STEP-NC Feature-based Cutting Tool Recommendation System

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Abstract. In the CNC machining process of parts, suitable cutting tool selection is crucial to machining efficiency and cost. In practices, cutting tool selection still mainly relies on the technicians' experiences because of the information loss from the part design to machining at the process planning stage. In this paper, a STEP-NC feature based cutting tool recommendation system is introduced for automatic tool selection during the CAD/CAM stage, which is composed of feature based integrated design module and the cutting tool selection module. A cutting tool combination evaluation model based on machining expense and energy consumption was integrated into the system of which the data structure is organized using STEP-NC. A typical part was tested to verify the feasibility of the proposed system.

Keywords: Cutting Tool Recommendation, STEP-NC, Machining Feature, Machining Expense, Energy Consumption
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1 INTRODUCTION

The CNC machining industry is on a trend to more customized products, where multi-species small-batch products will form the major orders. Quick response to product orders requires higher requirements of the capacity of designing and machining. Manpower-based cutting tool selection hinders the efficiency of integrated designing and machining and brings much uncertainty because of its heavily relying on technicians' experiences. Meanwhile, suitable cutting tool selection is crucial to machining efficiency and cost control. Thus, cutting tool selection should become automated and even intelligent in future integrated manufacturing.

Many researches have been initiated for the cutter selection in the last serval decades. Most of the researches focused on the toolpath generation, which almost exclusively considered the geometric information, and the main research idea is to optimize the toolpath in order to satisfy the machining requirement. In addition, the objectives of cutting tool selection mainly concentrate on time and expense. Fewer computer-aided tool selection systems were actually shown to help technicians to select proper cutting tools at the stage of CAD/CAM, thus not easy to evaluate its effectiveness in the highly integrated IT tools-based environment. In conclusion, the cutting tool selection evaluation index and adaptive selection methodology need to be rethought in the integrated design and manufacturing environment.

The STEP-NC provides an excellent data model for integrated designing and machining activities, including cutting tool selection, which is an extension of STEP and allows connecting CAD/CAM design to CNC machining. It not only gives the comprehensive description of machining features but also machining resources such as operation, working step, strategy, and machine tool, which provide the sufficient information for automatically cutting tool selection. Each machining feature defines the corresponding machining operations that contain cutting tools and machining strategy. The standard also gives the functionalized definition of the cutting tool model which is helpful to make full use of cutting tool parameters. Based on the standard, the machining expense and the energy consumption can be merged to machining features to establish a new cutting tool selection methodology. The methodology roundly takes many aspects into consideration including geometric parameters, process information, tool magazine, toolpath generation, tool expense, machining time, and cutting power.

In this paper, a two-step solution based on STEP-NC is used to deal with the cutting tool selection that contains constructing effective cutting tool combinations and choosing optimal tools. There are many factors influencing cutting tool selection, including geometry constraint, process parameters, workpiece and tool materials, tool magazine, as well as toolpath strategies. A comprehensive data model which contains all of the factors are needed to support selection schema. Except for time and expense, the research result [9] shows that energy consumption varies among different cutting tools. A multivariate and multi-objective evaluation model including expense and energy consumption based on feature is introduced to select proper tools for higher efficiency and lower cost.

A STEP-NC feature based cutting tool recommendation system is implemented to verify the feasibility and efficiency of the cutting tool selection algorithm. The system is composed of feature based integrated design module and the cutting tool selection module. The integrated design module established a necessary operation platform which supports geometry modeling, database inquiring, and the reading/writing of STEP-NC file. The proposed cutting tool selection methodology is realized in selection module and design module provides geometry and process parameters. Ultimately, all the designing and machining information are expressed by STEP-NC file that contains the geometry, process, and recommended tool information.

The paper is organized as follows. Section 2 presents a literature review about STEP-NC and cutting tool selection. STEP-NC feature based cutting tool recommendation system is introduced in Section 3. The recommendation system is demonstrated in section 4 and a typical part is tested to verify the feasibility. We end with the conclusion in Section 5.

2 LITERATURE REVIEW

STEP-NC is characterized by a comprehensive data structure and a bidirectional data flow for the CAD-CAM-CNC digital manufacturing chain. It provides traditional CAx activity with a novel operating notion to realize digitalized, automated, and even intelligent manufacture capacities. Many researchers devote themselves to improve the intelligence of CAx activities using STEP-NC as enabling technology. Newman et al.[13] introduced the framework for implementation of STEP-complaint CAD/CAM aiming at replacing traditional NC controller driven by G code. A STEP-compliant CNC machine tool and a G-code free machining scenario were established by Xu [23] to realize the STEP-NC enabled machining. A STEP-complaint process planning system with surface roughness chosen as the objective for CNC turning machining was presented by Zhang et al.[25], which illustrates the potential that a STEP-NC data model provides the basis for standardized process planning and CNC machining. For the optimization of machining parameters, Ridwan et al. [16] proposed a system that consists of optimization, process control, and evaluation module with STEP-NC as the underlying data model. Lei et al. [10] leveraged the STEP-NC inspection data model and establish a STEP-NC compatible on-machine measurement prototype system to realize the automated correlation of inspection data. Danjou et al. [3] exposed a STEP-NC solution to ensure closed-loop manufacturing from CNC machines to CAM systems aiming to assist CAM programmers in process planning. It can be inferred that STEP-NC can provide complete information for CAD/CAM and largely offer data support for cutting tool selection.

