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Setup and Operation Sequence Generation from Manufacturability Evaluation for Prismatic Parts

Hoo Gon Choi[1†] · Jung Hyun Han[2] · Mujin Kang[3]

[1]Department of Systems Management Engineering, Sungkyunkwan University, Suwon, 440-746
[2]Department of Computer Science and Engineering, Korea University, Seoul, 136-701
[3]School of Mechanical Engineering, Sungkyunkwan University, Suwon, 440-746

제조성 평가를 기반으로 한 비회전형상 부품의 작업준비 및 작업순서 생성

최후곤[1] · 한정현[2] · 강무진[3]

[1]성균관대학교 시스템경영공학과/ [2]고려대학교 컴퓨터학과 / [3]성균관대학교 기계공학부

Although some successful recognition algorithms have been developed, most of them did emphasize on extracting accurate interpretations without considerations of manufacturability. Evaluating the manufacturability for multiple features leads to produce the machining sequences. In this paper, the A* algorithm guarantees the optimal setup sequences with minimizing the machining cost. Also, tolerances including surface roughness are converted to STEP formats to be utilized for more reliable process plans. Finally, decision tables are used to create the detailed operational sequences based on geometric tolerances and surface roughness. Machining parameters such as feed, depth of cut, and cutting speed for each operation are added to the routing sheet. Windows are presented to show how the entire system works for a sample part.

***Keypwords*:** feature recognition, manufacturability, setup sequences, operational sequences, tolerances, surface roughness, decision tables, routing sheet, generative process planning

1. Introduction

CAPP determines how a design will be converted into a finished product in a manufacturing system and generates a detailed routing sheet. A typical routing sheet contains the information such as part drawing, operational sequences with setup methods, machining parameters, and tolerances including surface roughness. The completeness of the sheet promises the successful information transfer from the design stage to the production stage. However, the efforts made for optimizing the routing sheet are required to achieve economical machining. Both the setup sequence and machining parameters for a feature can be optimized as much as possible in terms of costs and/or times with manufacturability constraints.

Feature recognition has been regarded as a key bottleneck in the communication between CAD and CAM. Although some successful recognition algori-

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† Corresponding author : Professor Hoo-Gon Choi, School of Systems Management Engineering, Sungkyunkwan University, Suwon 440-746, Korea, Fax : +82-31-290-7610, E-mail : hgchoi@skku.ac.kr
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thms have been developed, most of them did extract accurate interpretations without considerations of manufacturability. In this paper, the **A*** algorithm guarantees the optimal setup sequences with minimizing the machining cost after assuring the manufacturability. Both the optimization of a machining process and the manufacturability are the keys in order to generate the economical and completed routing sheet for a given part.

Both tolerances including geometric tolerance and surface roughness of a feature affect to determining processes, sequences and parameters. CAD systems seem to cover this information as seen in drawings. However, this information is not real attributes of CAD models but simply represented as texts. Therefore, the tolerance data including surface roughness should be manually assigned to the CAD model. This paper addresses the problem of assigning tolerances to a solid model's entities. Features are then recognized from the model, and output with tolerances. STEP(Standard for the Exchange of Product model data) AP203 and AP224 of the ISO10303 are used for this purpose(Owen,1993).

This paper has the following features:

- STEP-based feature recognition for prismatic parts including holes
- Machining feature extraction based on minimizing the number of tool changes
- Decision table for process selection, intermediate dimension and tolerance determination, and process sequencing
- Machining parameter optimization based on machining times

This paper is organized into five sections: the description of machining feature recognition kernel, **IF^2**(Integrated Feature Finder) along with the conversion process to STEP AP203/224, feature recognition for setup minimization based on manufacturability, optimal machining sequence generation, operational sequences from decision table, and a process planning system for a sample part.

2. Machining Feature Recognition

The previous feature recognition research has focused on finding all or some possible features. Then, there are multiple feature models or interpretations for a part. This leads to multiple ways to machine the part, and usually incur different manufacturing costs. Therefore, features should be recognized with manufacturability guaranteed and an optimal interpretation should be generated based on manufacturing cost such as setup cost.

2.1 STEP AP203/224 and Tolerance Processing

Tolerance information is one of the most critical information for setup planning systems to select the necessary processes, machining sequences, and machining parameters. CAD systems seem to cover this information as seen in drawings. However, the information is not real attributes of CAD models but simply represented as texts on the drawings because most of the current CAD systems do not provide data structures to adopt them. Therefore, the tolerance data should be manually assigned to the CAD model. This paper addresses the problem of assigning tolerances to a solid model's entities. Features are then recognized from the model, and output with tolerances. STEP(Standard for the Exchange of Product model data) AP203 and AP224 of the ISO 10303 are used for this purpose(Owen,1993), which stands for configuration controlled design and mechanical part definition for process planning using machining features, respectively.

In this study, **IF^2**(Han and Requicha,1998) as a feature recognition kernel described in detail later is adapted to read and manipulate STEP data. **IF^2** can take STEP AP203 files as input, which can be generated from most of commercial CAD systems. Among the various geometry representation methods provided by STEP AP203, only the Boundary Representation(B-rep) is taken into account in this study.

For interpreting STEP files, the EXPRESS information model AP203 is compiled to produce C^{++} classes using ROSE library (ST-DEVELOPER™, 1996). Then **IF^2** can read and manipulate the STEP data through the created C^{++} classes.

<Figure 1> shows the information flow between **IF^2**'s components. The STEP AP203 Interpreter converts AP203 text files into B-rep data structures. The B-rep entities are then translated into a Parasolid® model by the Parasolid Translator, which uses Parasolid® API functions. Note that the entity structure of STEP AP203 is not identical to that of Parasolid®,

as depicted in <Figure 2>. Therefore, the B-rep model of STEP should be processed to match with Parasolid®'s.

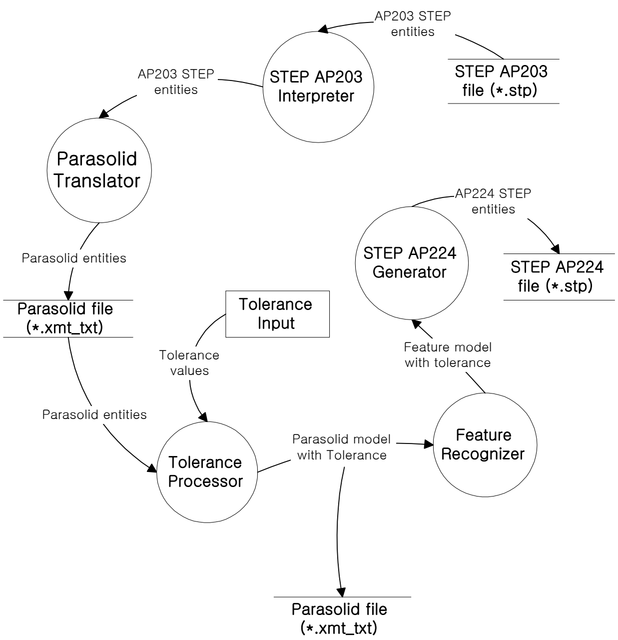


Figure 1. The information flow between IF^2's components.

