf:type	turned_flange	owl:Class

turned_boss_B

Property	Value	Type
diameter	75.0	float
height	20.0	float
rdf:type	turned_boss	owl:Class

Fig. 9 Instantiation of component features

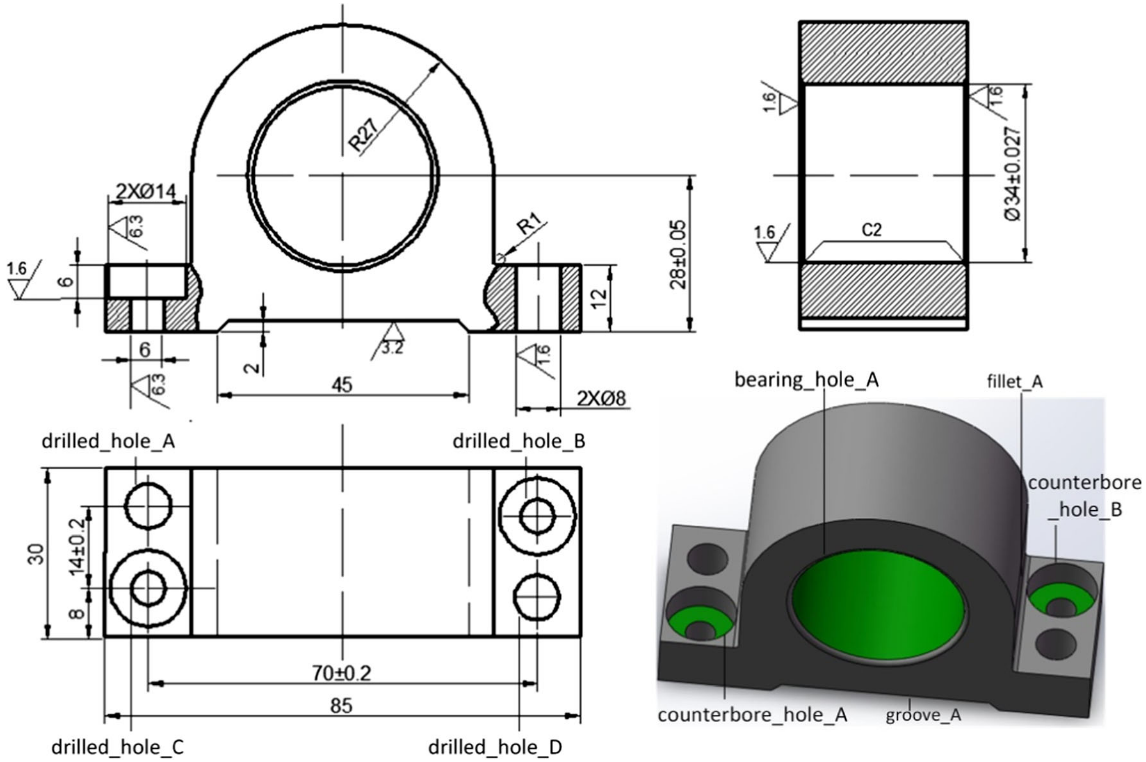


Fig. 10 A bearing block

are four constraint rules and one inference rule activated by considering manufacturability when designing this component.

First of all, due to the manufacturing constraints, the only available ordinary drilling tool is 8 mm. Therefore, when designing the drilling hole in the design phase, if the diameter of a drilling hole does not conform, then it will conclude that the diameter is unreasonable (see Fig. 11 and rule 3).

- Rule (3) drilled_hole(?x)∧diameter (?x,?y)∧sqwrl: notEqual(?y,8)→has_irrationnality (?x,"drilled_hole diameter wrong")

As shown in Fig. 12, a prototype system has been built. The user can input corresponding processing parameters in the system. For example, if the diameter of the drilling hole is wrong, that is, not equal to 8 mm, there will be a crossing behind the blank and the interface exists a warning that "Drill hole diameter wrong."

