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Ontology-Based Cutting Tool Configuration Considering Carbon Emissions

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KEYWORDS: Cutting tools, Configuration process, Ontology, Carbon emissions, Low-carbon manufacturing

In order to improve the precision and efficiency of cutting tool configuration and reduce carbon emissions during manufacturing process, an ontology-based cutting tool configuration process considering carbon emissions is put forward in the paper. Firstly, the architecture of ontology-based cutting tool configuration is established and key functional modules are described. Secondly, ontology is applied to describe the complex knowledge of cutting tool configuration and the Semantic Web Rule Language (SWRL) is used to build inference rules to reason feasible cutting tool configuration schemes according to machining requirements. Thirdly, taking carbon emissions as the objective, an evaluation method based on the c-PBOM-T (carbon emissions-Process Bill of Material for cutting Tools) table is studied to decide an optimal cutting tool configuration scheme from the feasible ones in the previous step for part machining. Finally, the proposed method is applied to a vortex shell workpiece to demonstrate its feasibility. The results show that the proposed method can improve the cutting tool configuration and reduce carbon emissions effectively for the machining processes. The presented method provides a valuable insight into the intelligent cutting tool configuration to support low-carbon manufacturing.

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NOMENCLATURE

$CT1$, $CT2$, $CT3$ = Cutting tool names
t_{CT1}, t_{CT2}, t_{CT3} = Cutting time (s) of $CT1$, $CT2$ and $CT3$
T_{CT1}, T_{CT2}, T_{CT3} = Cutting tool life (s) of $CT1$, $CT2$ and $CT3$
R = Times the cutting tools will be sharpened
F_{CT1}, F_{CT2}, F_{CT3} = Carbon emissions factor (kgCO$_2$/kg) of $CT1$, $CT2$ and $CT3$
W_{CT1}, W_{CT2}, W_{CT3} = Mass (kg) of $CT1$, $CT2$ and $CT3$
a_p = Cutting depth (mm) of cutting tools
f = Feed rate (mm/min) of cutting tools
v_c = Spindle speed (m/min) of cutting tools
F_e = Carbon emission factor of electricity (kgCO$_2$/kWh)
F_{wCT1}, F_{wCT2}, F_{wCT3} = Carbon emission factor (kgCO$_2$/kg) of waste cutting tool disposal of $CT1$, $CT2$ and $CT3$
L = Feature length to be processed (mm)
Δ = Machining allowance (mm)

1. Introduction

Cutting tools, as one of the most important auxiliary tool of modern machining tools, have accounted for 8% of the total manufacturing costs in the manufacturing phase of the product life cycle. The number can even increase to 34% due to machine down times and poor product quality.[1] In the modern equipment manufacturing industry, especially the high-end numerical control equipment, machining processes are characterized by diversification, flexibility, automation and customization, which results in a huge challenge in terms of manufacturing patterns, technologies, materials, information, etc. As the manufacturing mode of enterprises updates and transforms from the mass production into multiple species and small batch, the number and variety of cutting tools grow rapidly. The cutting tool configuration is a process which contains many resources and process feature information, such as workpiece material, part characteristics, machine tools and cutting tools characteristics.[2] Deciding a suitable cutting tool for a specific machining workpiece and identifying features of cutting tools from tool database become extremely complicated. Therefore, how to use, manage and

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select cutting tools has a great influence on the production costs and efficiency of enterprises. Unfortunately, most of cutting tool knowledge still remains in the minds of operators or in the cutting tool handbooks. From the above analysis, cutting tool configuration is a knowledge-based decision-making process. It is a very important subtask involved in process planning systems.[3] Plenty of knowledge is required to complete the configuration process. Within the field of traditional practice, cutting tools are often chosen by human intuition, which lacks a logical approach and a consistent standard.[4]

Moreover, going green has become a strategic priority in manufacturing which has evolved from the growing awareness of the need for environmentally friendly processes and products.[5] In view of mounting concerns over global climate change and greenhouse gas emissions, manufacturing enterprises are facing a growing pressure from carbon emissions reduction in the whole manufacturing process, in which the cutting tool configuration is involved. Environmental and economic factors spur manufacturing enterprises to take a series of substantial measures to minimize carbon emissions in the machining process. Therefore, how to configure the optimal and low-carbon based cutting tools effectively becomes one of the central issues.

In order to address the above challenges, on the one hand, a better knowledge representation and inference method of cutting tool configuration are needed in the cutting tool decision-making process. An ontology-based approach is applied in this paper to complete the complex knowledge description of cutting tool configuration. The method has advantages in expressing complex knowledge and setting up semantic relevance. Based on the ontology, the knowledge of cutting tools and part features is formalized in OWL (Ontology Web Language). In addition, the Semantic Web Rule Language (SWRL) is used to reason proper cutting tools. The SWRL is built on the same description logic foundation as OWL and provides similar strong formal guarantees when performing inference.[6] Thus, the inference rules can be written by using the relationships and terms described in ontology directly.[7] The feasible cutting tool configuration schemes, which contain one or several initial suitable cutting tools for the specific machining processes, will be obtained.

On the other hand, cutting tool configuration directly affects the amount of carbon emissions in the machining process. Carbon emissions need to be calculated to guide operators to acquire the optimal one in the evaluation process. However, the feasible cutting tool configuration schemes cannot meet the rising demand of low-carbon manufacturing though they are satisfied with the production requirement. That is to say, the ontology-based cutting tool configuration is to get the alternative and suitable cutting tools on the premise of meeting machining requests, and the low-carbon evaluation is to get the optimal cutting tools based on the consideration of environmental protection and energy conservation. Therefore, the main source of carbon emissions involving material carbon emissions, energy consumption carbon emissions and waste carbon emissions is considered in the paper. Thus, the evaluation method gives a good thinking way to deal with the low-carbon manufacturing problem in the aspect of cutting tool configuration.

The paper is aiming at studying an ontology-based cutting tool configuration process under the background of low-carbon manufacturing. By combining the effective cutting tool configuration process with carbon emissions evaluation, the optimal cutting tool will be selected for workpieces. Based on cutting tool information and feature information, the ontology model of configuration process will be established. Then the reasoning will be studied by using the SWRL to select the feasible cutting tool scheme. At last, the selected cutting tools will be evaluated by carbon emissions quantification. The optimal cutting tool is obtained for operators finally.

The rest of the paper is organized as follows. In Section 2, literature review for this study is discussed. Section 3 describes the architecture of cutting tool configuration and its key technologies. Section 4 studies the cutting tool configuration technologies. Section 5 verifies the proposed method by using a vortex shell workpiece as the case study. Finally, the conclusions are drawn and future work is discussed in Section 6.

2. Literature Review

Related research draws on and contributes to three streams of literature, which are about cutting tool configuration methods, ontology-based knowledge modeling and carbon emissions quantitative methods for manufacturing system.

2.1 Cutting tool configuration methods

Related researches have been published in recent years. One kind of methods is based on the artificial experience or subjective factors. Li et al.[8] used the analytic hierarchy process (AHP) method and the entropy weight method to judge the significance of material properties and determine criterion weight values for cutting tools. However, with the growing number of cutting tools and the complexity of tasks, large amounts of information about cutting tools would lead to the difficulty in judging suitable cutting tools, especially for the modern manufacturing mode. Another kind of methods is based on a mathematical way. The configuration is regarded as a multi-objective optimization problem. Generally, various aims including materials,[9,10] costs, cutting parameters[11] and optimal scheduling[12] are widely used in the manufacturing process. According to different objectives, cutting tools are configured or evaluated. Optimization methods such as the genetic algorithm, particle swarm optimization algorithm and neural network are used to obtain proper cutting tools. Saranya et al.[13] employed artificial intelligence techniques such as artificial neural networks, fuzzy logic and genetic algorithm to decide and optimize tools by taking the MRR (material removal rate), tool life and tool cost as the evaluating indicators. Gjelaj et al.[14] proposed an optimization method for the tool selection based on the genetic algorithm. Generally, geometry and shape of workpieces should be considered in the cutting tool configuration. Arunachalam et al.[15] implemented multi-criteria decision making methods (MCDMs) to rank the suitability of different polishing processes for a given workpiece geometry. They introduced new criteria such as compliance and surface integrity for selection. Mejia-Ugalde et al.[16] developed an automatic tool selection method based on a directional morphological approach by processing the shape of 3D models. The methods mentioned above discussed the configuration or selection for cutting tools with different focuses, which are not common to all issues. The configuration process can be seen as a process based on knowledge so it is easy to apply, share and expand.

2.2 Ontology-based knowledge modeling

The cutting tool configuration knowledge is a very complex set of information resources. The knowledge representation and modeling for cutting tools have been studied over past few years. Common knowledge presentation methods are predicate logic, production rule, frame, semantic web, etc. Tan et al.[17] developed an expert system to select suitable tips tool based on dimension, machining parameters, feed rate, turning speed and materials of workpieces for a CNC lathe machine. However, they did not explain how to describe and manage the knowledge-based carbide cutting tools selection process. Wu et al.[18] studied a data mining technology based on a cloud manufacturing platform to obtain the information of workpieces, machining features, cutting tools, and so on. With the rapid increase of information and knowledge in workshops, the complexity of cutting tool configuration knowledge is also on the rise. In the machining process, the knowledge contains a variety of contents including part information, manufacturing tasks, machining tools, cutting tools and relationships among these entities. Traditional knowledge representation methods cannot describe and construct the complicated relationship between cutting tools and processing requirement very well.

Ontology is widely used in the manufacturing field based on its advantages in complex knowledge description. It has a better performance than other concept modeling technology in classification, sharing and formalization. As Zhang's opinion,[19] an ontology-based knowledge representation framework will improve the interoperability and scalability of knowledge representation for unit manufacturing processes. Therefore, the ontology-based method is more suitable for the cutting tool configuration. Lemaignan et al.[20] presented a proposal for a manufacturing upper ontology, named MASON (MAnufacturing's Semantics ONtology). Rehage and Gausemeier[21] proposed an ontology-based decision-making system for the automated selection of alternative CNC machines. Eum et al.[22] proposed an applied ontology to select the most appropriate machining methods for part process planning. Zhang et al.[19] presented a new ontology-based knowledge representation model and built a SWRL-based rule base for unit manufacturing processes configuration. Although they described complex knowledge based on ontology in their papers, they were lack of effective evaluation methods considering environment factors for machining processes.