Tolerance information including surface roughness can be attached to the Parasolid® model. Dimensional tolerances and geometric tolerances specified in a part drawing are both important for developing a setup plan. Some tolerances such as straightness, flatness, cylindricity, etc. are self referenced and other tolerances such as parallelism, perpendicularity, angularity, concentricity, etc. are cross referenced. The self referenced tolerances including surface roughness can be treated as an attribute of an entity. However, the cross referenced tolerances including dimensional tolerances must be designed as 2D array data structures to store the datum and the target entity. For example, an entity couple for linear dimensional tolerance can be face to face, face to edge, face to vertex, edge to edge, edge to vertex, or vertex to vertex.

Tolerance information is assigned interactively with the aid of Tolerance Processor, which provides the graphical user interface shown in Figure 3. The datum and the target entity are selected from the visualized model, and geometric/dimensional tolerance types and upper/lower allowances. Some information relevant to manufacturing such as special comments can also be added in the form of text attributes. Tolerance Processor module produces a Parasolid® geometric model with tolerance information added, which input to the feature recognizer. An optimal feature model is generated and processed by the STEP AP224 Generator to produce a STEP AP224 file.

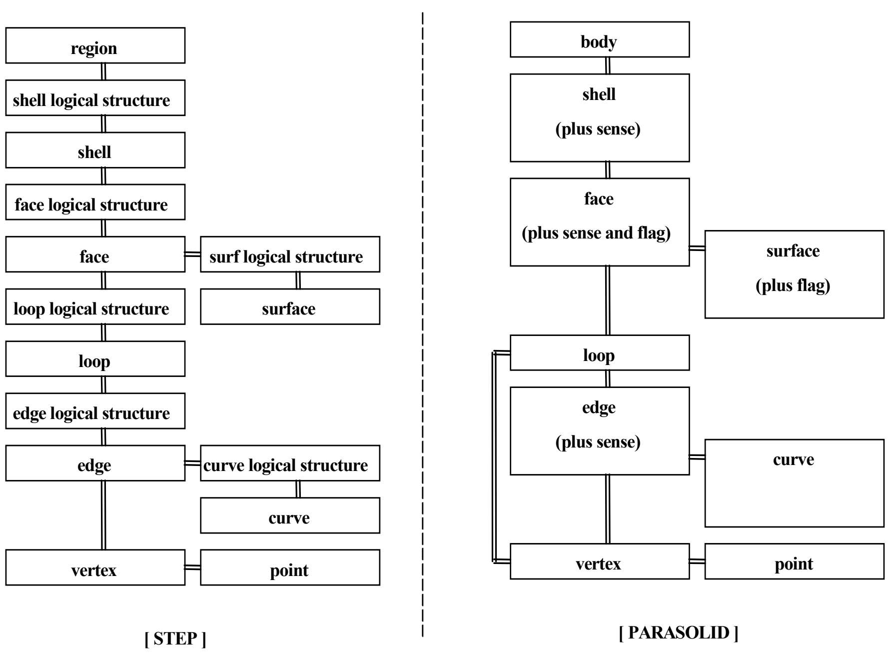
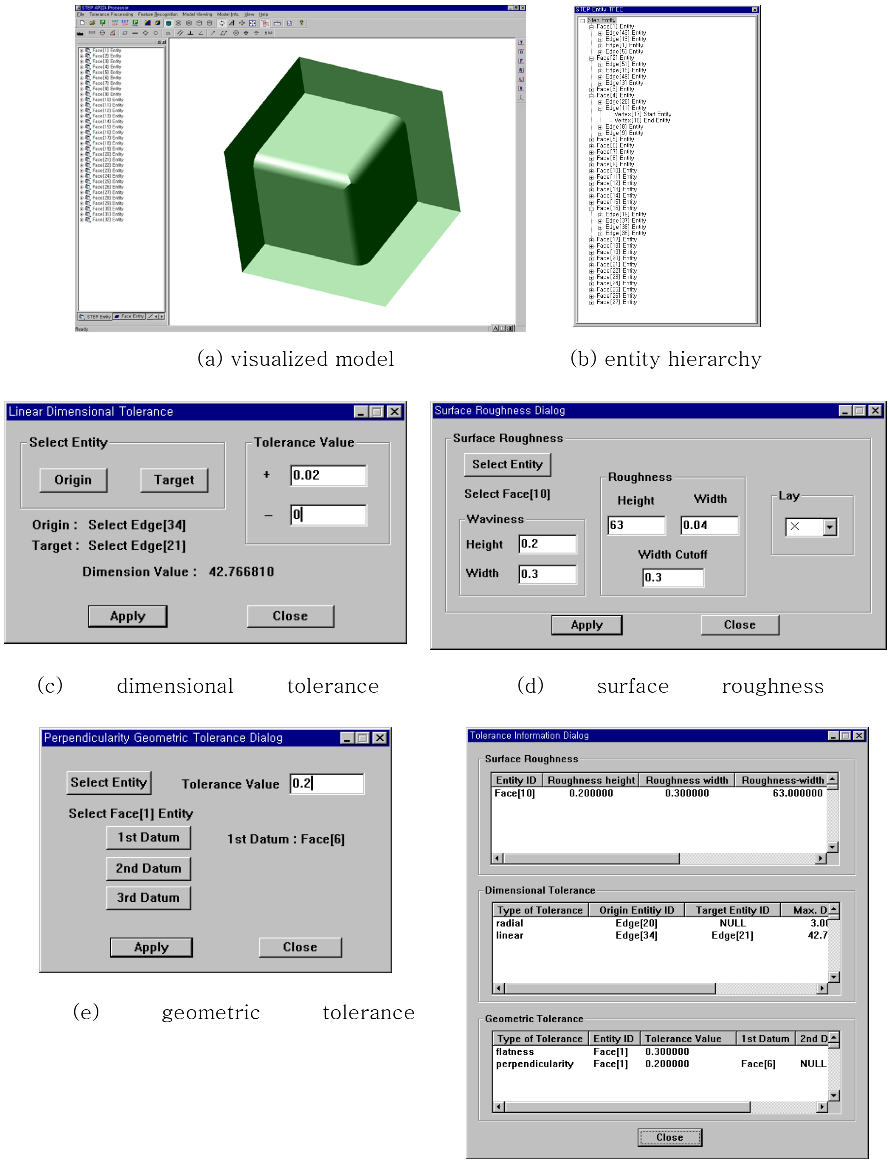


Figure 2. The entity structures of STEP and Parasolid®.