Earlier Literature analysis on cutting tool selection indicated that some researchers mainly focus on how to generate optimal toolpath or how to improve machining efficiency as well as reduce the cost. To select a reasonable tool sequence that minimizes the total rough-machining time for 2.5D machining slab, Mahadevan et al. [2] proposed an approach that contains an integer linear programming formulation to show the task complexity and a network flow formulation for obtaining an approximate solution to the problem. For the sake of reducing NC machining time effectively, Ding et al. [4] introduced a new methodology for complex mould machining based on an efficient interference detection algorithm without tool path generation before cutter selection. Chun et al. [24] converted the tool selection of arbitrarily shaped 3D pockets into 2D toolpath planning and the proposed method was used to choose the optimal cutting tool combination, which was quick and sufficient for CAPP and CAM environments. Similarly, for the polygonal pockets with islands, Hemant et al. [15] put forward a methodology to select a sequence of tools to minimize the total time with the algorithm which decomposes the pocket geometry into convex regions and deals with each region independently. The latest research mainly focused on improving cutting tool selection algorithms [20][21]. However, these algorithms were still a lack of complete information model support. Saranya et al. [17] took tool life and cost into account and employ artificial intelligence techniques such as neural networks, genetic algorithms, and fuzzy theory to implement cutting tool selection. A cutting tool selection method based on big data was proposed by Wang et al. [19] in the stage of CAPP to support users to select tools, in which production process data was effectively utilized and an intelligent tool selection model was built. Some cutting tool selection researches were down to feature level. An enriched machining feature-based approach on cutter selection was proposed by Ji et al. [8] which includes a two-step workflow: filtering according to workpiece material, geometries of manufacturing features and cutting tool inventory, and optimizing according to machining cost. Zhou et al. [26] proposed a deep learning-based cutting tool selection approach for special-shaped machining features of complex products which transform the problem of cutter selection into a feature recognition problem.

The energy consumption of CNC machining has received wide attention and obtained rich research results recently. Energy consumption is regarded as the assessment criteria of the cutting tool selection in this paper. The establishment of an energy consumption model is very important for establishing the relationship with cutting tools to assist the cutting tool selection. Avram et al. [1] proposed a methodology to estimate the mechanical energy requirements of the spindle and feed axes with respect to 2.5D machining strategies considering variable and constant power flows with respect to various use phase regimes of a machine tool system. Li et al. [11] presented an energy consumption model with high accuracy and well-defined coefficients to provide a reliable estimation of energy consumption under various machining conditions. A new energy consumption model considering cutting force for the machine tool system is introduced by Liu et al. [12] which shows a relatively good prediction effect. Tao et al. [14] proposed an interoperable energy analysis system for energy saving, which contains two important techniques, hybrid energy consumption modeling as well as the integrated, standardized, and STEP-NC compliant energy data models.

3 STEP-NC FEATURE BASED CUTTING TOOL RECOMMENDATION SYSTEM

The main function module of feature based cutting tool recommendation system will be introduced in this section. Firstly, a design module is necessary to support not only geometry modeling function but also process plan interface according to the specific machining feature. The STEP-NC provides a complete set of standardization schemas. Hence, a STEP-NC feature based integrated design module should be developed to build a cutting tool selection information platform that supports data transfer of STEP-NC format files. Secondly, the cutting tool model and reasonable cutting tools evaluation indexes will be analyzed in detail. The machining expense and energy consumption are regarded as evaluation index for cutting tools and necessary data elements are extended in the cutting tool model. They are the core of feature based cutting tool selection algorithm. Based on the cutting tool model and proposed cutting tool evaluation model, a specific algorithm that is based on full use of geometric and non-geometric information is introduced to realize final cutting tool selection.

3.1 STEP-NC Feature-based Integrated Design Module

Three kinds of information are defined in the STEP-NC which contains geometric information, process information, and cutting tool information. Process information and cutting tool information are defined as two properties of the operation that has a one-to-many relationship with the feature. The core of the integrated design is to complete the planning of geometric and non-geometric information as much as possible in the design stage.

- Feature modeling

ISO 14649-10 [5] specifies a feature catalogue containing machining features (planar_face, pocket, slot, step, round_hole, boss…) which have standardized definitions of geometric attributes. Assigning values to these attributes will result in the desired feature shape, that is the idea of parametric modeling. Machining features are normally decreased from the blank in terms of subtractive volumes. The designer is only required to provide the feature parameters according to the standard definition and modeling module removes corresponding geometric volume in the stock. During the modeling, all the geometry parameters will be stored according to the STEP-NC data structure. Except for STEP-NC feature-based modeling, feature recognition is another way to obtain the geometric parameters. However, designing by STEP-NC feature has two advantages comparing with general design-by-feature and feature recognition, which can be summarized as eliminating the error of conversion from design features to manufacturing features and binding machining process data to the single machining feature. It provides a promising idea of machining optimization in feature-level.

- Process parameter inquiry

Except for geometry information, ISO 14649-11 [6] defines necessary technology data for each machining feature. The technology data are organized in machining operation and each operation corresponds only with one feature while each machining feature has association with one or more operations. The machining feature and associated machining operation forms the machining workingstep. Some technology data depend on machining equipment but some are decided by process knowledge database. The key machining parameters, such as axial depth, radial depth, feed rate, and spindle speed, are usually determined by cutting tool material and workpiece material. In fact, machining parameters optimization is another important research filed. In this paper, an approach on building machining parameter database is adopted to realize the automatic acquisition of technology parameter. When a machining feature is finished modeling, the machining parameters are filled in machining operation data model by querying the parameter database.