2.3 Carbon emissions quantitative methods

Currently, due to the large consumption of resource and energy, manufacturing activities cause direct or indirect carbon emissions in multiple production links of the manufacturing system. More and more attention has been paid to energy saving and carbon emissions reduction. Ramesh et al.[23] pointed that new cutting techniques could reduce the use of cutting fluid for reaching the goal of eco-friendly machining. Thiede et al.[24] also indicated that environmentally related aspects were currently not sufficiently considered as standard functions in the manufacturing system. Duflou et al.[25] established a carbon emission impact assessing model of unit manufacturing process for discrete part manufacturing. Song and Lee[26] constructed a g-BOM (greenhouse gas-BOM) to estimate GHG emissions of a product in its life cycle stages. These quantitative methods provide the support for the evaluation of cutting tools. In the manufacturing stage, many factors[27] such as electricity, cutting fluids,[28] wear and tear of cutting tools, material consumption and disposal of chips, etc., affect energy and material consumption. Different cutting parameters also have an effect on power consumption. Yi et al.[29] proposed a multi-objective optimization model to explore the impact of cutting speed and feed rate on carbon emissions and processing time. Kara and Li[30] proposed unit process energy consumption models for material removal processes. Cutting tools not only affect machining quality, cost and productivity, but also affect energy consumption of the whole machining manufacturing process. Mativenga and Rajemi[31] pointed that energy footprint for cutting tools was one of the key factors influencing the selection of optimum tool-life for achieving minimum energy footprint. Tan et al.[32,33] considered five factors, namely time, quality, cost, resource and environmental impact to decide the cutting tool configuration.

A lot of literature proposes cutting tool configuration methods based on multi-objective optimization algorithms and artificial experience, which lack the support for the low-carbon manufacturing. Furthermore, most of the methods have the shortage of knowledge description and reasoning for cutting tools in the actual process. They will lead to low precision and efficiency of cutting tool configuration. In conclusion, although there are many published articles on ontology modeling and evaluation methods based on environmental factors, the topic on the ontology-based cutting tool configuration considering carbon emissions is little, which cannot meet the new requirement of climate change and environmental influence for manufacturing enterprises.

3. Architecture of the Cutting Tool Configuration

For overcoming the shortcomings of traditional cutting tool configuration methods, an ontology-based cutting tool configuration approach considering carbon emissions is proposed. The architecture of the cutting tool configuration process is shown in Fig. 1.

The architecture includes three main functional modules: cutting tools and machining features construction, ontology-based configuration model and inference, and scheme evaluation considering carbon emissions. Here, the cutting tools and machining features construction provides the data support for the configuration process; the ontology-based configuration model and inference is used to produce feasible cutting tool schemes; the scheme evaluation considering carbon emissions is used to evaluate the obtained feasible schemes to acquire the optimal cutting tool by taking carbon emissions as the evaluation factor. In this way, an optimal cutting tool scheme is produced finally and recommended to the operators. The key technologies are described as follows.

- Cutting tool information model and part feature information model

The cutting tool configuration is a matching process between part features and cutting tools. The cutting tool information model and part feature information model will provide the detailed and standard information for supporting the whole procedure of cutting tool configuration. At the same time, it is necessary to study the coding schemes of part features and cutting tools in order to manage them effectively.

- Ontology-based complex knowledge description and reasoning

The cutting tool configuration in the machining process involves

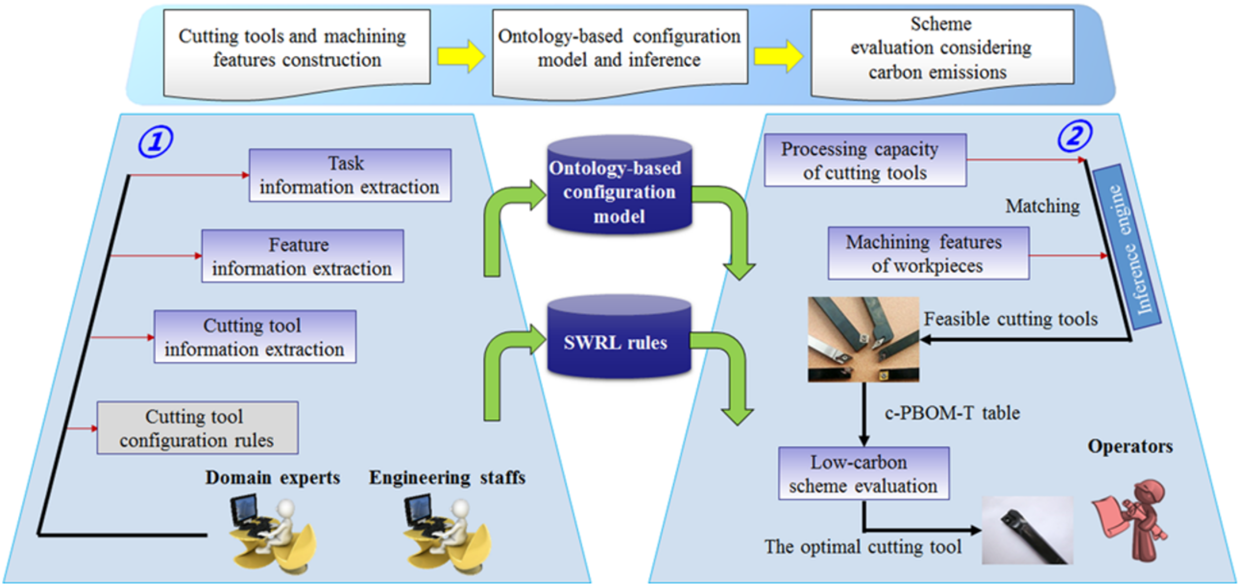


Fig. 1 Architecture of the cutting tool configuration process

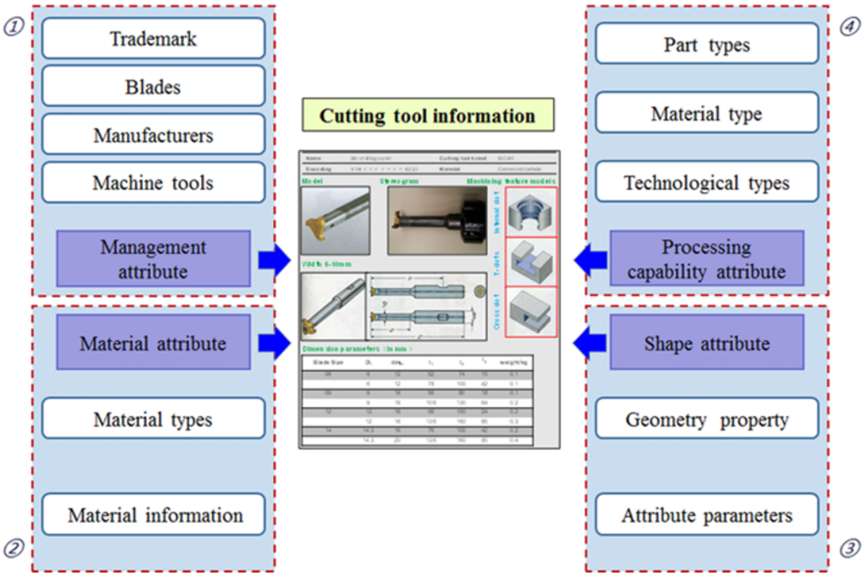


Fig. 2 Cutting tool information model

various kinds of information and knowledge. In order to define the core concepts, express relationships between them, and improve the reasoning efficiency, the ontology is introduced to describe the complex knowledge and the reasoning technology is also studied to obtain the configuration schemes. The domain knowledge, framework and inference rules for the cutting tool configuration are studied. In addition, by using the FaCT++ inference engine of Protégé, the feasible cutting tool schemes for the machining process will be matched successfully.

- Cutting tool scheme evaluation considering carbon emissions

Carbon emissions produced by electricity and materials become the main source in the machining process. Different cutting tools have the different impact on carbon emissions. By using the c-PBOM-T (carbon emissions-Process Bill of Material for cutting Tools) table method based on the c-PBOM (carbon emissions-Process Bill of Material), the cutting tool scheme which has the minimum carbon emissions can be obtained from the above-mentioned feasible ones and as the optimal scheme of the corresponding machining process. As a result, the final configuration cutting tool scheme is more suitable for the actual multiple requirements.

Table 1 Basic structure of cutting tool encoding

Encoding	Encoding bit	Meaning
Part I	The first bit	Classification code
Part II	The 2nd-13rd bit	Information encoding bit
Part III	The 14th bit	Brand bit
Part IV	The 15th and 16th bit	Auxiliary reservation bit

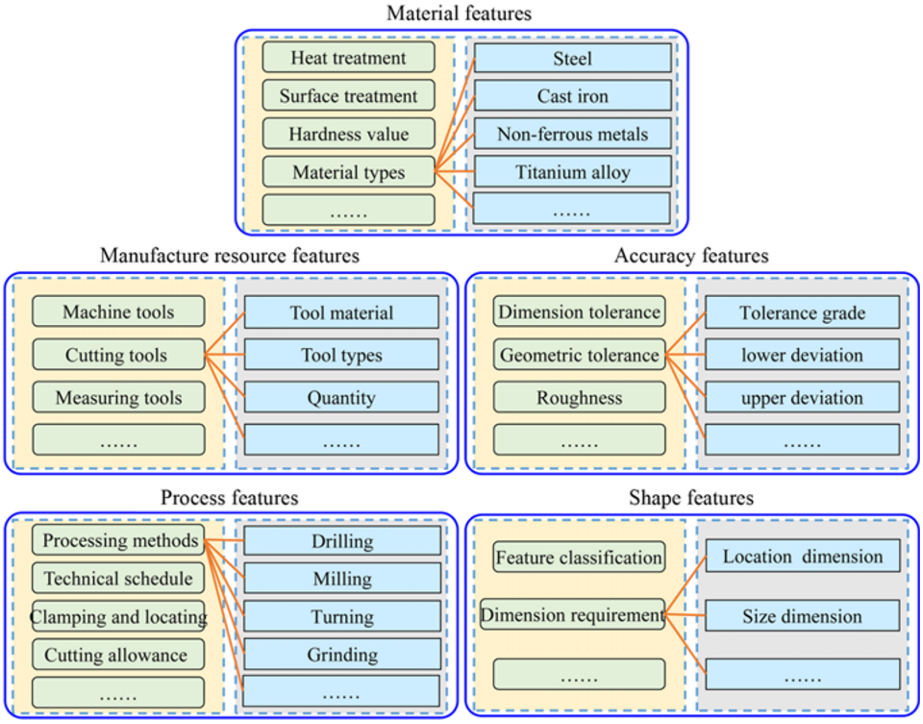


Fig. 3 Part feature information model

4. Cutting Tool Configuration Technologies

4.1 Cutting tool information model and part feature information model

To manage cutting tools and machining features, the first thing is to establish the cutting tool information model and the part feature information model respectively.