(a) visualized model (b) entity hierarchy

(c) dimensional tolerance (d) surface roughness

(e) geometric tolerance (f) tolerance & roughness

Figure 3. The graphical user interface for tolerance information.

2.2 Feature Recognition Kernel-IF^2

As a feature recognition kernel, **IF^2** recognizes holes, slots and pockets. Holes and slots are both the instances of a pocket in milling processes with either flat end mills or ball end mills.

IF^2 is a hint based reasoning system. Conceptually, a hint is a suggestion that a specific machining feature might exist in a part. If a pocket is considered, it can leave, in the part, a floor set or a wall set. A floor is perpendicular to the tool axis direction. The wall set is composed of aligned faces, all of which are parallel to the tool axis direction. Therefore, two types of hints can be obtained for a pocket: floor and wall. Wall hints are also called axis hints in **IF^2**. <Figure 4> shows two hints: a floor hint f1 and an axis hint corresponding to a floorless pocket(P2). The axis hint is an axis vector of the cylindrical face or a cross product of two non-parallel planar faces' normal.

Given a hint, **IF^2** performs extensive geometric reasoning to recognize a feature from it. **IF^2** provides two geometric reasoning routines for pocket recognition: floor based recognition and axis based recognition. The floor based recognition routine sweeps the floor hint f1 horizontally and then vertically to obtain the pocket P1. If a floor hint has a face normal **N**, the pocket will be machined by a mill with tool axis direction –**N**.

Floorless pockets such as P2 in <Figure 4> can be recognized through a complex recognition process, exposition of which is beyond the scope of this paper. Interested readers are referred to(Han and Requicha, 1998).

IF^2 kernel generates all pocket hints(both floor hints and axis hints) at a time, and group them by setups. A setup denotes tool axis direction in 3 axis machining depending on either a floor hint or an axis hint. **IF**^{2} assigns a heuristic strength to each hint(Han and Requicha, 1997), sums up all hints' strength in each setup, and ranks the setups. These constitute a priority queue ordered by the ranks.

IF^2 processes the hints one at a time until the delta volume which is the material to be removed and is computed by subtracting the part from the stock is completely decomposed, starting from the top-ranked setup and from the strongest hint in a setup. **IF**^{2} updates the total volume(the entire delta volume) to be removed subtracting the new feature from it, and checks for a null solid. If the result is null, **IF**^{2} stops because the delta volume is fully decomposed.

Otherwise, **IF**^{2} takes the next strongest hint and repeats the same process. This is called as the recognizetest cycle.

3. Feature Recognition for Setup Minimization

3.1 Manufacturing Cost Estimation

The optimization processes are critical to generate a more economical process plan. Machining parameters, processing sequences, and operational sequences are typically optimized by various optimization approaches such as mathematical programming, simulation, probabilistic modeling, etc. Machining time and cost, as the basic variables, are minimized individually or together to determine the parameters or sequences.

Machining costs incurred in removing unnecessary portions from a stock are estimated by times required for setup, part handling, cutting, tool change, etc. Note that tool changing occurs in two cases: replacing a worn tool with a sharp one and changing either tool orientation or diameters. In this study, no tool wear is assumed and so tool changing time due to tool wear is not considered.

Total machining cost function can be defined as follows(Han *et al.*, 2001):

$$C_{total} = \sum_{setup}\left\{C_s + \sum_{feature}\left(C_r + C_f\right) + C_{tc}\right\}$$

$$= \sum_{setup}\left\{\alpha N_s + \sum_{feature}(\beta V + \gamma\varpi_f A) + \lambda N_{tc}\right\}$$

where

C_s = setup cost
C_r = roughing cost
C_f = finishing cost
C_{tc} = tool change cost
α = setup cost coefficient (\$/setup)
N_s = number of setups
β = volumetric cost coefficient (\$/in^3)
V = feature volume to be removed (in^3)
γ = area cost coefficient (\$/in^2)
ϖ_f = weighting factor
A = area of the surface with a roughness (in^2)
λ = tool change cost coefficient (\$/tool change)
N_{tc} = number of tool changes

Setup cost C_s is proportional to the number of setups. Roughing cost C_r is mainly determined by the constant MRR(Metal Removal Rate). A surface with a roughness needs a finish cutting process in addition to roughing operations. The surface area and surface orientation with respect to the tool axis affect finishing cost C_f. If the surface is perpendicular to the tool axis direction(perpendicular machining), the planing opera-

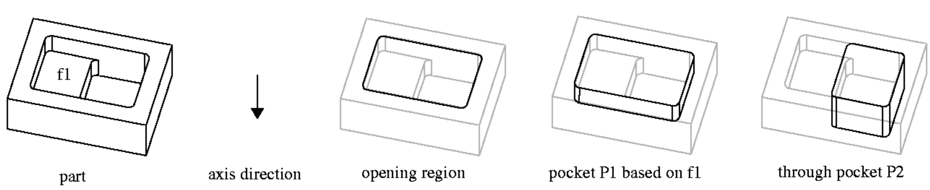


Figure 4. A floorless pocket.

tion is done in a single path using the face cutting edge of a milling cutter. In contrast, if the surface is parallel to the tool axis direction(parallel machining), the operation is done in multiple paths using the cutting edges. Since the parallel machining is subject to a larger lateral cutting force, it should be performed at a lower feed speed with a smaller depth of cut. So, parallel machining costs more than perpendicular machining.

Weighting factor ϖ_f reflects such differences in costs between perpendicular machining and parallel machining. Of course, it is set to 0 for a surface without roughness. Consider the part in <Figure 5>, where the ball end mill is of cutter length 4 and therefore only op_2 and op_3 turn out manufacturable with the available tool. Suppose now that f_2 is assigned a roughness value. As a result of cost estimation described above, the machining op_2 will cost less than machining op_3.