Secondly, similar to drilling holes, due to the limitation of the available reaming drilling tools, the size of counter bore holes is considered to be too large as shown in Fig. 11. Rule 4 shows that if the diameter of a counter bore hole is larger than 12 mm, then it will conclude that the diameter is oversized.

- Rule (4) counterbore_hole(?x) ∧ diameter(?x, ?y) ∧ swrlb:greaterThan(?y, 12) ∧ reaming_drilling(?z) ∧ drilled_by(?x,?z) → has_irrationnality(?x, "diameter oversize")

Thirdly, there is a fillet that requires machining by turning machine. However, the available reaming turning the tool's diameter is not small enough as shown in Fig. 11. Rule 5 shows that if the diameter of a fillet is smaller than 5 mm, then it will conclude that the fillet diameter is wrong.

- Rule (5) fillet(?x) ∧ diameter(?x, ?y) ∧ swrlb:lessThan(?y, 5) ∧ turning(?z) ∧ turned_by(?x, ?z) → has_irrationnality(?x, "fillet diameter wrong")

As shown in Fig. 13, if the diameter of the counter bore hole the user input is larger than 12 mm, then there will be a crossing behind the blank and the interface exists a warning that "Diameter oversize."

Fourthly, due to the limitation on precision of the available milling machine, the design of the roughness of bearing hole

Fig. 11 Unreasonable parameters for case study 1

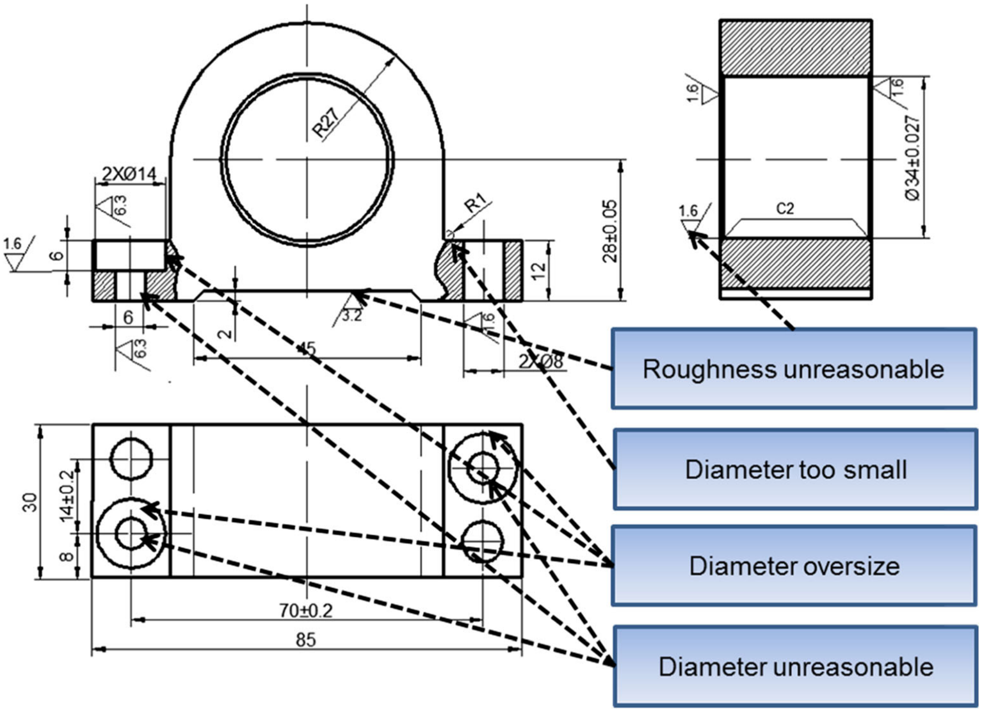
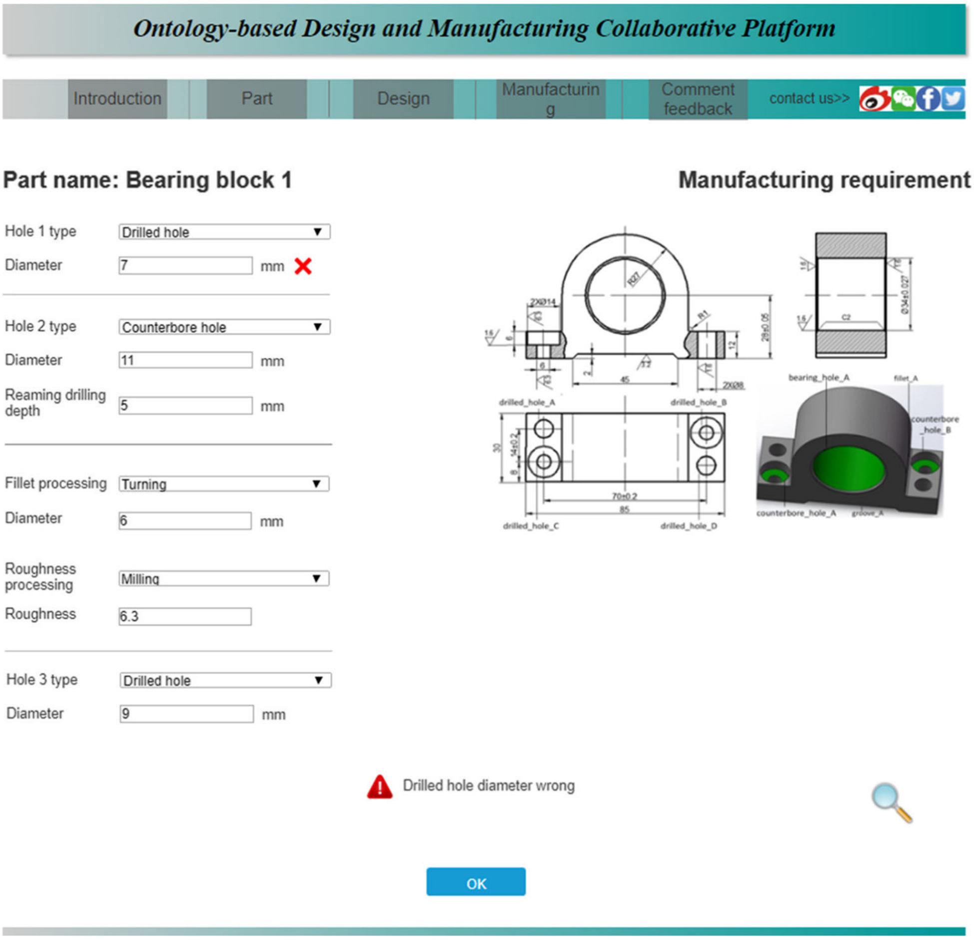