(1) Cutting tool information model

In order to describe the tool information model, the information of cutting tools is divided into four major attributes according to the features of cutting tools themselves. The attributes are management attributes, material attributes, shape attributes and processing capability attributes. The cutting tool information model is shown as Fig. 2.

When the classification is finished, the cutting tool encoding is required to support the management and reasoning process. The unified encoding rules are adopted by applying a 16-bit length encoding based on the cutting tool information model. The basic structure of the cutting tool encoding is showed in Table 1. The detailed encoding bit instruction of cutting tools is listed in Appendix A (Table A.1). Then, the corresponding encoding rules are implemented by programming for blades, cutting tools and tool system (mainly includes tool shank, cutter bar, tool-case, connecting rods and other aids). At last, the cutting tool information table is established and entered into the underlying database.

(2) Part feature information model

The part features are the bridge between machining workpieces and cutting tools. They are analyzed according to the actual production situation of enterprises as shown in Fig. 3.

The part features are classified and encoded reasonably for the convenience of unified management, retrieval, query and better support for the tool matching process. The length of feature encoding is 21. The basic structure of feature encoding is showed in Fig. 4 .The detailed encoding bit instruction of part features is listed in Appendix A (Table A.2).

The feature encoding is mainly composed of four parts: the subordinate part encoding, which is based on the machining process of a part, represents the corresponding relationship between features and parts; the feature type and process information encoding are the major basis of feature recognition; the reservation encoding ensures the scalability of the whole encoding system.

According to the analysis of the part feature information model, the elements of machining features such as types, attributes and geometrical parameters are described. At last, the database of machining features is built.

4.2 Ontology-based complex knowledge description and reasoning

According to machining features and machining ability of cutting tools, the basic attributes of features should be considered in the configuration process. The matching process is shown as Fig. 5. Only all matching processes of attributes are accomplished, the feasible cutting tools can be gained. Attributes can be divided into qualitative attributes (including machining features, production stability and materials, etc.) and quantitative attributes (including size, roughness and accuracy, etc.). Correspondingly, reasoning rules can be also divided into two parts, namely qualitative rules and quantitative rules.

(1) Complex knowledge description

The cutting tool configuration involves many types of domain information, such as machine tools, parts, cutting tools, technique methods, and so on. Combined with the demand of actual situations of the cutting tool configuration, plenty of domain terms are summarized and analyzed based on some relevant data to get the ontology-based

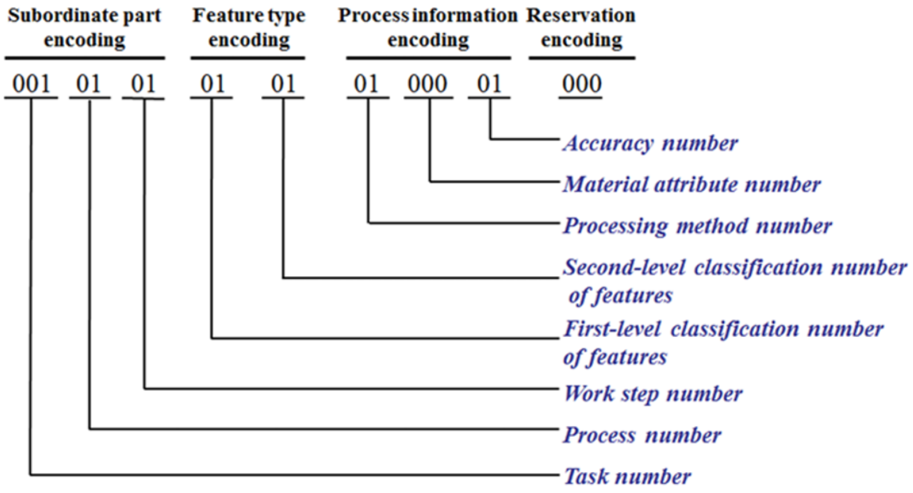


Fig 4 Basic structure of feature encoding

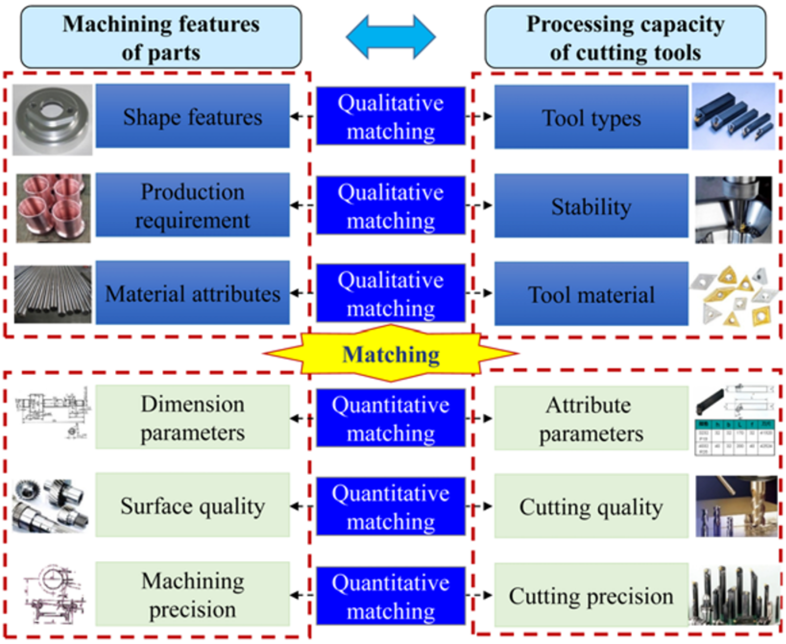


Fig. 5 Matching process between machining features and cutting tools

knowledge framework of the cutting tool configuration. The domain terms are divided into entity terms (workpiece, cutting tools and machine tools), machining terms (cutting parameters, machining methods and machining types), attribute terms (category, material, geometric parameters and machining features) and evaluation terms (lifetime, surface quality and performance). The ontology-based knowledge framework is shown in Appendix B (Table B.1).

Under the guidance of experts, the ontology model is obtained according to the cutting tool information model and part feature information model. The ontology model contains concepts and matching relationships of cutting tools and machining features. The entity or concept of the configuration process, such as workpieces, cutting tools, machine tools and machining types, will be encapsulated as the “class” based on the semantic description method of ontology technologies. The instances of workpieces, cutting tools, machine tools and machining features will be expressed in the form of “individual”. The property between classes and instances as well as instances and data are expressed as “individual property” and “data property” respectively. Constraint is described by the self-defined configuration rules at the time of building the ontology model. Thus, the knowledge about cutting tools used in the matching processes is completely defined. The ontology model of cutting tool configuration knowledge can be built with Protégé 4.3 as Appendix B (Table B.2).

(2) Inference rules

Rules are used to restrain the relationships between modules and instances in the configuration model. The rationality of configuration schemes is ensured by limiting instances in the configuration process.

In the rule expression, the symbol “→” divides a rule into two parts, namely the premise (body) and conclusion (head). The conclusion would be true if the premise is true. The premise or conclusion has zero or more atoms, which can be treated as a conjunction with a symbol “^”. The atoms mainly have two forms: C(x) and P(x,y). C is class; and P is property. The symbols of x and y are variables, individuals or instances.[6] The two types of inference rules are described in details as follows.

1) Qualitative ontology rules

a) Rules of machining features

Generally, different machining features require different machining methods and cutting tools. Therefore, the cutting tool type is always determined by the machining features. The same feature may have different machining methods, which is determined by the shape characteristics. For example, if a face feature belongs to a rotational part, then an end-face turning tool will be needed. But if it belongs to a shell part, an end-face milling tool will be needed. The SWRL rules written as follows:

Machining feature (? Plane 1) ^ Feature name (? Plane 1, ? End face) ^ Part type (? Plane 1, ? Rotational part) → Cutting tool type (? Turning tool x, ? End-face turning tool)

Machining feature (? Plane 2) ^ Feature name (? Plane 2, ? End face) ^ Part type (? Plane 2, ? Shell part) →Cutting tool type (? Milling tool x, ? End-face milling tool)

The explanation of the first rule is: if the machining feature of workpiece is Plane 1, the feature name of Plane 1 is End face and the part type of Plane 1 is a rotational part, the type of cutting tool will be the end-face turning tool which is one of the turning tools. The second rule is similar to the first rule.

b) Rules of machining materials

The material of machining parts will determine the material of configured cutting tools directly. For example, if the material of a machining part is aluminum alloy, a carbide tool is better to be configured as the machining cutting tool. The SWRL rule is shown as follow:

Machining feature (? Step surface 1) ^ Membership workpiece (? Step surface 1, Supporting cylinder) ^ Material of a part (? Supporting cylinder,? Aluminum alloy) → Material of a cutting tool (? Milling tool x, ? Cemented carbide)

c) Rules of tool joints

CNC cutting tool is normally comprised of the working module (blade), middle module (arbor) and main handle module (toolholder). The matching sequence is commonly from the both ends toward the middle of cutting tools. For example, if a connecting rod needs to connect the tool bit of a face milling and a main tool holder, the left and right joint types must be matched with each other. The SWRL rule is shown as follow:

Right joint type (? Face milling tool 1, ?d) ^ Left joint type (? Main handle 1,?D) ^ Left joint type (?Connecting rod 1,? d_0) ^ Right joint type (? Connecting rod 1, ?D_0) ^ Equal (? d?? d_0) ^ Equal (? D_0??D)→Select (?Connecting rod 1,? Yes)

d) Rules of machining stability

In order to ensure the maximum stability in the whole machining process, the cutting tool configuration should meet some corresponding requirements. For example, the extension distance of an internal turning tool bit should be as small as possible to ensure the machining stability during the internal hole machining. The SWRL rule is shown as follow:

Machining method (? internal hole turning) ^ Extension distance of internal turning tool bit (? Internal turning tool 1, ? a_{r1}) ^ Extension distance of internal turning tool bit (? Internal turning tool 2, ? a_{r2}) ^…^ Extension distance of internal turning tool bit (? Internal turning tool N, ?a_{rN}) ^ greaterThan (?a_{r1}??a_{r2}) ^…^ greaterThan (?$a_{r?n-1?}$??a_{rn}) →Select (? Internal turning tool N, ? Yes)

2) Quantitative ontology rules

a) Rules of machining dimension

Same types of cutting tools generally have the same attributes of parameters, but the value of parameters is always different. The attribute value should be determined by the specific geometric parameters of machining features. For example, the maximum cutting depth of an end-face groove tool should be greater than the depth of groove features themselves in the end-face groove machining. The SWRL rule is shown as follow:

Machining feature (? End-face groove 1) ^ Groove depth (? End-face groove 1, ? h) ^ Cutting tool name (? End-face groove tool 1) Maximum cutting depth a_{max} ^ greaterThan (? a_{max}?? h) →Select (? End-face groove tool 1, ? Yes)

b) Rules of machining accuracy

The accuracy range of cutting tools should be considered to ensure the requirement of dimensional accuracy of machining features. For example, the machining precision range of a cylindrical turning tool must be within ±0.05 when the upper and lower deviations are ±0.05 in external circular surface machining. The SWRL rule is expressed as:

Machining feature (? Excircle 1) ^ Upper deviation (? Excircle 1, ? E_+) ^ Lower deviation (? Excircle 1, E_-) ^ Machining precision (? Cylindrical turning tool 1, e_+) ^ Machining precision (? Cylindrical turning tool 1, e_-) ^ greaterThan (? E_+?? e_+) ^ greaterThan (? e_-?? E_-) →Select (? Cylindrical turning tool 1,? Yes)

c) Rules of surface roughness

The corresponding class of cutting tools should be matched with surface roughness of machining features. The SWRL rule is shown as:

Machining feature (? Plane 1) ^ Feature name (? Plane 1,? End face 1) ^ Roughness (? End face 1,? l) ^ Cutting tool type (? Turning tool x, Facing tool) ^ Cutting tool surface level (? Turning tool x,? L) ^ Equal (? L,?L)→ (? Turning tool x, ? Yes)

(3) Reasoning process

The instances and rules are respectively regarded as the fact base and rule base in the inference engine. The feasible cutting tools which satisfy all matching conditions will be obtained by using the FaCT++ inference engine. The reasoning process is shown in Fig. 6. The reasoning steps are described as follows.

1) Configure machine tools and cutting tools according to machining features of the part to be machined;

2) According to the material of the part to be machined, different materials of cutting tools which meet the requirement of the machining part are configured from the cutting tools obtained in Step 1;

3) Configure several cutting tools of which tool joint is matched with the spindle of machine tools obtained in Step 1 from the cutting tools obtained in Step 2;

4) Configure the machining parameters of cutting tools which meet the requirement of specific geometric parameters of the part features to be machined from the cutting tools obtained in Step 3;

5) Configure the feasible cutting tools which meet the requirement

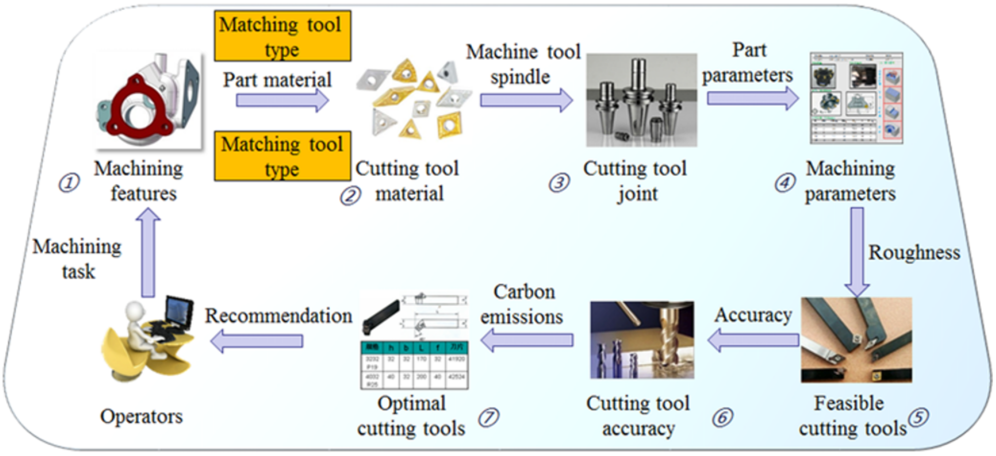


Fig. 6 Reasoning process of cutting tool configuration

Table 2 BOM of a part

Part	Feature encoding	Basic feature	Specification		
			Replicate	Shape	Allowance
P	FE	F	Re	S	A

Table 3 The known c-PBOM of a part

Basic feature	Operation content				Carbon emissions evaluation models		
	Method	Material	Device	Tool	Material	Energy	Waste
F	M	Ma	D	T	MatModel	EModel	WModel

Table 4 The c-PBOM-T of a part

Feature encoding	Tools		Cutting parameters			Carbon emissions of cutting tools			
	Priorities	Tool encoding	a_p	f	v_c	Material	Energy	Waste	Sum
FE	PR	TE				Mat	E	W	Sum

of roughness of the part features to be machined from the cutting tools obtained in step 4;

6) Configure the accuracy of cutting tools which meet the requirement of machining accuracy of the part features to be machined from the cutting tools obtained in step 5;

7) Configure the optimal cutting tools which meet the requirement of carbon emissions of the part features to be machined from the cutting tools obtained in step 6.

At last, the feasible cutting tool scheme will be achieved. Although the initial configuration can ensure the machining correctness and feasibility, it is not the optimal scheme under the background of low-carbon manufacturing.

4.3 Cutting tool scheme evaluation considering carbon emissions

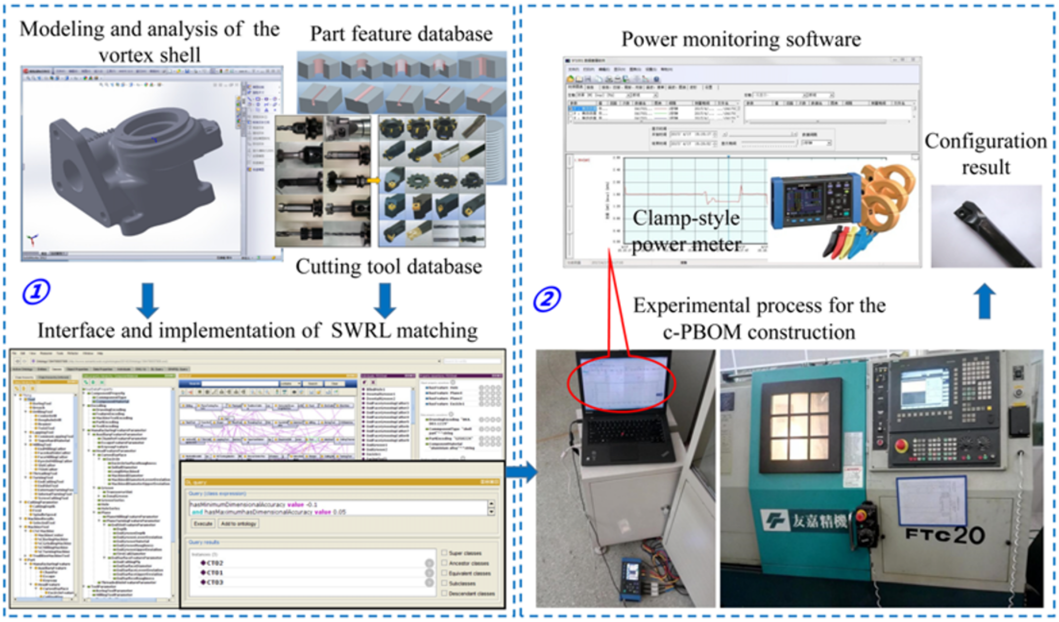
To reduce energy consumption and eliminate the negative effect on the environment as much as possible, carbon emissions should be paid high attention to in the manufacturing process. The cutting tool evaluation method is based on our previous study, which is a formalized table named c-PBOM (carbon emissions-Process Bill of Material) relying on the machining features.[34] The available carbon emissions evaluation models for different machining features can be obtained through the table-lookup method.

In the machining process, carbon emissions have multiple sources, such as machining operations, no-load running power consumption, waste and raw material preparation. However, for cutting tools, three aspects could cause carbon emissions. They are: (1) Material carbon emissions, i.e., raw material production of cutting tools. (2) Energy consumption carbon emissions, i.e., material removal processes by cutting tools. (3) Waste carbon emissions, i.e., disposal of abandoned cutting tools. These three types are the direct reasons relating to cutting tools to cause carbon emissions in the machining process. The c-PBOM is modified further to accommodate the cutting tool configuration issue, which is called the c-PBOM-T (c-PBOM for cutting Tools). To establish the c-PBOM-T, three steps should be completed as follows.

(1) According to the part feature information model and encoding, the geometric structure of a part is extracted to form the BOM as shown in Table 2.

(2) According to the established c-PBOM of the part, carbon emissions evaluation models of cutting tools can be selected. Table 3 shows the form of c-PBOM of a part. These models, such as energy carbon emission models, which have been verified by experiment, can be used to calculate carbon emissions directly.

(3) According to the carbon emissions evaluation models, carbon emissions of features corresponding to different cutting tools are calculated and the c-PBOM-T table is established as Table 4.



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hasMinimumDimensionalAccuracy value -0.1
 and hasMaximumhasDimensionalAccuracy value 0.05
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◆CT02
◆CT01
◆CT03
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Fig. 7 Implementation of the cutting tool configuration

Finally, the carbon emissions of the feasible cutting tools are calculated based on the construction process of the c-PBOM-T. The operators can choose the optimal cutting tool which has the minimum carbon emissions.