- Exchange use STEP-NC file

The STEP-NC file is expressed by STEP (ISO 10303) Part21 which is the neutral text encoding standard for the file exchange structure in STEP standard. It is an implementation method of STEP standard. It specifies the exchange structure format of product data using text encoding. The file format is suitable for the exchange of product data between different computer systems. The STEP-NC data model adopted the concept of object-oriented programming, which is completely compose of numerous entities. The data model has good scalability and can be extended by defining necessary entities. The reading and writing function of STEP-NC file can be realized through Standard Data Access Interface (SDAI) provided by ISO 10303. All the functions are encapsulated in the dynamic link library to facilitate the STEP-NC file reading and writing operation. A typical STEP-NC file is shown in Figure 1.

3.2 Milling Cutting Tool Model

- Extended STEP-NC model for milling cutting tool

In order to work with ISO 14649-11, the ISO specifies data elements needed as tools for milling. The original purpose of the data model gives the NC controller enough information to select the tool specified in the NC-program. Therefore, the data elements do not describe a complete information of a particular tool but include most key information especially about geometry. In fact, it is reasonable to build the necessary data elements rather than the whole information according to the specific requirements. The STEP-NC cutting tool data for milling in ISO 14649-111 [7] mainly describe three types of static data containing tool type, tool geometry, and tool's expected life. It is enough for traditional NC program to select proper tools. When expense and energy consumption are incorporated into the evaluation rules for tool selection, the data elements contained in the existing tool model are insufficient. Fortunately, the STEP-NC data structure provides a flexible mechanism for researchers to extend necessary data elements based on the existing standard. Thus, necessary data elements about expense and energy consumption are extended for the milling cutting tool model, as shown in Figure 2.