Fig. 12 A snapshot of ontology-based design and manufacturing collaborative platform



Part name: Bearing block 1

Hole 1 type: Drilled hole
Diameter: 7 mm ✗

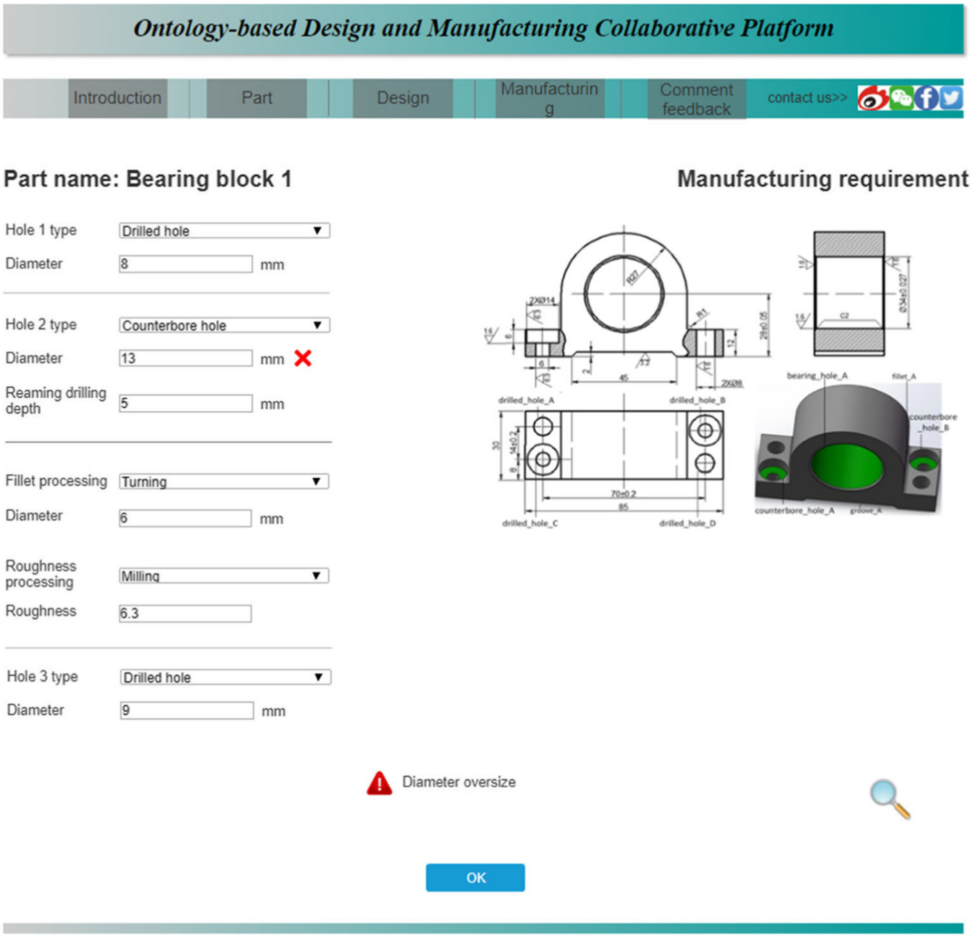
Hole 2 type: Counterbore hole
Diameter: 11 mm
Reaming drilling depth: 5 mm

Fillet processing: Turning
Diameter: 6 mm

Roughness processing: Milling
Roughness: 6.3

Hole 3 type: Drilled hole
Diameter: 9 mm

⚠ Drilled hole diameter wrong



Part name: Bearing block 1

Hole 1 type: Drilled hole
Diameter: 8 mm

Hole 2 type: Counterbore hole
Diameter: 13 mm ✗
Reaming drilling depth: 5 mm

Fillet processing: Turning
Diameter: 6 mm

Roughness processing: Milling
Roughness: 6.3

Hole 3 type: Drilled hole
Diameter: 9 mm

Diameter oversize

Fig. 13 A snapshot of ontology-based design and manufacturing collaborative platform

and that of groove is considered as unreasonable as shown in Fig. 11. Rule 6 shows that if the required roughness of a feature is smaller than 3.5, then it will conclude that the required roughness is unreasonable.

- Rule (6) feature(?x) ∧ roughness(?x, ?y) ∧ swrlb:lessThan(?y, 3.5) ∧ milling(?z) ∧ milled_by(?x, ?z) → has_irrationnality(?x, “roughness unreasonable”).

Lastly, there is one inference rule activated. There are four drilling holes with diameter less than 10 mm, two of them is conflicted with rule (3); hence, only the other two of them which can be machined by drilling. Rule (7) shows the SWRL format of the inference rule.

- Rule (7) hole(?x) ∧diameter(?x,?y) ∧swrlb:lessThan(?y,10) ∧drilling(?z)→machined_by(?x, ?z)

Thus, based on the previous constraint and inference rules, designers can consider manufacturing constraints in advance during the design phase, which can minimize the iterations between the design process and the production process.

4.2 Case study 2

As shown in Fig. 14, it is a component of a male mold that is used to manufacture a component of triangular rubix by injection molding. Similar to case 1, we construct the ontologies based on the proposed approach. Based on different requirements of customers, the required precision is different and hence the required manufacturing processes are also different. Hence, it is selected in this case study to demonstrate the flexibility of the OBPD framework.