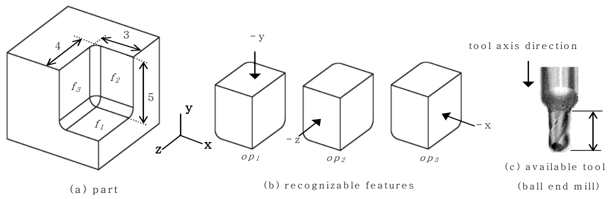


Figure 5. Manufacturable features with an available tool.

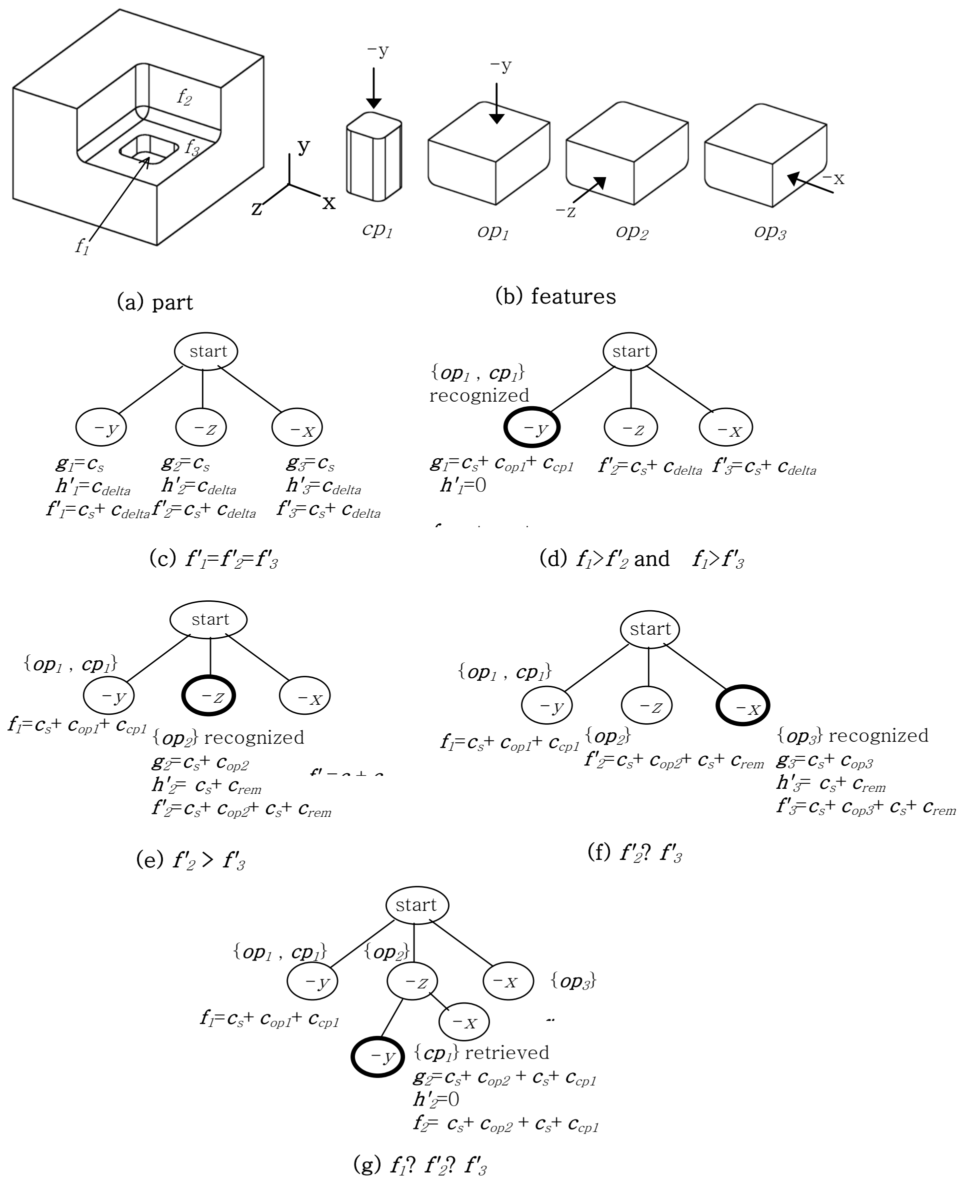


Figure 6. Setup direction determination.

The smaller number of setups eventually requires less machining cost and is critical to achieve less production time. Also, more setups adversely affect precision. **IF^2** produces an interpretation that requires as small number of setups as possible.

A setup means a fixed tool axis direction in which either open pockets or closed pockets can be machined. An open pocket provides multiple tool axis directions being possible. In contrast, a closed pocket leads to a required setup as shown in <Figure 6(a)> where op_1 based on f_1 can be machined only at the setup **－y**. Such limited setups are determined at the hint generation stage of feature recognition. If every edge of a floor is shared by a part face at a concave angle, the floor is a hint for a closed pocket. In <Figure 6(a)>, the floor f_1 meets the conditions. Suppose that f_2 is assigned a roughness. Then, the face has to be machined by a mill with its axis perpendicular to it due to less machining costs. The axis **－z** is selected for f_2 as a tool axis direction and this setup is called as a preferred setup.

3.2 Search for Optimal Setup Planning

At the hint generation stage, **IF^2** computes and classifies all possible setups for a part. For example, in <Figure 6>, the floor hint f_1 provides **-y**, f_3 also provides **-y**, f_2 provides **－z**, and the axis hints from the cross product of f_2 and f_3 provide **±x**. There are six possible setups in total: **±x**, **±y** and **±z**. Only three setups among them, **-x**, **-y**(the required setup) and **-z**(the preferred setup) have accesses to the stock without intrusion and evaluated as the candidate setups. In this example, the setups are ranked in the order of(**-y**, **-z**, **-x**). Then, **IF^2** starts recognizing specific features.

An optimal interpretation is to make the cumulative machining cost from the current state to the goal state be minimum. This interpretation is obtained by the **A*** algorithm(Hart *et al.*,1968) by which the optimal path from a state to another state is determined in a search space. In the **A*** algorithm, a heuristic function f' evaluates a state generated by **IF^2**. The function is defined as a guessed cost of a state, which is a sum of two cost components, g and h' where g is a cumulative cost of getting from the start state to the current state and h' is an additional cost to be expected from the current state to a goal state.