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('Cutting Tool Selection Test Part',''),'1');
FILE_NAME('stepNcFile.stp','2021-03-26T11:10:33',(''),
('Beihang University'),$,'ISO 14649',$);
FILE_SCHEMA(('MACHINING_SCHEMA','MILLING_SCHEMA'));
ENDSEC;
DATA;
...
#7=MILLING_CUTTING_TOOL('T1 End Mill D4',#8,(#10),$,$,$,#21);
...
#43=MILLING_CUTTING_TOOL('T1 End Mill D12',#44,(#46),$,$,$,$);
...
#49=WORKPIECE('SIMPLE
WORKPIECE',#50,0.,$,$,$,(#52,#53,#54,#55));
#50=MATERIAL('ST-50','STEEL',(#51));
...
#62=PROJECT('EXECUTE EXAMPLE1',#63,(#49),$,$,$);
#63=WORKPLAN('MAIN WORKPLAN',(#65),$,#80,$);
#64=SETUP('SETUP 0',#71,#70,(#56));
...
#92=CLOSED_POCKET('POCKET1',#18,(#68,#71),#75,#80,(),$,#81,#8
3,#85,#91);
...
#133=TOOLPATH_LIST((#134,#148,#156,#164,#172,#186,#194,#202
,#210,));
#134=CUTTER_LOCATION_TRAJECTORY(.F.,.TRAJECTORY_PATH.,$,#135
,$,$,#136,#142,$);
...
#135=MILLING_TECHNOLOGY(1000.,.TCP.,$,1000.,$,.F.,.F.,.F.,$);
...
#2248=MACHINING_WORKINGSTEP('Pocketing.2',#75,#1348,#1353,$);
#2249=MACHINING_WORKINGSTEP('Pocketing.3',#75,#1525,#1530,$);
ENDSEC;
END-ISO-10303-21;
```

Header Section
Cutting Tool
Workpiece
Workplan
Machining Feature
Toolpath
Technology
Workingstep

Figure 1: A typical STEP-NC file.

On the basis of the existing cutting tool model, an entity **Tool_Selection_Extension_Data** is supplemented to the **Milling_Cutting_Tool** in the STEP-NC. This extended entity mainly defines the necessary data of tool expense and power consumption. The entity contains four attributes including **Machining_Time**, **Tool_Expense**, **Toollife_Coefficients**, and **Cutting_Fore_Coefficients.** Their EXPRESS schema definitions are as follows. Entity **Machining_Time** defines the time that the tool cuts the entire machining feature. The cutting tool and the machining feature have corresponding relationship during machining process. The **Machining_Time** is a dynamic data that change as machining feature which is an important reference index for certain machining feature to select cutting tools. Because it has a strong association with the tool, it is included as part of the data element of the cutting tool model.

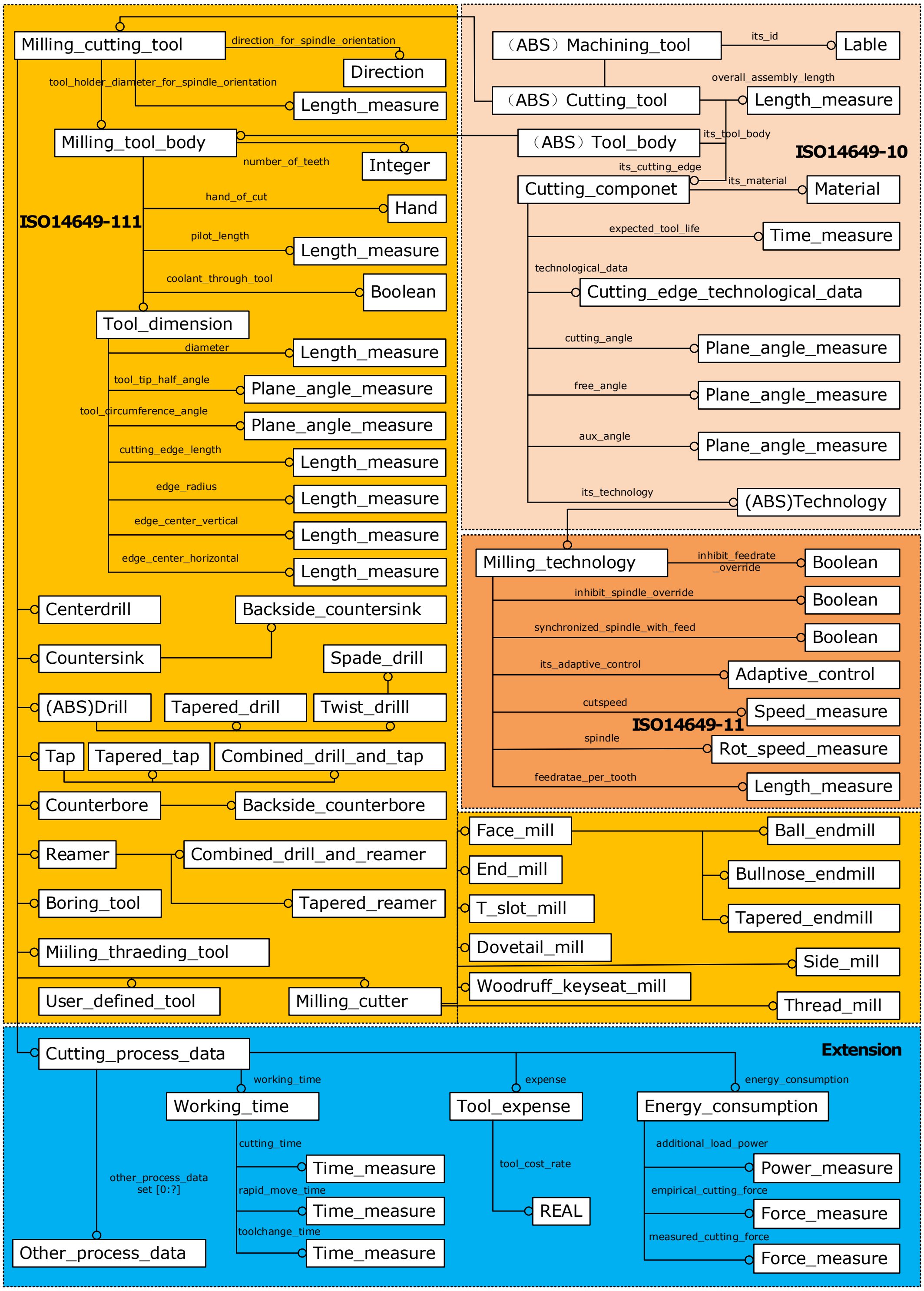


Figure 2: The cutting tool model and its extension based on STEP-NC.

The **Cutting_Time** is the actual time that cutter is in contact with material. In addition to **Cutting_Time**, the **Machining_Time** also include **Rapid_Move_Time** and **Tool_Change_Time**. The tool expense is defined in the entity **Tool_Expense** which is used to be calculated tool expense. Although the existing cutting tool model gives a static numerical description of the cutting tool life. According to the classical tool life formula, different cutting parameters will result in different tool life. The entity Toollife_Coefficients defines the computation coefficient, which is benefical to obtain more accurate tool life in term of machining conditions. The cutting force is the key parameter to calculate energy consumption. Thus, the relevant computing coefficients is defined in the **Cutting_Fore_Coefficients**.

- Cutting tools evaluation index

Machining expense and energy consumption are introduced as the major evaluation index for cutting tool selection. The necessary calculation parameters of cutting tools evaluation can be obtained from the STEP-NC data model and extended cutting tool model. The automatic and intelligent cutting tool selection can be realized in the STEP-NC framework. The combination of STEP-NC data structure and tool selection evaluation is the basis of the cutting tool selection algorithm. The calculation method of machining expense and energy consumption as well as the relationship with the STEP-NC data model will be introduced in detail in this subsection.