5. Case Study

Xi'an Winway Tools Co.,Ltd., as an integrated tooling company, has a very high demand on the cutting tool configuration and carbon emissions reduction. A vortex shell workpiece produced by the company is taken as the example to verify the proposed method in this paper. The main features are listed in Appendix A (Table A.3). Based on the presented cutting tool configuration architecture, the optimal cutting tools for this workpiece can be easily obtained. The implementation of the cutting tool configuration is given firstly in order to clarify the process, as shown in Fig. 7. The detailed procedures are described as follows.

5.1 Ontology-based configuration process

Firstly, the detailed information of the machining features is entered into the ontology model by using Protégé. The knowledge of features is written by the SWRL for the cutting tool matching. Then the FaCT++ inference is used to reason the feasible cutting tools based on the machining requirement and available cutting tool information. Feature F14, which is a hole feature, is studied as the example to explain the configuration process. The details of the hole feature are shown in Fig. 8. The reasoning process of cutting tools is illustrated with Protégé 4.3 as Fig. 9. The serial number marked in the picture explains the input of every matching step. Three cutting tools named CT1, CT2 and CT3 are obtained in the configuration result. It means that they are the feasible schemes to complete the hole machining. Certainly, for other features, there are one or several feasible cutting tools respectively. Their matching processes are similar to feature 14.

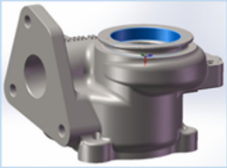
Feature type	Hole	**3D model**	
Part type	Casting		
Feature material	Cast iron		
Feature attributes			
Hole Diameter D	53.02mm	**Dimensional accuracy**	(+0.05/0) (0/-0.1)
Hole length L	9.9mm	**Surface roughness**	6.3

Fig. 8 Hole feature information of the vortex shell

Table 5 Feasible cutting tool configuration schemes

No.	Tool names	Cutting tool encoding
1	CT1	C01 E00 07 15 20 49 01
2	CT2	C01 E00 08 16 40 49 02
3	CT3	C01 E00 08 18 20 49 03

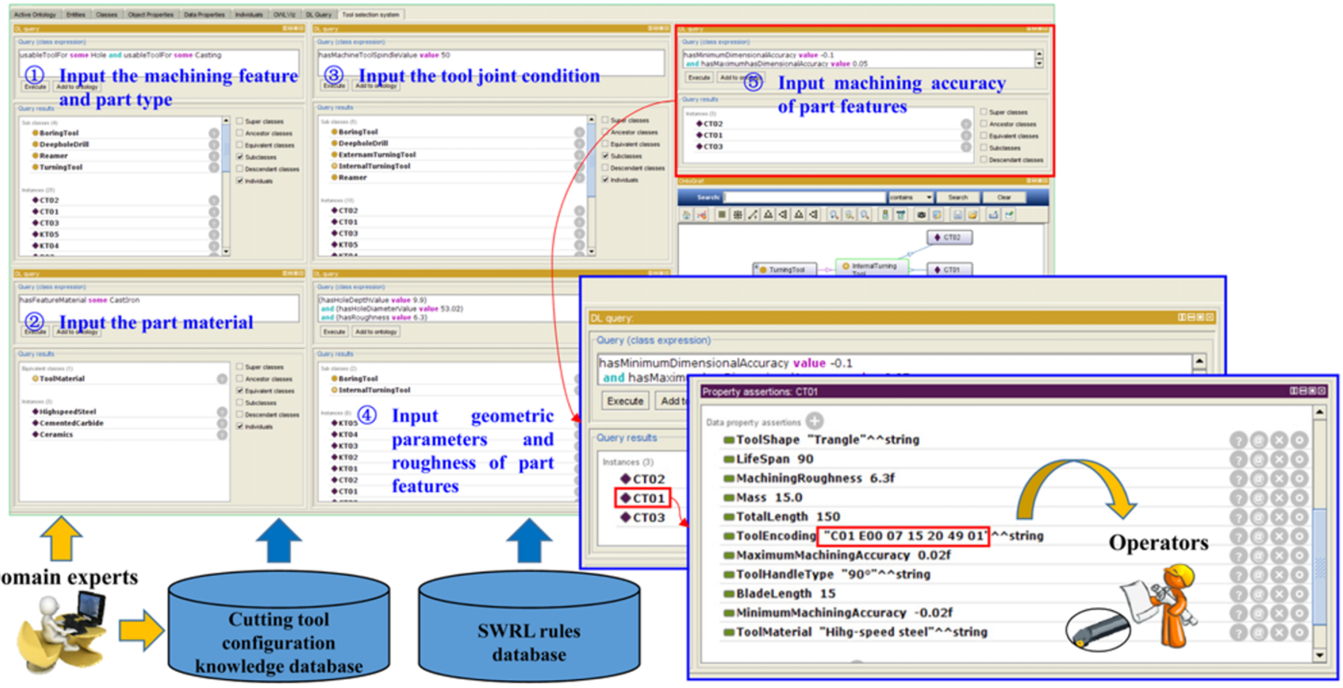
The tool name and tool encoding is shown in Table 5. According to the cutting tool product catalog and encoding, more detailed information about these three cutting tools is shown in Table 6.

5.2 Scheme evaluation process

The next step is to evaluate and choose the most appropriate cutting tool under the condition of minimum carbon emissions. The evaluation process is described as follows:

(1) Establish the BOM

The BOM of the vortex shell workpiece is established based on the geometry features, which are shown in Table 7.



usableToolFor some Hole and usableToolFor some Casting

hasFeatureMaterial some CastIron

hasMachineToolSpindleValue value 50

(hasHoleDepthValue value 9.9)
and (hasHoleDiameterValue value 53.02)
and (hasRoughness value 6.3)

hasMinimumDimensionalAccuracy value -0.1
and hasMaximumhasDimensionalAccuracy value 0.05

ToolShape "Trangle"^^string
LifeSpan 90
MachiningRoughness 6.3f
Mass 15.0
TotalLength 150
ToolEncoding "C01 E00 07 15 20 49 01"^^string
MaximumMachiningAccuracy 0.02f
ToolHandleType "90°"^^string
BladeLength 15
MinimumMachiningAccuracy -0.02f
ToolMaterial "Hihg-speed steel"^^string

Fig. 9 Reasoning process of cutting tools of the hole feature

Table 6 Detailed information of the configuration schemes

Cutting tool	Type attribute		Material attribute	Dimension attribute	
	Tool type	Tool handle type		Blade length (mm)	Total length (mm)
CT1	Turning	90	High-speed steel	15	150
CT2		90	Cemented Carbide	16	140
CT3		75	High-speed steel	18	145
Cutting tool	**Machining roughness**	**Machining accuracy**		**Mass (g)**	**Life span (min)**
CT1	6.3	[-0.02,0.02]		15	90
CT2	3.2	[-0.03,0.03]		13	45
CT3	6.3	[-0.02,0.02]		18	85

Table 7 BOM of the vortex shell workpiece

P	FE	F	Specification		
			Re	S	A
Vortex shell	FE1: 001 10 01 03 01 02 153 01 000	F1: Plane	1	100×80	3
	FE2: 001 10 02 03 01 02 153 03 000		1	100×80	2
	FE3: 001 10 03 01 02 03 153 01 000	F2: Hole	1	D6.8×20	1
	FE4: 001 10 04 01 01 02 153 01 000	F3: Hole	1	D8×20	2
	…	…	…	…	…

(2) Check the available carbon emissions evaluation models based on the c-PBOM

The carbon emissions evaluation models can be obtained based on the established c-PBOM. Partial c-PBOM of the company is shown in Appendix A (Table A.4). Here, the carbon emissions evaluation models CE_1, CE_2 and CE_3 are different for different features, machining methods, part material, machine devices and cutting tools.

With the whole c-PBOM, the three types of carbon emissions evaluation models of feature 14 are listed in Table 8 as follows (Operation content: Turning-Cast iron-FTC-20-CT1/CT2/CT3).

(3) Establish the c-PBOM-T for cutting tools

According to Table 8, carbon emissions of the three cutting tools can be calculated. The calculation process of CT1 is as follows. Firstly, cutting time t_{CT1} is calculated as Eq. (1).

$$t_{CT1} = \frac{60L\Delta}{fa_p} = \frac{60\times 9.9\times 3}{80\times 0.5} = 44.55\text{s} \tag{1}$$

- Carbon emissions CE_1 caused by cutting tool production

$$\begin{aligned} CE_1 &= \frac{t_{CT1}}{T_{CT1}(R+1)}F_{CT1}W_{CT1} \\ &= \frac{44.55}{90\times 60\times 1}\times 27.67\times 15\times 10^{-3} \\ &= 0.00342\text{kg} \end{aligned}$$

where R equals to 1 and F_{CT1} equals to 27.67 kgCO$_2$/kg when the

Table 8 Carbon emissions evaluation models of feature 14

T	Carbon emissions evaluation models		
	MatModel (kg)	EModel (kg)	WModel (kg)
CT1	$\frac{t_{CT1}}{T_{CT1}(R+1)}F_{CT1}W_{CT1}$	$65.04a_p^{0.961}f^{0.391}v_c^{0.733}t_{CT1}F_e$	$\frac{t_{CT1}}{T_{CT1}(R+1)}F_{wCT1}W_{CT1}$
CT2	$\frac{t_{CT2}}{T_{CT2}(R+1)}F_{CT2}W_{CT2}$	$57.26a_p^{0.986}f^{0.431}v_c^{0.813}t_{CT2}F_e$	$\frac{t_{CT2}}{T_{CT2}(R+1)}F_{wCT2}W_{CT2}$
CT3	$\frac{t_{CT3}}{T_{CT3}(R+1)}F_{CT3}W_{CT3}$	$63.74a_p^{0.953}f^{0.331}v_c^{0.791}t_{CT3}F_e$	$\frac{t_{CT3}}{T_{CT3}(R+1)}F_{wCT3}W_{CT3}$

Table 9 c-PBOM-T of feature 14

FE	Tools		Cutting parameters			Carbon emissions of cutting tools			
	PR	TE	a_p	f	v_c	Mat	E	W	Sum
001 30 01 01 02 01 153 01 000	1	C01 E00 07 15 20 49 01	0.5	0.2	66.59	0.00342	0.0309	0.000002	0.034
	3	C01 E00 08 16 40 49 02	0.6	0.05	99.89	0.01319	0.1098	0.000006	0.123
	2	C01 E00 08 18 20 49 03	0.6	0.15	133.2	0.00242	0.0397	0.000001	0.042

carbon emission factor of electricity is 0.63095 kgCO$_2$/ kWh.[27]

- Carbon emissions CE_2 caused by electrical energy consumption

$$\begin{aligned}CE_2 &= 65.04a_p^{0.961}f^{0.391}v_c^{0.733}t_{CT1}F_e\\ &= 65.04\times0.5^{0.961}\times80^{0.391}\times66.59^{0.733}\times44.55\times\frac{0.63095}{3.6\times10^6}\\ &= 0.0309\text{kg}\end{aligned}$$

where the value of F_e is adopted by the baseline emission factor of regional power grids of China in 2015,[35] which is 0.63095 kgCO$_2$/kWh.