In a two-layered search(Han and Han, 1999) shown in <Figure 7>, a node of the upper layer corresponds to a specific setup, and a node of the lower layer corresponds to a specific process for a feature. If a node of the upper layer is selected for a setup, all manufacturable features are recognized in the setup. Then, the lower layer search is invoked to produce the optimal machining sequence among the features. <Figure 6(c) through (g)> show the search trees spanned until a goal state is found. The start state has three children: setups **－x**, **-y**, and **－z**. Assume that g is set to c_s which is a constant for a setup. For computing h', the cost of machining the remaining volume with a single mill under the given setup is evaluated. Tolerances and roughness are not considered. For three children nodes, the delta volume itself is the remaining volume to be machined, and therefore c_{delta} is not changed for them and h' as well. Then, the three nodes have the same f' values determined by $c_s + c_{delta}$ as shown in (c).

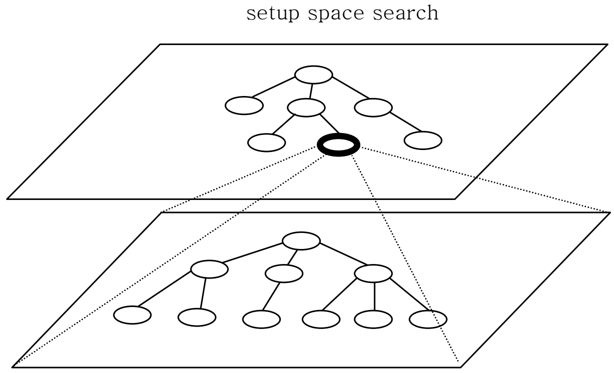


Figure 7. Two layer search.

Recall that the setups are ranked in the order of (**-y**, **-z**, **-x**). The node **－y** is visited first. In each setup, features should be recognized as many as possible. At node **－y**, both op_1 and cp_1 are recognized as shown in (b), that can completely decompose the delta volume. The **－y** will not be expanded any further. Total machining cost $c_{op1} + c_{cp1}$ is obtained by invoking the lower layer search with the two features. Then, the accumulated cost g_1 at the node **－y** is equal to $c_s + c_{op1} + c_{cp1}$. As the delta volume is completely decomposed by op_1 and cp_1, h'_1 is set to 0 and therefore f_1 is set to $c_s + c_{op1} + c_{cp1}$ as shown in (d). If tool change is assumed for machining op_1 and cp_1 and c_{delta} is machined with a single tool, f_1 is greater than $f'_2 = f'_3 = c_s + c_{delta}$. Therefore, a better interpretation might be found by visiting **－z** or **－x**. **－z** can be selected next because of its rank higher than **－x**.

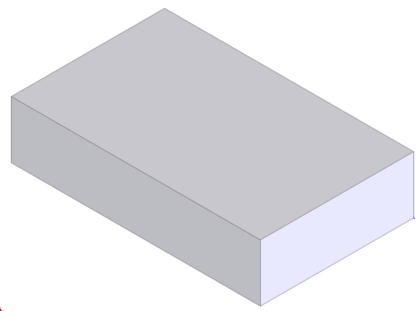
Then, a feature op_2 can be recognized. Machining cost c_{op2} is computed and g_2 is set to $c_s + c_{op2}$. The volume of op_2 is subtracted from the delta volume and the remaining volume is a new delta volume. The guessed cost h'_2 is set to $c_s + c_{rem}$ where c_{rem} is the expected machining cost for the new delta volume. The evaluated cost f'_2 becomes $g_2 + h'_2 = c_s + c_{op2} + c_s + c_{rem}$ as shown in (e). If f'_2 is greater than f_1 of the 'completed' node **-y**, the current node **-z** is marked 'dead' and never be visited in the future. Otherwise, **-z** can be later expanded to find a possibly better interpretation. Suppose that f'_3 of node **-x** is found to be currently smaller than f_1 and f'_2. Then, **-x** node will be expanded by the same process described so far. <Figures 6(f) and (g)> show the expanded search trees.

The above procedure is repeated to find the optimal interpretation with the least machining cost for all node combinations. The **A*** algorithm always finds an optimal solution if the additional machining cost incurred from the current state to the goal state, h', is not be overestimated. In reality, the actual cost h is definitely larger than h' due to more tool changes, more setups, tighter tolerances, smoother surfaces, etc. Therefore, **IF²** always finds an optimal interpretation.

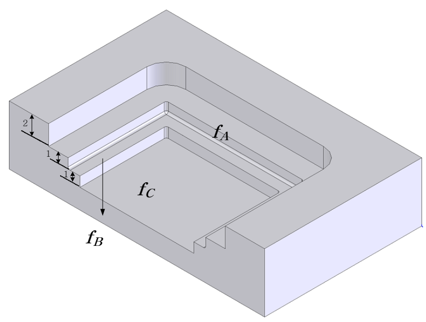
4. Manufacturability Analysis and Optimal Machining Sequence Generation

4.1 Manufacturability Analysis

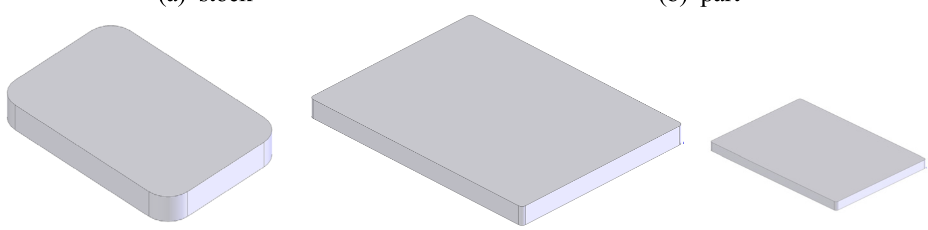
As the lower layer search is done per a single setup, we will use in this section the example part in Figure 8, all features of which are machinable in a setup. Once a feature is recognized, it is tested for manufacturability with the available tool set. In Figure 8, the pocket B's height is 3(because **IF²** recognize features in maximally extended shapes) and its blend's diameter is 0.4, as denoted by [3, 0.4]. Suppose that



(a) stock



(b) part



A:[height, diameter] =[2,2] B:[3,0.4] C:[4,0.5]

(c) features

ID	type	diameter	cutter length
t1	flat end mill	2	3
t2	flat end mill	0.5	3
3	ball end mill	0.4	2

(d) tool database

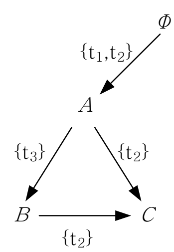


Figure 8. Feature dependencies.

IF^2 is linked with a tool database such as the table shown in <Figure 8(d)>. *B* should be machined by a ball end mill but the only ball end mill t_3's cutter length 2 is too short to machine *B*. Then *B* would have to be rejected because it is not manufacturable with the available tool set. However, *B* turns out to be manufacturable if *A* is machined prior to it. This relation leads to *feature dependency*.