The actual machining expense (C_m) for certain machining feature can be refined as cutting tool expense (C_T), machine tool depreciation expense (C_M), and expense of operations (C_P). The three expenses can be calculated by machining expense rate (C_k) multiplying machining time (T_m). The formula is expressed as Equation (1.1) (1.2). C_{tool} is the expense of single cutting tool, T is the life expectancy of cutting tool, M and C_0 represent machine tool expense rate and operation expense rate. The cutting tool lifespan is related to the tool material and cutting parameter. The cutting parameters differ using different diameter of cutting tool. The calculation formula of tool life in the machining state can be expressed as Equation (1.3). C_r is the cutting tool durability coefficient, D、V_c、f_z、a_p、a_e、Z represent tool diameter, cutting speed, feed per tooth, cutting depth, cutting width, and cutting tool number of tooth. $k^0 \sim k^4$ are the index of the corresponding variable, which is used to measure the influence degree of each variable on the tool life. They can be determined by handbook or experiment. The machining time is defined as the sum of cutting time (t_c), rapid move time (t_u) and tool change time (t_g).

$$C_m = C_T + C_M + C_P = T_m C_k = T_m(C_{tool}/T + M + C_0). \tag{1.1}$$

$$T_m = t_c + t_u + t_g \tag{1.2}$$

$$T = \frac{C_r D^{k0}}{V_c f_z^{k1} a_p^{k2} a_e^{k3} z^{k4}} \tag{1.3}$$

The machining energy consumption (E) of machine tool contains auxiliary system energy consumption (E_0), empty load energy consumption (E_u), cutting energy consumption (E_c) and additional load energy consumption (E_a), whose formula is expressed as Equation (1.4). P_0 is the fixed power of machine tool, mainly including the power of auxiliary systems such as lighting, NC system, cooling and lubricating system, etc. P_u is the power required by the machine tool spindle and servo system when the machine tool is running without load, which is called empty load power. P_c is the power loss caused by the cutting load. P_a is the additional load power caused by the increase of cutting force and torque during cutting process. P_u and P_a are approximately linearly proportional according to experimental study which is expressed as Equation (1.5). Different cutting tool diameters will lead to different empty load power, cutting power and additional load power, which will result in different machining energy consumption. Empty load power is mainly composed of the power loss caused by machine tool motor, frequency conversion servo system and, mechanical drive system. It satisfies a quadratic function relation with the spindle speed as Equation (1.6). $a_1 \sim a_2$ are the power loss coefficient of mechanical transmission and P_{loss} is the empty load power loss which is caused by motor and friction loss. The spindle speed will increase as the diameter decrease in order to ensure the rigidity of the cutter which leads to empty load power increased with the decreasing cutting tool diameter. Cutting power has a complex relationship with cutting tool diameter and corresponding cutting parameters. The empirical estimation formula can be expressed as Equation (1.7). F_c is the cutting force, C_F is the force factor, f_z is the feed per cutting tooth and k_{fc} is the cutting correction factor. $m_1 \sim m_5$ are the corresponding cutting force influence indexes. Cutting parameters are mainly determined by cutting tools and workpiece material [18]. The influence indexes can be obtained in the experimental handbook.

$$E = E_0 + E_u + E_c + E_{a=}(P_0 + P_u) * (t_u + t_c + t_g) + (P_c + P_a) * t_c \tag{1.4}$$

$$P_a = kP_u \tag{1.5}$$

$$P_u = P_{loss} + a_1 n + a_2 n^2 \tag{1.6}$$

$$P_c = F_c V_c = k_{fc} C_F \frac{a_p^{m1} f_z^{m2} a_e^{m3} z}{D^{m4} n^{m5}} V_c \tag{1.7}$$

It can be found that key data for calculating machining expense is machining time, tool expense, and tool life. Similarly, the calculation of energy consumption mainly depends on cutting force and machining time. Most of the key data are included in the STEP-NC cutting tool model. The cutting parameters for the dynamic calculation of tool life and cutting force are defined in the operation of the workingstep while the relevant coefficients are defined in the cutting tool model. The machining time depends on the toolpath algorithm and can be provided by the cutting tool selection module. Hence, the STEP-NC data model provides sufficient information support for the cutting tool evaluation index.