- Carbon emissions CE_3 caused by waste disposal of cutting tools

$$\begin{aligned}CE_3 &= \frac{t_{CT1}}{T_{CT1}(R+1)}F_{wCT1}W_{CT1}\\ &= \frac{44.55}{90\times60\times1}\times0.0135\times15\times10^{-3}\\ &= 0.000002\text{kg}\end{aligned}$$

where F_{wCT1} equals to 0.0135 kgCO$_2$/kg.[36]

Then the carbon emissions of feature 14 can be filled in the c-PBOM-T of the vortex shell workpiece as shown in Table 9.

It can be clearly seen that the total carbon emissions of these three cutting tools, which are 0.034, 0.123 and 0.042, are significant different. As a result, the first turning tool should be selected to complete the hole machining of the vortex shell workpiece when they all meet the requirement of processing conditions. The recommended sequence of cutting tools is: CT1 > CT3 > CT2, which is in the ascending order of carbon emissions. At the same time, for the same cutting tool, the three types of carbon emissions are different as well. The maximum carbon emissions are produced by the electrical energy consumption and the minimum carbon emissions are produced by the waste disposal.

5.3 Discussion

Cutting configuration is the critical link in the machining process. To create a unified, eco-friendly, and simple process is a challenge for workshop operators. The ontology-based cutting tool configuration method has more advantages, especially when the factor of carbon emissions is considered. The case study is just illustrative of this point. The key findings from the case study are described as follows.

(1) The ontology-based cutting tool configuration architecture provides an effective and common process for operators

Based on the architecture, operators can easily configure the optimal cutting tools for a part and its features. Although the case study only gives the configuration process of feature 14, all features of the vortex shell workpiece can be reasoned and evaluated in the same way. Thus, an optimal recommended sequence of cutting tools considered carbon emissions will be obtained and recorded in the database of the company.

(2) The cutting tool configuration knowledge can be represented and modeled by using ontology tools and SWRL rules.

In the process of cutting tool matching, many concepts, such as materials, structure, equipment, and machining condition, are very complex in representation. Ontology and SWRL rules are used to describe the configuration process knowledge and inference rules. The case study validates the ontology-based configuration process. In addition, the established cutting configuration ontology can be reused, shared, and extended to other companies with similar requirements.

(3) The evaluation method considering carbon emissions can provide a strong support for low-carbon manufacturing

Different cutting tools have different effects on carbon emissions. The carbon emissions source of material, energy consumption, and waste is evaluated in the case study. Obviously, the carbon emissions of the chosen cutting tools are apparently different. The real cutting tool users are the workers, even the computer programs, so the table-looked method (that is, the c-PBOM-T) is more direct and simple for them. Compared with the traditional cutting tool selection methods, the method proposed in this paper is more suitable for current demands in environmental friendliness.

The key findings from this case could be converted into significant managerial implications, which could be used for helping different manufacturing companies to facilitate their behaviors in the cutting tool configuration and management. Firstly, the common configuration process for cutting tools can increase the matching efficiency. There are two reasons: a) to realize cutting tool configuration, the company should construct their cutting tool database, part feature database, ontology model, and configuration rules. Once the basic work is completed, the cutting tools can be acquired rapidly. b) The evaluation process is based on a kind of table look-up way, so the optimal cutting tool is easy to be determined. Secondly, the presented knowledge-based method will decrease the costs caused by human errors and carbon emissions. Thirdly, low-carbon manufacturing is a strong tendency for industrial companies. Low-carbon technologies and evaluation are crucial for enterprise development. Therefore, the cutting tool evaluation method considering carbon emissions is important to the implementation of enterprise green management.

6. Conclusions

To configure the optimal cutting tools for matching features of workpieces under the background of low-carbon manufacturing is a challenging problem in the modern machining process. This paper introduces an ontology-based cutting tool configuration process to provide the optimal schemes considering carbon emissions. An overall architecture of the cutting tool configuration is proposed, which includes three key technologies. The first technology is to construct the cutting tool information model and part feature information model to provide knowledge. Considering the complexity of configuration process, the second technology is to use the ontology to describe the configuration process knowledge and the SWRL to build the inference rules. Then the feasible configuration schemes are obtained based on the FaCT++. The third technology is to evaluate the feasible schemes based on the c-PBOM table and c-PBOM-T table to acquire the recommended sequence of cutting tools. Lastly, the proposed method is demonstrated through an example of the vortex shell workpiece.

This paper contributes on several aspects related to the cutting tool configuration. Firstly, the overall architecture of cutting tool configuration establishes the link between the cutting tool matching and carbon emission evaluation, which is more consistent with the background of green manufacturing. Secondly, the ontology-based approach is an effective knowledge modeling method to construct the configuration knowledge of cutting tools and features. The feasible cutting tool configuration schemes are obtained easily by using the SWRL rules, which are classified into two types in this paper, i.e., qualitative ontology rules and quantitative ontology rules. The ontology-based reasoning helps operators to select the feasible cutting tools instead of the error-prone artificial experience. Thirdly, the c-PBOM-T table provides the available resources of a company. When the table integrates all cutting tools, devices and features within the company and the content is rich enough, selecting the optimal cutting tools for similar features of parts will become much easier. The table-lookup method is more effective and simple to decide the proper cutting tool sequence under the constraints of carbon emissions. The low-carbon-oriented evaluation method of cutting tools will reduce carbon emissions for the whole machining manufacturing process and has a strong role in guiding actual production.

Future research directions are carried out as follows. First, the cutting tool information model and part feature information model should be improved, especially part feature types and cutting tool types. Second, the inference rules should be improved and enriched to support the intelligent push technology of cutting tools for operators. Third, other factors such as the cutting tool life span, inventory, costs and production quota will be considered in the evaluation method.

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REFERENCES

1. Brenner, D., Kleinert, F., Imiela, J., and Westkämper, E., “Life Cycle Management of Cutting Tools: Comprehensive Acquisition and Aggregation of Tool Life Data,” Procedia CIRP, Vol. 61, pp. 311-316, 2017.
2. Mookherjee, R. and Bhattacharyya, B., “Development of an Expert System for Turning and Rotating Tool Selection in a Dynamic Environment,” Journal of Materials Processing Technology, Vol. 113, No. 1, pp. 306-311, 2001.
3. Oral, A. and Cakir, M.C., “Automated Cutting Tool Selection and Cutting Tool Sequence Optimisation for Rotational Parts,” Robotics and Computer-Integrated Manufacturing, Vol. 20, No. 2, pp. 127-141, 2004.
4. Lin, A. C. and Wei, C.-L., “Automated Selection of Cutting Tools Based on Solid Models,” Journal of Materials Processing Technology, Vol. 72, No. 2, pp. 317-329, 1997.
5. Avram, O., Stroud, I., and Xirouchakis, P., “A Multi-Criteria Decision Method for Sustainability Assessment of the Use Phase of Machine Tool Systems,” The International Journal of Advanced Manufacturing Technology, Vol. 53, No. 5, pp. 811-828, 2011.
6. Yan, W., Zanni-Merk, C., Rousselot, F., Cavallucci, D., and Collet, P., “Ontology-Based Knowledge Modeling for Using Physical Effects,” Procedia Engineering, Vol. 131, pp. 601-615, 2015.
7. Chen, R.-C., Huang, Y.-H., Bau, C.-T., and Chen, S.-M., “A Recommendation System Based on Domain Ontology and SWRL for Anti-Diabetic Drugs Selection,” Expert Systems with Applications, Vol. 39, No. 4, pp. 3995-4006, 2012.
8. Li, A., Zhao, J., Gong, Z., and Lin, F., “Optimal Selection of Cutting Tool Materials Based on Multi-Criteria Decision-Making Methods in Machining Al-Si Piston Alloy,” The International Journal of Advanced Manufacturing Technology, Vol. 86, Nos. 1-4, pp. 1055-1062, 2016.
9. Campatelli, G., Scippa, A., and Lorenzini, L., “Workpiece Orientation and Tooling Selection to Reduce the Environmental Impact of Milling Operations,” Procedia CIRP, Vol. 14, pp. 575-580, 2014.
10. Zhou, D. and Dai, X., “A Granulation Analysis Method for Cutting Tool Material Selection Using Granular Computing,” Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical

Engineering Science, Vol. 230, No. 13, pp. 2323-2336, 2016.