4.2.1 Scenario A

In scenario A, there is a customer who requires the manufactured component to have relatively higher precision and sharp corners. CNC turning machine can achieve the required roughness and precision, but the component is needed to be redesigned in order to have the sharp corners. Rules (8–10) are inferred to obtain the recommended redesign and process. Rule (8) presents that if the required surface roughness is greater than or equal to Ra0.8 and the dimension precision is between 0.01 and 0.02, then it should use CNC turning. Rules

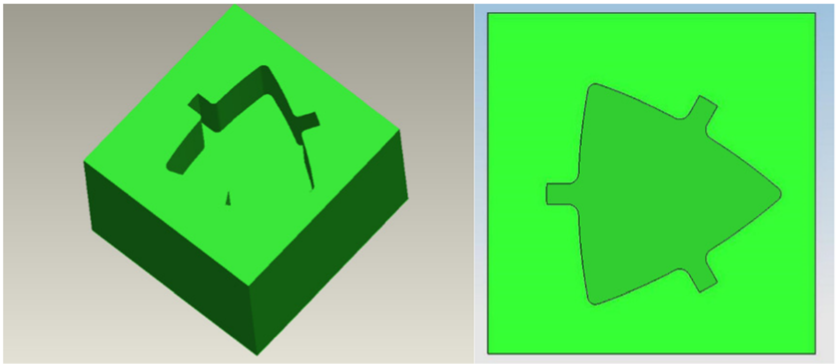
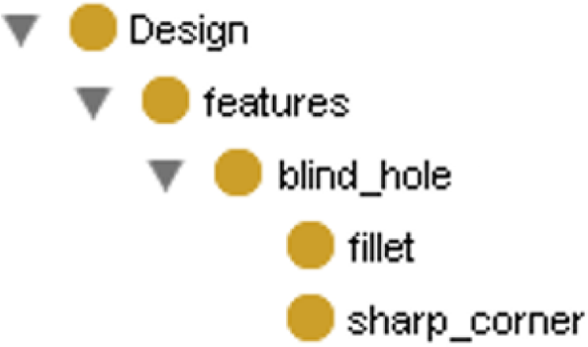


Fig. 14 A component of male mold for manufacturing triangular rubix



(9) and (10) mean that if there is a blind hole which has a fillet with diameter equals to 0, then the blind hole should be redesigned by dividing into pieces or changed the blind hole to a through hole.

- Rule (8) feature(?x) ∧ roughness(?x, ?r) ∧ swrlb:greaterThanOrEqual(?r, 0.8) ∧ precision(?x, ?a) ∧swrlb:greaterThanOrEqual(?a, 0.01) ∧ swrlb:lessThanOrEqual(?a, 0.02) ∧ cnc_turning(?y) → machined_by(?x, ?y)

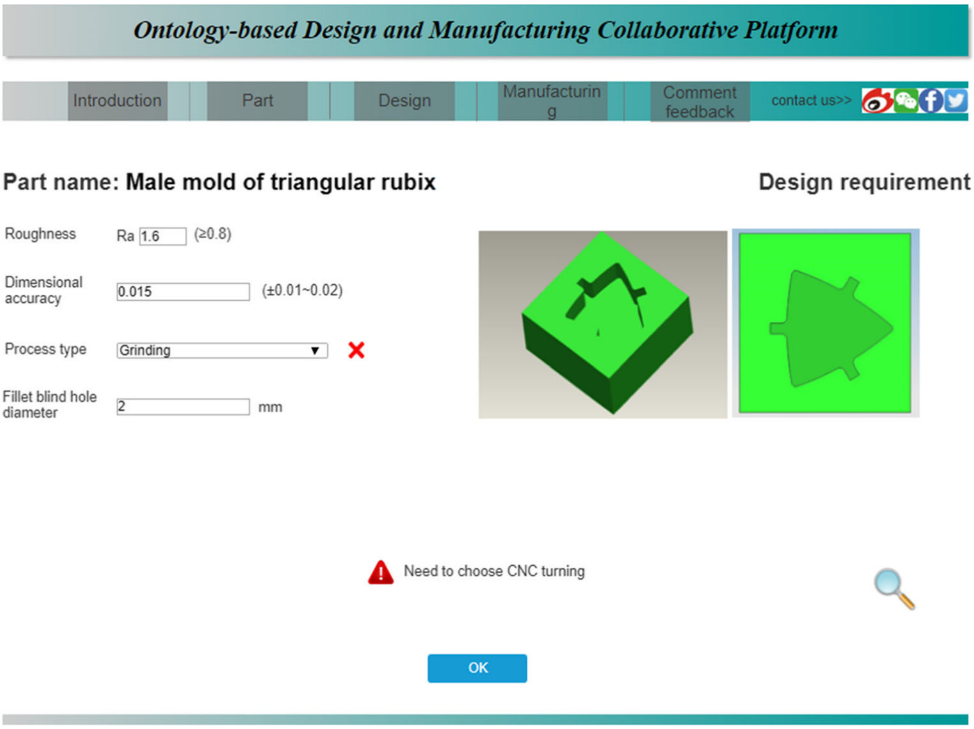
- Rule (9) blind_hole(?x) ∧ fillet(?f) ∧ isParentChild(?x, ?f) ∧ diameter(?f, ?y) ∧ swrlb:equal(?y, 0) → has_irrationnality(?x, "redesign from 1 pieces to several pieces")