3.3 Cutting Tool Selection Module

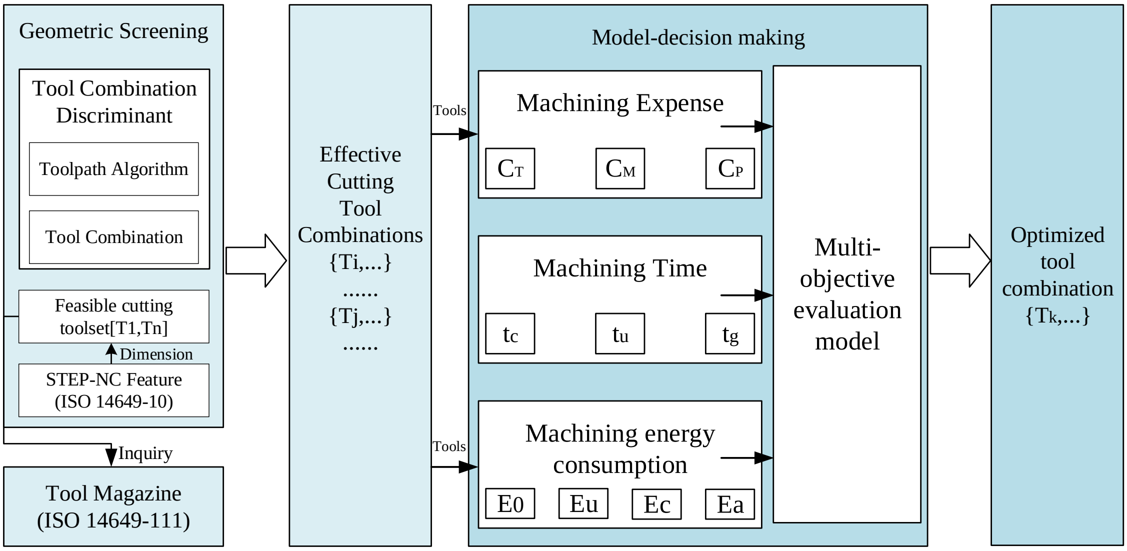


Figure 3: The flow of cutting tool selection algorithm.

The STEP-NC feature based cutting tool selection algorithm can be summarized into two parts: constructing effective cutting tool combinations and choosing the optimized cutting tool combination, as shown in Figure 3. The cutting tools which are theoretically feasible and practically owned by the factory are singled out through the feature geometry parameters. There are a lot of possible cutting tool combinations including one or more cutting tools for machining the feature region. One of the achievable discriminating methods is generating a toolpath by selected cutting tools using the toolpath algorithm. The cutting tools are effective combinations if the generated toolpath sweeping region covers the whole machining region without overcutting and remaining material. Then, an optimal solution can be obtained among the effective cutting tool combinations through a multi-objective decision model in which machining expense and energy consumption are considered. The cutting tool combination with the minimum cost function's value will be selected.

Three significant geometry parameters of the machining region are defined as follows to support feasible cutting toolset construction. (1) Minimum Corner Radius (MICR) is defined as the outer contour's minimum radius. (2) Channel tends to occur in machining region that contains boss so Minimum Channel Width (MICW) is defined as the minimum distance between the inner contour and the outer contour or between the inner contour and the inner contour. (3) If a circle is tangent to each edge of a contour, the circle is called the incircle of the contour. Maximum Incircle Diameter MAID is the maximum incircle diameter among the satisfactory circles. These three parameters provide a reference for the dimension limit of the cutting tool, as shown in Figure 4.

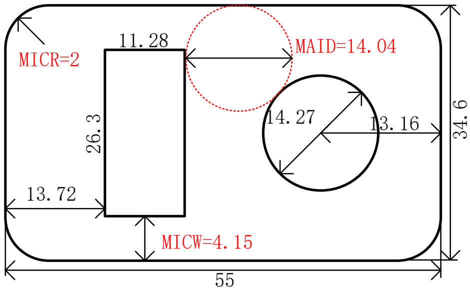


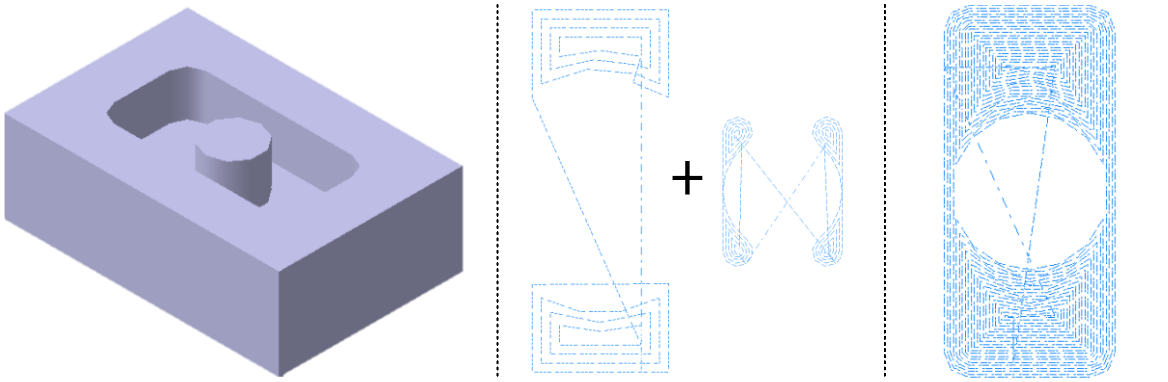
Figure 4: The key geometry parameters of machining region.

The preliminary diameter range of the theoretically feasible cutting toolset is simply determined according to the contour parameters of the machining region. One important determinant of effective cutting tool combination is the area covered by the toolpath. Hence, the toolpath generation based on features must be integrated into the cutting tool selection algorithm. For example, Figure 5 (c) shows the generated toolpath by 2mm tool which accomplishes the removal of the entire machining region. The larger cutting tool with a diameter of 4mm removes most of the material and the smaller cutting tool with a diameter of 2 mm removes the remaining uncut area in Figure 5 (b). Hence, [T_2] and [T_2 T_4] can be deemed to be two effective cutting tool combinations for machining. It is important to notice that the tool combination takes machining area and toolpath strategies into consideration.

The optimal cutting tools will be selected among the effective cutting tool combinations. The decision-making model is introduced to comprehensively consider machining expense and energy consumption. The weighted summation method is used to transform the above multi-objective optimization problem into a single-objective optimization problem. No direct comparison can be made by weighted sum owing to that the unit of measure is different between machining expense and energy consumption. Dimensional normalization needs to be carried out first and the weight coefficient is determined by the analytic hierarchy procedure.

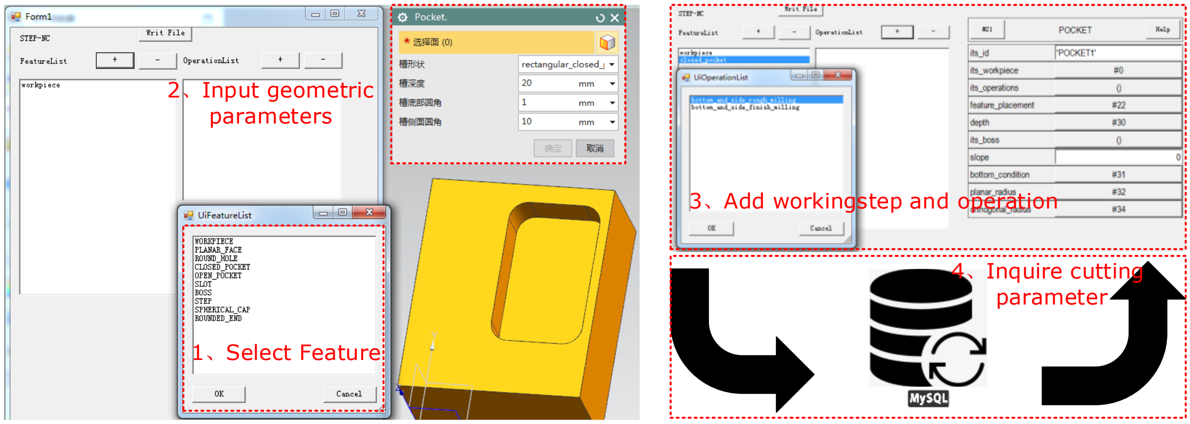
4 IMPLEMENTATION