IF^2's dependency detection mechanism(Han and Requicha, 1997) produces the dependency graph depicted in <Figure 8(e)>. In the graph, ***P→Q*** with ***T*** assigned on the arrow implies that ***P*** should be machined prior to ***Q*** if ***T*** is used for machining ***Q***. In the graph, Φ represents no prerequisite and there- fore *A* is taken as manufacturable with no dependency on other features. Interestingly, *C* is associated with two dependencies: *A→C* and *B→C*. Both *A* and *B* are not prerequisites for machining *C*. Instead, *C* can be machined when either *A* or *B* is removed first.

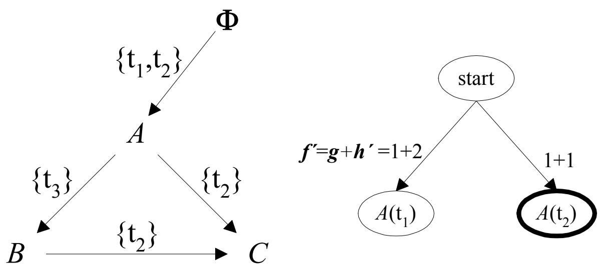
4.2 Optimal Machining Sequence Generation

Out of 4 components of the cost function, setup cost is computed at the upper layer while the other three(roughing, finishing and tool change costs) are computed at the lower layer. For simplicity of discussion, this section focuses on tool change cost only. Therefore, ***g*** measures 'how many tool changes have occurred,' and ***h'*** guesses 'how many tool changes may occur'.

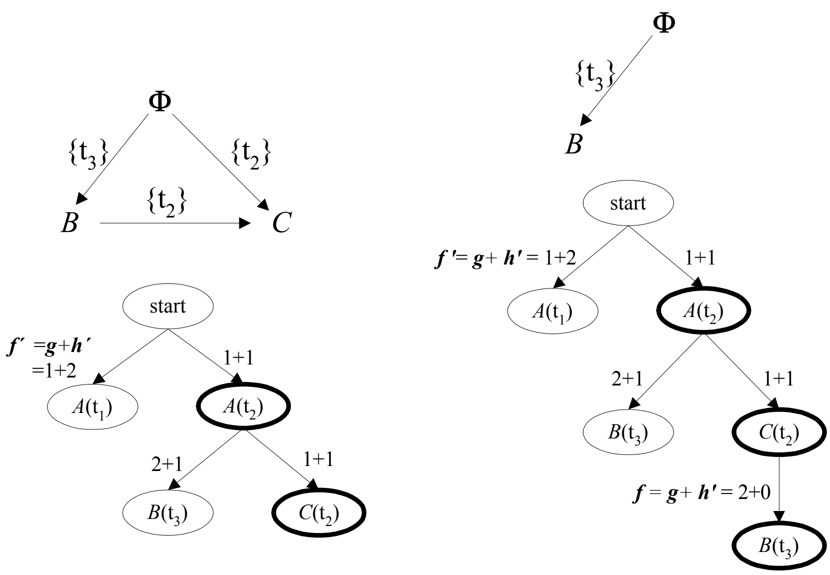
Given the dependencies among *A*, *B*, and *C* in <Figure 8>, two feasible machining sequences are *A→B→C* and *A→C→B*. Between these two, the sequence *A→C→B* is optimal because it requires two tool changes(counting the installation of the first tool

	t_1	t_2	t_3
A	V	V	
B			V
C		V	

(a) feature-tool table



(b) level 2



(c) level 3 (d) when a goal is found

Figure 9. Machining sequence determination.

as a tool change) whereas $A \rightarrow B \rightarrow C$ requires three tool changes.

Such an optimal sequence can also be found by **A*** algorithm, and <Figure 9> illustrates search trees explored by **A*** algorithm. In this example, machining can start only from *A*, which can be removed by either t_1 or t_2. Therefore, the start state has two child nodes, $A(t_1)$ and $A(t_2)$, as depicted in <Figure 9(b)>. Here, $A(t_1)$ represents machining *A* with t_1. For both $A(t_1)$ and $A(t_2)$, ***g*** is 1 because the first tool installation is counted as a tool change.

For computing ***h'***, we will use a simple heuristic. <Figure 9(a)> shows a table, where, for each feature, all available tools are listed. This table will help understand the heuristic. For $A(t_1)$, our heuristic proposes that, as t_1 is already installed, all remaining features that can be machined by t_1 be machined by it. The table shows, however, that such features do not exist. Then, *B* and *C* remain, which require different tools. Therefore, ***h'*** is set 2: for example, from t_1 to t_3, and then to t_2. Finally, ***f'*** is set to 3, which is a sum of ***g*** and ***h'***. In contrast, for the second child node $A(t_2)$, both *A* and *C* can be machined by t_2 according to the heuristics. Then, only *B* remains, ***h'*** is set to 1, and therefore ***f'*** is set to 2. $A(t_2)$ looks more promising and is chosen to be expanded. Because *A* is machined out, the feature dependency graph is changed as shown in <Figure 9(c)>. $A(t_2)$ has two child nodes: $B(t_3)$ and $C(t_2)$, which are assigned ***f'*** values 3 and 2, respectively. $C(t_2)$ looks most promising among all of the three leaf nodes and therefore will be expanded. <Figure 9(d)> shows the updated dependency graph and the search tree explored one more step. Moving from $C(t_2)$ to $B(t_3)$, a tool change is needed and therefore $B(t_3)$'s *g* is set to 2. In contrast, its ***h'*** is set to 0 because no more feature remains. Therefore, we drop the prime from ***f'*** and set ***f=g+h'*** to 2. Because $B(t_3)$ has the smallest *f* value among all leaf nodes and all features have been machined out, we take the sequence $A \rightarrow C \rightarrow B$ as an optimal one.

5. Operational Sequences from Decision Table

5.1 An Overview

Both tolerances and surface roughness values are critical for process planning systems to select the necessary processes, operational allowances, cutting parameters, and appropriate references. No data structures are provided to adopt them in most CAD systems. To overcome this problem, STEP AP203 and AP224 of the ISO 10303 are used in this paper. Features are recognized by $\mathbf{IF^2}$ and then their tolerances and surface roughness values are output. That is, the system developed in this paper uses the neutral product data standard STEP as input and output formats, which include all relevant information such as machining features, surface roughness, and dimensional and geometric tolerances.