- Rule (10) blind_hole(?x) ∧ fillet(?f) ∧isParentChild(?x, ?f) ∧diameter(?f, ?y) ∧ swrlb:equal(?y, 0) → has_irrationnality(?i, "redesign blind_hole to through_hole")

As shown in Fig. 15, the related rules will be activated based on the users' input. For example, if the process type the user input is not CNC turning, a warning that "Need to choose CNC turning" will be shown in the system. If the fillet blind hole diameter the user input is 0, the interface will prompt two warnings. One is "Redesign from 1 piece to several pieces," the other is "Redesign blind hole to through hole."

4.2.2 Scenario B

In scenario B, there is a customer who has changed the blind hole to a through hole as shown in Fig. 16, and he has a lower requirement on surface roughness and does not require sharp corners. Due to the looser requirements, more options are provided by the OBPD framework. Firstly, it can use rules (8) and (9) which is as same as scenario A by redesigning the component into several pieces and machined the component by CNC turning. Secondly, it can redesign the sharp corners into round corners, so that the component can be machined by wire cut EDM. Thirdly, it can redesign the through hole with a 3 degree taper, so that so that the component can be machined by wire cut EDM. The related rules are shown in rules (11) to (13). Rule (11) represents that if the surface roughness is greater than or equal to 1.2 and the dimension precision is between 0.02 and 0.03, then it can be processed by wire cut EDM in medium speed. If the surface roughness the user input is greater than or equal to 1.2 and the dimension precision input is between 0.02 and 0.03, but the process type is not EDM in medium speed, then there will a warning "Medium speed wire cutting" will be prompted. Rule (12) represents that if the diameter of fillet of the through hole is equal to 0 and it is processed by wire cut EDM in medium



Ontology-based Design and Manufacturing Collaborative Platform

Part name: Male mold of triangular rubix

Design requirement

Roughness: Ra 1.6 (≥0.8)

Dimensional accuracy: 0.015 (±0.01~0.02)