A human-computer interaction interface for feature modeling, process parameter inputting, and STEP-NC file generating is provided in feature based integrated design module. The machining features can be quickly created by inputting key parameters through the developed plug-in based on UG/CATIA. The plug-in provides an interface for adding the operation information conveniently. The process parameter is determined by material and the parameter is the input data of the tool selection module meanwhile. In fact, cutting tool selection is closely related to process parameters, such as axial depth, radial depth, feed rate, and spindle speed. The data of the process information comes from the process manual and stored in a process database. All the information is stored using the STEP-NC data structure and the read and write functions of STEP-NC file are embedded in the module. The interface of the integrated design platform is shown in Figure 6.



(a)A part with a pocket (b) The toolpath of [T_2, T_4] tool combination (c)The toolpath of T_2 tool

Figure 5: Effective cutting tool combinations.



(a)Feature modeling (b) Process parameter inquiry

Figure 6: The inferface of integrated design module.

An independent cutting tool selection module is established based on Qt, OpenCasCade (OCC), and OSG, which contains the model operation interface and cutting tool recommendation interface, as shown in Figure 8 (1). The majority of necessary data elements of cutting tool selection index can be obtained from design. However, the actual machining time is dependent on toolpath length, it is necessary to generate the corresponding tool path according to each tool combination, as shown in Figure 8 (1)-a. The module has the toolpath generation function according to the specified machining feature. The usual operation flow of the CAM operator using commercial CAM software is extracting geometry parameter, inputting technology parameter, determining toolpath strategy, and selecting cutting tool dimension. The rationality of process parameters largely relies on CAM operators' experiences. When a model file from feature based integrated design module is imported, the cutting tool recommendation interface will show the feature parameters and the intuitive procedure process of cutting tool selection by activating the specified machining feature. The toolpaths among different cutting tools are generated and shown in the main interface of the system. The theoretically feasible cutting tool sets are presented as a table and the chart shows the comparison of expense and energy consumption among different effective cutting tool combinations. The final optimal cutting tools are recommended and shown at length.

Material	Parameters												
	k_{fc}	C_F	$m1$	$m2$	$m3$	$m4$	$m5$	k0	k1	k2	k3	k4	C_r
Aluminum alloy	1	119	1.0	0.85	0.75	0.13	0.73	0.8	0.26	0.1	0.24	0.13	200

Table 1: Parameters related to the model.

Diameter (mm)	4	5	6	7	8	9	10	11	12	13	14
Price (￥)	45	50	50	60	60	70	80	90	100	110	150

Table 2: Cutting tool price.

A part that contains a closed pocket with two islands is used to test the cutting tool recommendation system. The geometry of the closed pocket is shown in the Figure 8 (1)-b. The workpiece material is aluminum alloy and the tool material is cemented carbide. The calculation parameters related to the model are shown in the Table1. The price of the cutting tool varies with the diameter as shown in Table2 (for this paper only). The machine tool cost and operation cost are set as 35 and 20 RMB per hour. The process parameters under different tool diameters can be determined by referring to the process manual [22]. When the model created in the integrated design module is imported to the cutting tool selection module, the dimension and key geometry parameters are shown in the selection interface. The diameter of the smaller cutting tool is set as 4 mm. The theoretical cutting tool set is inferred as [T_4, T_{14}] by the cutting tool recommendation system. The effective cutting tool combinations {[T_4], [T_4, T_5], [T_4, T_6], [T_4, T_7] [T_4, T_8], [T_4, T_9], [T_4, T_{10}], [T_4, T_{11}], [T_4, T_{12}], [T_4, T_{13}], [T_4, T_{14}]} are inferred through geometry parameter when one-or-two tool strategy is adopted. All the selection procedure is displayed in the cutting tool recommendation interface, shown