Either a ball end mill or a flat end mill machines all features recognized and sequenced. A setup with a selected cutter includes several operations such as locating a part on the work table, fixturing, loading NC program, tooling, etc. for cutting a feature. The number of setups required for a part has been computed when the manufacturable features and their sequences has been obtained. However, a well-developed process plan should contain a routine to determine operation sequences to meet the surface roughness and tolerances specified by a designer.

In this paper, a process means a machine tool such as mills for prismatic parts, drills for hole making, etc. An operation is a cutting job to be done by a tool under a given setup. Examples of the operation are rough milling, semi-finish milling, and finish milling. A tool pass means a tool travel from the one end to the other. That is, a feature has been cut through a number of passes of a specified tool under an operation. Therefore, an appropriate process, operations, and passes must be serially selected to achieve surface roughness specified for a feature in a drawing and to meet tolerances.

5.2 Economical Operation Selection by Shapes

<Table 1> shows a possible process for a given prismatic feature type(Gao and Huang, 1996; Wong and Siu, 1992). A process can have three possible operations such as rough cutting, semi-finish cutting, and finish cutting. Surface roughness levels and tolerances affect to select the operation(s). As described in the optimal machining sequence, a process selected for a feature must be applicable to other features as many as possible.

Each process may attain certain machining accuracy and surface finish under certain machining conditions.

The economically attainable accuracy and surface finish of each process are attained under normal machining conditions.

The normal machining conditions include the normal machine tool and general tooling, the operator with an average proficiency, and the standard time consumption(Wang and Li, 1991). <Table 2> and <Table 3> list the economically attainable machining accuracy and surface quality of various operations for the prismatic parts and the holes, respectively(Halevi and Weill, 1995).

Table 1. Selected processes for features

Feature Types		Selected Processes
Prismatic Part	Pocket	Milling → Grinding
	Blind slot, through slot	
	Blind step, back step	
Hole(through hole, blind hole, threaded hole, countersink hole, counterbore)		Drilling → Boring → Reaming

Table 2. Economically attainable surface roughness ranges for prismatic features

Operation	Range((m)	Index
Rough milling	$5.0 \le Ra \le 25.0$	S_1[1]
Semi-finish milling	$1.25 \le Ra \le 10.0$	S_2
Finish milling	$0.8 \le Ra \le 1.25$	S_3
Rough grinding	$0.63 \le Ra \le 2.50$	S_4
Semi-finish grinding	$0.1 \le Ra \le 0.80$	S_5
Finish grinding	$0.08 \le Ra \le 0.16$	S_6

1. S_i = 0 or 1 for decision tables

Table 3. Economically attainable surface roughness ranges for holes

Operation	Range(㎛)	Index
Drilling	$1.6 \le Ra \le 25.0$	S_1[1]
Rough reaming	$1.25 \le Ra \le 5.0$	S_2
Semi-finish reaming	$0.63 \le Ra \le 1.25$	S_3
Finish reaming	$0.16 \le Ra \le 0.63$	S_4

1. S_i = 0 or 1 for decision tables

After an economically attainable operation is selected for a feature, a subsequent operations chain must be picked out for meeting with given tolerance and surface finish requirement. <Table 4> and <Table 5> show some selected geometric tolerances for prismatic and holes, respectively(Halevi and Weill, 1995; Wang and Li, 1991).

Table 4. Defining the indexes according to geometric tolerance for prismatic features

Condition	Range	Index
Parallelism	$0.01 \le Pa \le 0.02$	M[1]
	$0.001 \le Pa \le 0.01$	G[2]
Perpendicularity	$0.02 \le Pe$	M
	$0.02 \le Pe < 0.02$	G
Angularity	$0.01 \le An$	M
	$0.002 \le An \le 0.01$	G

1: M = milling 2: G = grinding

Table 5. Defining the indexes according to geometric tolerance for holes

Condition	Range	Index
Concentricity	$0.01 \le Co$	*D*
	$Co<0.01$	*R*

D = drilling, R = reaming

The listed surface roughness ranges and geometric tolerances are a few ranges that have been experienced by the process experts. More complete process planning systems require the overall coverage of all geometric tolerance types and surface roughness values. We need more efforts to collect those data and to gather them into an advanced process planning system.

5.3 Decision Table Development

A decision table is partitioned(conditions and decisions) by vertical and horizontal lines as shown in <Table 6>. The portion of the table above the horizontal line specifies the condition, while the portion below that line indicates the action.

The left portion of the vertical line contains the indices specified by both operations and geometric tolerances as shown in <Tables 2, 3, 4, and 5>. Decision rules are identified by columns in the entry part of the decision table(Chang and Wysk, 1985). <Tables 6 and 7> are an example of a sequenced decision table in which an operation sequence is assigned to each applicable action entry. Each entry has either 0 or 1, or a blank if it does not matter.

Table 6. An example of a decision table for prismatic parts

	Rule											
	1	2	3	4	5	6	7	8	9	10	11	12
S_1	1	1										
S_2			1	1								
S_3					1	1						
S_4							1	1				
S_5									1	1		
S_6											1	1
M	1		1		1		1		1		1	
G		1		1		1		1		1		1
Rough Milling	1	1	1	1	1	1	1	1	1	1	1	1
Semi-finish Milling		1	1	1	1	1	1	1	1	1	1	1
Finish Milling					1							
Rough Grinding		1		1		1	1	1	1	1	1	1
Semi-finish Grinding									1	1	1	1
Finish Grinding											1	1

Table 7. An example of a decision table for holes

	Rule									
	1	2	3	4	5	6	7	8	9	10
S_1	1	1								
S_2			1	1						
S_3					1	1				
S_4							1	1		
S_5									1	1
D	1		1		1		1		1	
R		1		1		1		1		1
Drilling	1	1	1	1	1	1	1	1	1	1
Rough Reaming		1		1	1	1	1	1	1	1
Semi-finish Reaming							1	1	1	1
Finish Reaming									1	1

Either an operational sequence or a decision rule can be decided by the following steps:

1. Select a process to machine a feature such as pocket, slot, step, and hole. <Table 1> presents the selected processes for each feature. The selected processes can be adjusted by considering tolerances and surface roughness for a feature in the next step.
2. Select an operation to meet a given surface roughness range and a geometric tolerance such as parallelism(Pa), perpendicularity(Pe), concentricity(Co), and angularity(An) and to meet a dimensional tolerance. <Table 2> and <Table 4> present the surface roughness range for each operation to machine the prismatic parts and the indices to be used in a decision table for the surface roughness range and selected geometric tolerance range. <Table 3> and <Table 5> are these ranges and the indices for machining holes.
3. Develop a decision table to determine the processes(operations) based on surface roughness and tolerances. Suppose that a surface roughness value required for a prismatic feature is 0.09 μm and its parallelism is 0.015mm. An index S_6 is given for the surface roughness and M is for the specified parallelism by referring <Table 2> and <Table 4>. Then, Rule 11 is selected for this prismatic feature to be machined by rough milling, semi-finish milling, rough grinding, semi-finish grinding, and finish grinding to satisfy with the given surface roughness and parallelism. Refer to <Table 6>. A similar decision process can be applied to hole making cases(<Table 7>).