11. Liu, Z.-J., Sun, D.-P., Lin, C.-X., Zhao, X.-Q., and Yang, Y., “Multi-Objective Optimization of the Operating Conditions in a Cutting Process Based on Low Carbon Emission Costs,” Journal of Cleaner Production, Vol. 124, pp. 266-275, 2016.
12. Buyurgan, N., Saygin, C., and Kilic, S. E., “Tool Allocation in Flexible Manufacturing Systems with Tool Alternatives,” Robotics and Computer-Integrated Manufacturing, Vol. 20, No. 4, pp. 341-349, 2004.
13. Saranya, K., Jegaraj, J. J. R., Kumar, K. R., and Rao, G. V., “Artificial Intelligence Based Selection of Optimal Cutting Tool and Process Parameters for Effective Turning and Milling Operations,” Journal of the Institution of Engineers (India): Series C, pp. 1-12, 2016. (DOI: 10.1007/s40032-016-0264-7)
14. Gjelaj, A., Balič, J., and Fičko, M., “Intelligent Optimal Tool Selections for CNC Programming of Machine Tools,” Transactions of FAMENA, Vol. 37, No. 3, pp. 31-40, 2013.
15. Arunachalam, A. P. S., Idapalapati, S., and Subbiah, S., “Multi-Criteria Decision Making Techniques for Compliant Polishing Tool Selection,” The International Journal of Advanced Manufacturing Technology, Vol. 79, Nos. 1-4, pp. 519-530, 2015.
16. Mejia-Ugalde, M., Trejo-Hernandez, M., Dominguez-Gonzalez, A., Osornio-Rios, R. A., and Benitez-Rangel, J. P., “Directional Morphological Approaches from Image Processing Applied to Automatic Tool Selection in Computer Numerical Control Milling Machine,” Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 227, No. 11, pp. 1607-1619, 2013.
17. Tan, C. F., Ranjit, S. S. S., and Kher, V. K., “An Expert Carbide Cutting Tools Selection System for CNC Lathe Machine,” International Review of Mechanical Engineering, Vol. 6, No. 7, pp. 1402-1405, 2012.
18. Wu, X., Feng, G., and Wu, T., “Intelligent Service Platform of Manufacturing Process and Tool Based on Data Warehouse,” Procedia CIRP, Vol. 56, pp. 338-343, 2016.
19. Zhang, Y., Luo, X., Zhang, H., and Sutherland, J. W., “A Knowledge Representation for Unit Manufacturing Processes,” The International Journal of Advanced Manufacturing Technology, Vol. 73, Nos. 5-8, pp. 1011-1031, 2014.
20. Lemaignan, S., Siadat, A., Dantan, J.-Y., and Semenenko, A., “Mason: A Proposal for an Ontology of Manufacturing Domain,” Proc. of IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications, pp. 195-200, 2006.
21. Rehage, G. and Gausemeier, J., “Ontology-Based Determination of Alternative CNC Machines for a Flexible Resource Allocation,” Procedia CIRP, Vol. 31, pp. 47-52, 2015.
22. Eum, K., Kang, M., Kim, G., Park, M. W., and Kim, J. K., “Ontology-Based Modeling of Process Selection Knowledge for Machining Feature,” Int. J. Precis. Eng. Manuf., Vol. 14, No. 10, pp. 1719-1726, 2013.
23. Ramesh, S., Palanikumar, K., Elangovan, K., and Karunamoorthy, L., “Machining Titanium Alloy with Pulsed Injecting Coolant Technique to Improve a Eco-Friendly Enviornment in Industries,” Proc. of the 19th AeroMat Conference and Exposition, 2008.
24. Thiede, S., Seow, Y., Andersson, J., and Johansson, B., “Environmental Aspects in Manufacturing System Modelling And Simulation - State of the Art and Research Perspectives,” CIRP Journal of Manufacturing Science and Technology, Vol. 6, No. 1, pp. 78-87, 2013.
25. Duflou, J. R., Kellens, K., and Dewulf, W., “Unit Process Impact Assessment for Discrete Part Manufacturing: A State of the Art,” CIRP Journal of Manufacturing Science and Technology, Vol. 4, No. 2, pp. 129-135, 2011.
26. Song, J.-S. and Lee, K.-M., “Development of a Low-Carbon Product Design System Based on Embedded GHG Emissions,” Resources, Conservation and Recycling, Vol. 54, No. 9, pp. 547-556, 2010.
27. Li, C., Tang, Y., Cui, L., and Li, P., “A Quantitative Approach to Analyze Carbon Emissions of CNC-Based Machining Systems,” Journal of Intelligent Manufacturing, Vol. 26, No. 5, pp. 911-922, 2015.
28. Lin, W., Yu, D., Zhang, C., Zhang, S., Tian, Y., Liu, S., and Luo, M., “Multi-Objective Optimization of Machining Parameters in Multi-Pass Turning Operations for Low-Carbon Manufacturing,” Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 231, No. 13, pp.2372-2383, 2016. (DOI:10.1177/0954405416629098)
29. Yi, Q., Li, C., Tang, Y., and Chen, X., “Multi-Objective Parameter Optimization of CNC Machining for Low Carbon Manufacturing,” Journal of Cleaner Production, Vol. 95, pp. 256-264, 2015.
30. Kara, S. and Li, W., “Unit Process Energy Consumption Models for Material Removal Processes,” CIRP Annals-Manufacturing Technology, Vol. 60, No. 1, pp. 37-40, 2011.
31. Mativenga, P. T. and Rajemi, M. F., “Calculation of Optimum Cutting Parameters Based on Minimum Energy Footprint,” CIRP Annals-Manufacturing Technology, Vol. 60, No. 1, pp. 149-152, 2011.
32. Tan, X. C., Liu, F., Cao, H. J., and Zhang, H., “A Decision-Making Framework Model of Cutting Fluid Selection for Green Manufacturing and a Case Study,” Journal of Materials Processing Technology, Vol. 129, No. 1, pp. 467-470, 2002.
33. Tan, X. C., Liu, F., Cao, H. J., Zhang, P., “A Decision-Making Framework Model of Tool Selection for Green Manufacturing and Its Applications,” Journal of Chongqing University, Vol. 26, No. 3, pp. 117-121, 2003.
34. Zhou, G., Zhou, C., Lu, Q., Tian, C., and Xiao, Z., “Feature-Based Carbon Emission Quantitation Strategy for the Part Machining Process,” International Journal of Computer Integrated Manufacturing, 2017. (DOI:10.1080/0951192X.2017.1328561)

35. National Development and Reform Commission," Baseline Emission Factor of Regional Power Grids of China in 2015," http://cdm.ccchina.gov.cn/Detail.aspx?newsId=61599&TId=19 (Accessed 17 OCT 2017) (in Chinese)

36. Narita, H., Desmira, N., and Fujimoto, H., "Environmental Burden Analysis for Machining Operation Using LCA Method," in: Manufacturing Systems and Technologies for the New Frontier: The 41st CIRP Conference on Manufacturing System, Mitsuishi, M., Ueda, K., Kimura, F., (Eds.), pp. 65-68, 2008.

APPENDIX A

Table A.1 Encoding bit instruction of cutting tools

The 1st bit		The 2nd and 3rd bit	The 4th-6th bit	The 7th-12th bit	The 13th bit	The 14th bit
Processing method		Category	Dimension parameter	Blade information	Assembly method	Brand
C	Turning	00 External /facing turning tool 01 Boring tool 02 Forming tool 03 Cut-off tool 04 Threading tool 05 Slotting tool 06 Compound tool	Length	Relief angle, length of cutting edge, material, machining precision	0 Integral type 1 Welded type 2 Sintered type 3 Assembly type 4 Indexable type	0 SECO 1 Mitsubishi 2 BIG 3 ISDBR 4 Kennameta 5 Sandvik 6 Tungaloy 7 NIKKEN 8 Starrag 9 Others
X	Milling	00 Face and side cutter 01 Face milling cutter 02 End mill 03 Disc milling cutter 04 Non-curved milling cutter 05 Gang milling cutter 06 Formed milling cutter 07 Thread milling cutter	Diameter, length, number of teeth	Relief angle, length of cutting edge, material, machining precision		
K	Hole processing	00 Twist drill 01 Center drill 02 Polygon-hole drill 03 Boring tool 04 Reamer 05 Deep-hole drilling 06 Expanding drill 07 Screw tap	Diameter, length	Relief angle, shape, material, machining precision		
B	Planing	00 Flat cutter 01 Offset tool 02 Angle offset tool	Diameter, length	Relief angle, length of cutting edge, material, machining precision		
L	Broaching	00 Round hole broach 01 External broach 02 Keyway/spline broach 03 Push-type broach	Diameter, length, number of teeth	Relief angle, shape, material, machining precision		
CL	Gear cutting	00 Gear shaping cutter 01 Gear cutter hob 02 Slotting cutter 03 Turbine tool	Diameter, number of teeth	Relief angle, length of cutting edge, material, machining precision		

Table A.2 Encoding bit instruction of part features

First-level classification	Second-level classification	Processing method
01 Hole	01 Through hole 02 Blind hole 03 Thread through hole 04 Thread blind hole 05 Square hole…	01 Turning 02 Milling 03 Drilling 04 Grinding 05 Boring 06 Gear cutting 07 Slotting 08 Broaching 09 Non-traditional machining
02 Groove	01 Straight flute 02 Arc groove 03 Square groove 04 T-groove 05 Dovetail groove 06 V-groove…	
03 Plane	01 General plane 02 Stepped faces 03 End face 04 Bevel	
04 Surface	01 Sphere 02 Cone 03 Torus 04 Cylinder 05 External circular surface 06 Irregular surface	
05 Blend	01 Fillet 02 Right angle…	
06 Others	01 Thread…	

Material attribute			Accuracy
1st	2nd	3rd	Rank
Material	Heat treatment method	Rockwell hardness	
0 Steel 1 Cast iron 2 Stainless steel 3 Nonferrous metals 4 Titanium alloy 5 Hardening material 6 Aluminum bar 7 Special materials	0 Normalization 1 Anneal 2 Quench 3 Temper 4 Carburize 5 None	0 20-30 1 30-40 2 40-50 3 50-60 4 60-70 5 70-80	01 Rough machining 02 Semifinishing 03 Finish machining 04 Superfinish