in Figure 8 (1)-c. The decision-making model between machining expense and energy consumption works out that [T_4, T_{12}] is the optimal tool combination. The cutting tool selection time for a single machining feature is about half a minute plus human-computer interaction using the tool selection system. To verify the effectiveness of the selected tool, the selected cutting tool is used for simulation with the toolpath using CATIA, as shown in Figure 8 (2). The geometry and process parameters of the modeling are used as the input of the tool selection module, then the cutting tool recommendation system returns the optimal cutting tools to the design module with a STEP-NC file containing the whole design information at the same time. Table3 shows the machining time, energy consumption, and costs for all the tool combinations. The energy consumption and cost are normalized respectively, the weighting coefficient is 0.5 and the final results are shown in the last column of the table. The Figure 7 shows the direct comparison among all the feasible cutting tool combinations. Another test part is example2 in the ISO 14649-11. Six typical STEP-NC machining features are chosen to verify the effectiveness of the cutting tool recommendation system, as shown in Figure 9. Table4 shows the final recommended cutting tools and the relative estimated energy consumption and costs for all the machining features.

Tool combination	*Machining time1(s)*	*Air cut time1(s)*	*Machining time2(s)*	*Air cut time2(s)*	*Energy consumption(kw·h)*	*Cost (￥)*	*Normalization*
4	0	0	1427.56	7.95	0.50	44.72	1
4,5	45.28	22.52	536.1	4.78	0.20	19.85	0.284
4,6	127.75	7.2	545.26	5.62	0.25	23.27	0.373
4,7	114.04	19.91	282.76	3.92	0.15	15.83	0.160
4,8	120.42	19.72	432.19	5.4	0.20	21.18	0.296
4,9	184.64	12.52	89.22	2.02	0.11	10.20	0.028
4,10	212.13	17.32	93.96	3.08	0.12	12.06	0.074

4,11	229.26	19.72	33.69	1.33	0.10	9.48	0.011
4,12	235	24.52	15.67	0.68	0.09	8.98	0
4,13	528.52	25.24	28.82	1.2	0.21	19.08	0.277
4,14	1057.33	25.24	2.3	2.2	0.38	34.01	0.695

Table 3: The final result of cutting tool selection.

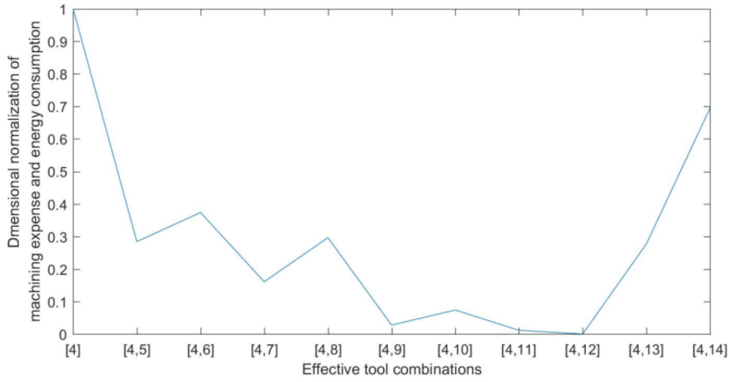


Figure 7: Optimal result by decision-making between expense and energy consumption.

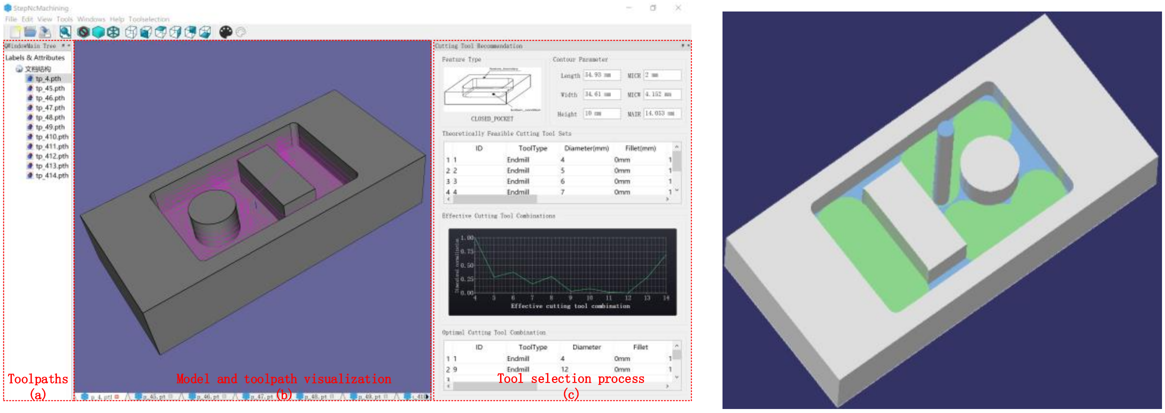


Figure 8: (1) The cutting tool selection module (2) Simulation verification for the selected cutting tool using CATIA.

Feature	*Diameter range*	*Selected tool*	*Energy consumption(kw·h)*	*Cost (¥)*
1	[16,30]	20	2.73	595.88
2	[10,20]	14	0.059	16.79
3	[10,24]	14	0.252	49.67
4	[4,10]	6	0.054	0.66
5	[6,18]	14	0.008	1.58
6	[18,32]	18	0.126	45.12

Table 4: Recommended results for the test part2.

5 DISCUSSION AND CONCLUSION

The feature-based programming concept and object-oriented data model of STEP-NC which contains rich data in geometry and process provide a promising idea for the automatic and intelligent cutting tool selection. The milling cutting tool extension model supplements non-geometry information for cutting tool selection and the selection method is validated by the proposed recommendation system prototype. The cutting tool selection is a significant part of the CAD/CAM activity. Realizing the automation of cutting tool selection will largely improve the efficiency of the whole CAD/CAM design routine, even laying the foundation for intelligent design. In future researches, emphasis will be paid to further enhancing the tool recommendation system. One of the future researches is to work on a better friendly combination between the tool recommendation system and the existing design software. The cutting simulation function based on the generated toolpath will be developed to further verify the effectiveness of tool selection. The range of effective cutting tool combinations will be enlarged and different toolpath strategies will be adopted to search for a better solution. Meanwhile, more complex parts are also going to be tested.

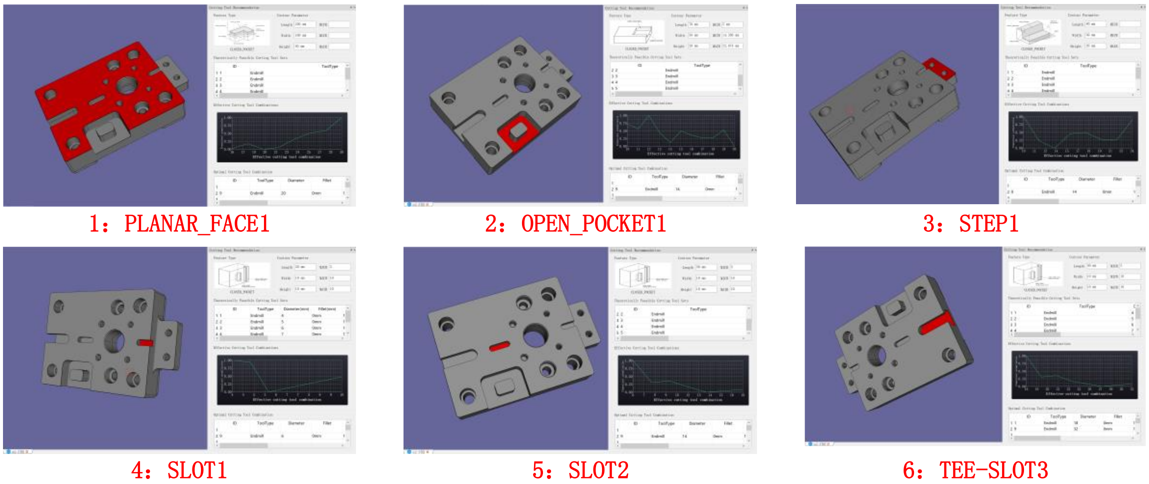


Figure 9: The final recommended results for the test part2.

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