Process type: Grinding ▼ ✗

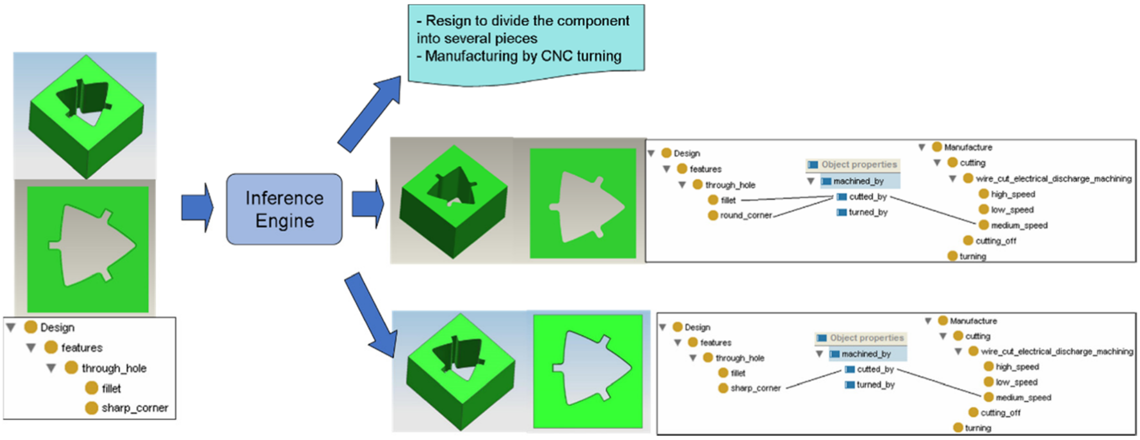
Fillet blind hole diameter: 2 mm

Need to choose CNC turning

Fig. 15 A snapshot of ontology-based design and manufacturing collaborative platform

speed, then the fillet should be resigned to be a round corner. If the diameter of fillet of the through hole is equal to 0 and the process type input is medium speed wire cutting, then a warning "Redesign fillet to round corner" will be prompted. Rule (13) represents that if the diameter of fillet of the through hole is greater than 0 and it is processed by wire cut EDM in medium speed, then the hole can be resigned to have a 3 degree taper. If the diameter of fillet of the through hole the user input is greater than 0 and the process type input is medium speed wire cutting, then the system will prompt a tip that "Redesign the hole with 3 degree taper."

- Rule (11) feature(?x) ∧ roughness(?x, ?r) ∧ swrlb:greaterThanOrEqual(?r, 1.2) ∧ precision(?x, ?a) ∧swrlb:greaterThanOrEqual(?a, 0.02) ∧ swrlb:lessThanOrEqual(?a, 0.03) ∧ wire_cut_edm(?y, medium_speed) → machined_by(?x, ?y)
- Rule (12) through_hole(?x) ∧ fillet(?f) ∧ isParentChild(?x, ?f) ∧diameter (?f, ?y) ∧ swrlb:equal(?y, 0) ∧ wire_cut_edm(?z, medium_speed) ∧machined_by(?x, ?z)→has_irrationnality(?x, "redesign fillet to round corner")
- Rule (13) through_hole(?x) ∧ fillet(?f) ∧ isParentChild(?x, ?f) ∧ diameter(?f, ?y) ∧ swrlb: greaterThan(?y, 0) ∧ wire_cut_edm(?z, medium_speed) ∧machined_by(?x, ?z)→has_irrationnality(?x, "redesign the hole with 3 degree taper")



- Resign to divide the component into several pieces
- Manufacturing by CNC turning

Fig. 16 A component of male mold for scenario B.

5 Conclusion and further work

Traditionally, designers and manufacturing engineers work based on their own experience. Designers focus on the feasibility of the design, but they do not consider the actual situation of manufacturing. Manufacturing engineers focus on the feasibility in production, but they do not take the aesthetic and design concepts into consideration. This kind of experience-based design method is no longer able to meet today's needs of rapid product development. Recently, many researchers adopt knowledge management in the design and manufacturing process. However, they are focused on developing knowledge management method to represent the knowledge on either side of process. There is a need to bridge the gap by mapping the design knowledge with manufacturing knowledge.

In this study, we proposed an OBPD framework by using ontology and SWRL. We established a rule base for mapping design knowledge with manufacture knowledge based on constraint rules and inference rules. We developed an ontology and rule-based inference engine by providing consolidated recommendations on both design and manufacturing process. So that designers can have an automatic and interactive guide during the early design stage. Previous design knowledge and current situation of manufacturing constraints can be effectively shared and reused. Two case studies demonstrate the proposed framework is practical. It can be used to design mechanical parts that integrate design and manufacturing knowledge for manufacturability verification and knowledge reuse in actual production.

Nevertheless, the presented study only deals with designing simple part according to uncomplicated manufacturability constraint, and SWRL-based rule base cannot deal with complicated manufacturing environment. Future research is required for investigating more effective method to handle the complexity.

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