Table A.3 Main features of the vortex shell

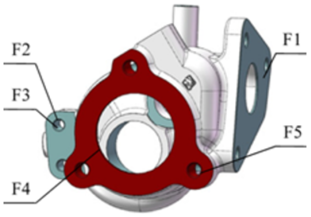
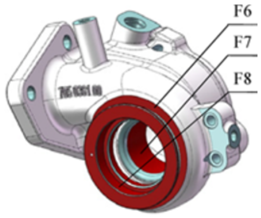
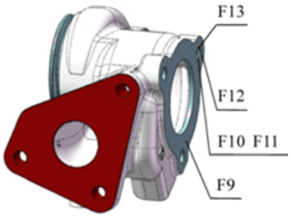
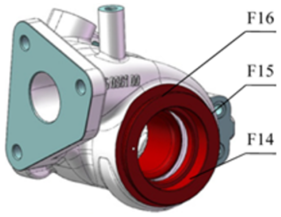
No.	Feature names	Feature encoding	Features
1	F1	001 10 01 03 01 02 153 01 000	
2		001 10 02 03 01 02 153 03 000	
3	F2	001 10 03 01 02 03 153 01 000	
4	F3	001 10 04 01 01 02 153 01 000	
5	F4	001 10 05 01 01 02 153 01 000	
6	F5	001 10 06 05 02 02 153 01 000	
7	F6	001 10 07 03 01 02 153 01 000	
8	F7	001 10 08 01 01 05 153 03 000	
9	F8	001 10 09 01 02 05 153 03 000	
10	F9	001 20 01 03 01 02 153 01 000	
11		001 20 02 03 01 02 153 03 000	
12	F10	001 20 03 01 01 03 153 01 000	
13	F11	001 20 04 01 01 02 153 01 000	
14	F12	001 20 05 05 02 02 153 01 000	
15	F13	001 20 06 01 03 03 153 01 000	
16	F14	001 30 01 01 02 01 153 01 000	
17	F15	001 30 02 01 02 01 153 01 000	
18	F16	001 30 03 02 02 01 153 01 000	
…	…	…	
38	F35	001 40 20 05 02 02 153 01 000	

Table A.4 c-PBOM of parts

F	Operation content				Carbon emission evaluation models		
	M	Ma	D	T	MatModel	EModel	WModel
External cylindrical surface	Turning	Alloy steel	CA6140	T1	CE_1	CE_2	CE_3
External cylindrical surface	Turning	Alloy steel	FTC-20	T2	CE_1	CE_2	CE_3
Hole	Turning	Alloy steel	FTC-20	T3	CE_1	CE_2	CE_3
Hole	Turning	Cast iron	FTC-20	T3	CE_1	CE_2	CE_3
Hole	Drill	Alloy steel	VDL1000	T4	CE_1	CE_2	CE_3
Plane	Milling	Aluminum alloy	XKA5032	T5	CE_1	CE_2	CE_3
…	…	…	…	…	…	…	…

APPENDIX B

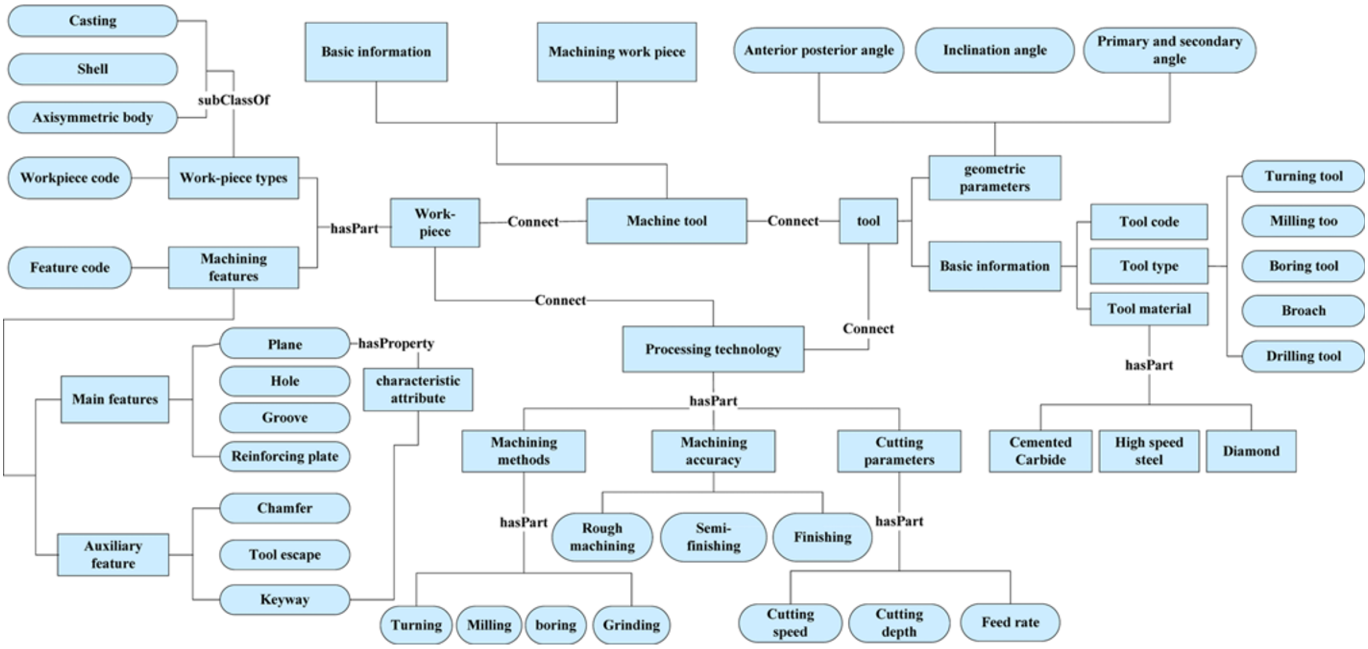
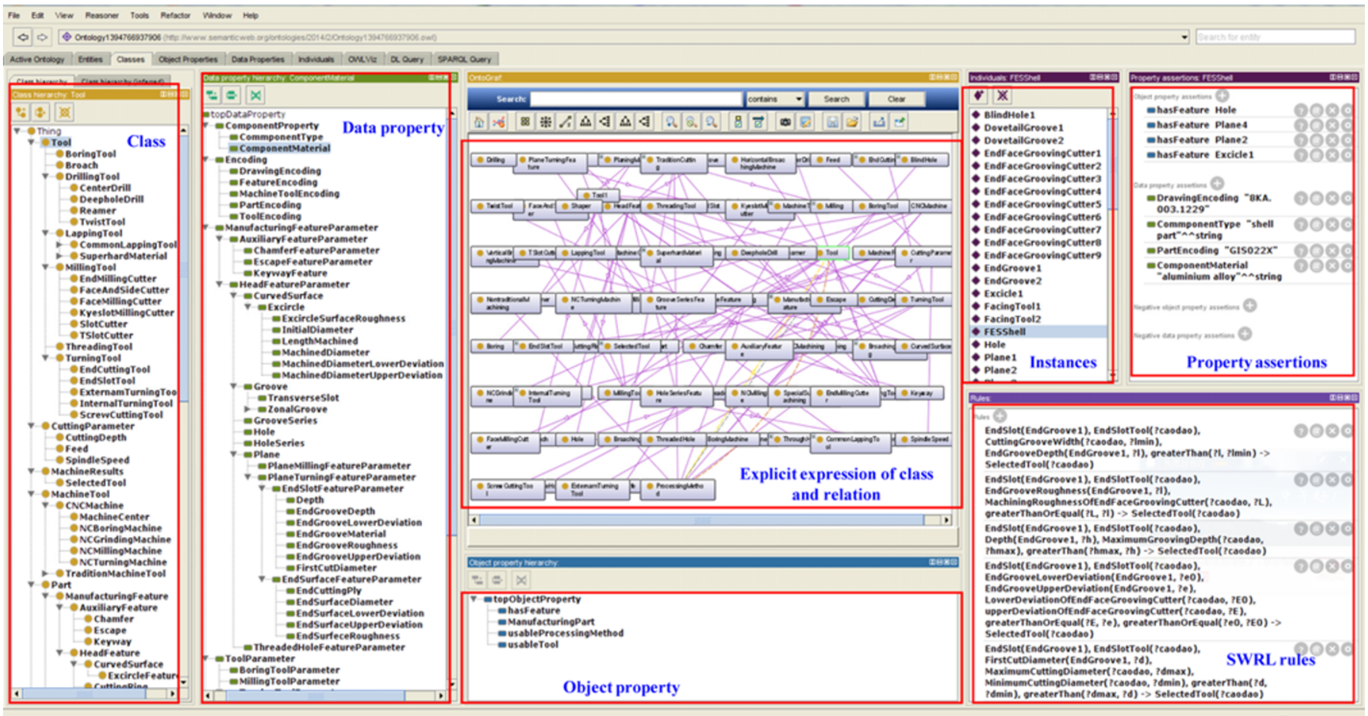


Fig. B.1 Ontology-based knowledge framework of the cutting tool configuration



Property assertions: FESShell

Object property assertions
- hasFeature Hole
- hasFeature Plane4
- hasFeature Plane2
- hasFeature Excicle1

Data property assertions
- DrawingEncoding "8KA. 003.1229"
- CommmponentType "shell part"^^string
- PartEncoding "GIS022X"
- ComponentMaterial "aluminium alloy"^^string

Rules:

```
EndSlot(EndGroove1), EndSlotTool(?caodao),
CuttingGrooveWidth(?caodao, ?lmin),
EndGrooveDepth(EndGroove1, ?l), greaterThan(?l, ?lmin) ->
SelectedTool(?caodao)
EndSlot(EndGroove1), EndSlotTool(?caodao),
EndGrooveRoughness(EndGroove1, ?l),
MachiningRoughnessOfEndFaceGroovingCutter(?caodao, ?L),
greaterThanOrEqual(?L, ?l) -> SelectedTool(?caodao)
EndSlot(EndGroove1), EndSlotTool(?caodao),
Depth(EndGroove1, ?h), MaximumGroovingDepth(?caodao,
?hmax), greaterThan(?hmax, ?h) -> SelectedTool(?caodao)
EndSlot(EndGroove1), EndSlotTool(?caodao),
EndGrooveLowerDeviation(EndGroove1, ?e0),
EndGrooveUpperDeviation(EndGroove1, ?e),
LowerDeviationOfEndFaceGroovingCutter(?caodao, ?E0),
upperDeviationOfEndFaceGroovingCutter(?caodao, ?E),
greaterThanOrEqual(?E, ?e), greaterThanOrEqual(?e0, ?E0) ->
SelectedTool(?caodao)
EndSlot(EndGroove1), EndSlotTool(?caodao),
FirstCutDiameter(EndGroove1, ?d),
MaximumCuttingDiameter(?caodao, ?dmax),
MinimumCuttingDiameter(?caodao, ?dmin), greaterThan(?d,
?dmin), greaterThan(?dmax, ?d) -> SelectedTool(?caodao)
```

Fig. B.2 Ontology modeling with Protégé 4.3