5.4 Operational Design Algorithms

After the decision table provides the operational sequences for either a prismatic part or a hole, a process planner must design each operation to meet the final surface roughness and tolerances given in part drawings. The design activities include the determination of operational allowances, operational dimensions, machining parameters, and number of passes of a selected tool, and computing machining time.

5.4.1 Operational allowance determination

The final surface roughness and dimension are obtained by successive operations in an operational sequence. Also, each operation has its own ranges of roughness and tolerance to be met. Therefore, the appropriate machining allowances of the current operation must be set for the very next operation within a sequence. The roughness and tolerances of the current operation would affect to the next operation's roughness and tolerances. The following procedure describes how to assign empirically the allowance in each operation:

1. maximum surface roughness that can be produced in the next operation is searched from <Table 2> and <Table 3> for prismatic parts and holes, respectively. For example, the maximum roughness for semi-finish milling operation in a prismatic part is 10 μm in <Table 2>.

2. the obtained roughness value is converted to dimensional tolerance based on <Table 8> (Gu and Zhang, 1993).
3. the allowance is determined by multiplying 10 with the converted dimensional tolerance. The constant '10' is an empirical value.

Suppose a part's operational sequence obtained from the decision table consists of successive operations such as rough milling, semi-finish milling, rough grinding, and semi-finish grinding. In this sequence, the roughness and tolerance produced by the rough grinding operation as a preceding operation would affect the semi-finish grinding operation as a next operation. The surface roughness of the semi-finish grinding operation can be read from <Table 2> as 0.8µm. This roughness value is corresponding to 0.02 mm as a dimensional tolerance by using <Table 8>. Then, the machining allowance for the rough grinding becomes 0.2 mm after multiplying 10.

The above procedure empirically decides the allowances for each operation. As a more accurate way to determine the allowances, the tolerance chart method(Jung *et al.*, 2003) is available in which dimensional tolerances are used to construct a tolerance chain. However, the chain does not include the surface roughness and the geometric tolerance. Therefore, the empirical method still gives good approximation to determine the allowances, but needs more actual data from the shops.

Table 8. Converting from surface roughness to dimensional tolerance

Dimensional Tolerance (± mm)	Surface Roughness (Ra, ㎛)
< 0.005	< 0.2
0.010	0.32
0.015	0.45
0.020	0.80
0.030	1.00
0.040	1.32
0.050	1.60
0.060	1.80
0.080	2.12
0.100	2.50
0.150	3.75
0.200	5.00
0.250	6.25
0.350	9.12
0.600	12.50
1.000	25.00

5.4.2 The number of tool passes determination

After the **A*** algorithm decides the feature sequence for machining, the dimension of a feature to be machined in each axis is specified, then the number of tool passes is determined by a tool diameter of a selected tool.

The number of tool passes is defined by the following equation:

$$N_p = \left|\left(\frac{W_p}{D_t}+1\right)\right|^{+} * \left|\left(D_p \div \frac{D_t}{2}\right)+1\right|^{+}$$

where N_p = number of tool passes
W_p = width
D_p = depth
D_t = tool diameter

Both width and depth are defined by the direction of tool movement. For example, if **x** axis is the direction of tool movement, the remaining axes can be either width or depth. The first term of the above equation is the number of passes in the direction perpendicular to the tool movement direction. The minimum value of the term is 1. The machinist handbook(ASM International Handbook Committee, 1989) (Machinability Data Centre, 1980) suggests empirically that the depth of cut (the direction of depth) is a half of the tool diameter. So, the second term of the above equation is developed in that way. Again, the minimum value of the term is 1.

5.4.3 Machining time determination

The feed rate affects mostly the machining time if machining cost is not a factor. The higher feed rate is set, the shorter would the machining time be. However, the high feed rate causes fast tool wear rate and tool changing cost becomes critical to attain the economical machining conditions. Therefore, the machining parameters must be set in the way of minimizing times and costs together. When the feature dimensions(L_p), surface roughness(R_a), tool diameter(D_t), material hardness(*HBN*), and the corner radius of a tool(a_r) are given for the prismatic parts, the optimal machining time can be found from cutting speed, and feed rate. For hole making processes such as drilling and reaming, the diameter and length of a hole must be given.

1. total cutting length determination for prismatic parts

The total cutting length(T_L) is determined by the cutting length per tool pass(C_L), number of tool passes(N_p), and average overlap length(O_m). The cutting length per tool pass is dependent on the shape of features such as through slot, pocket, blind step, or blind slot. The following equations are used for determining T_L, C_L, O_m, and N_p under a given tool size and direction:

$$C_L = L_P - D : pocket$$

$$C_L = L_P : through\ \ slot\ ,\ through\ \ step$$

$$C_L = L_P - \frac{D}{2} : blind\ \ step\ ,\ blind\ \ slot$$

$$O_m = \frac{W_P}{N_P}$$

$$N_P = \left|\left(\frac{W_P}{D} + 1\right)\right|^{+} * \left|\left(D_P \div \frac{D}{2}\right) + 1\right|^{+}$$

$$T_L = N_P * C_L + (N_P - 1) * O_m$$

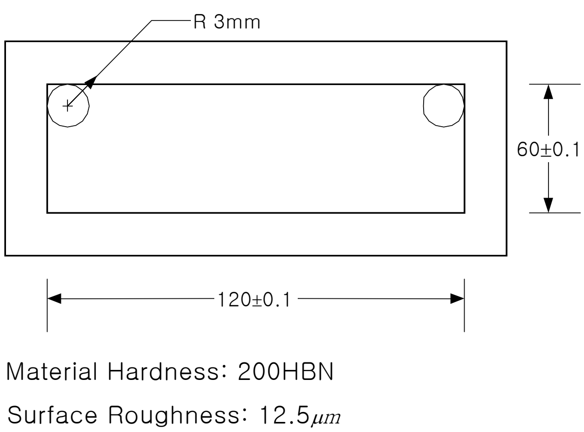


Figure 10. An example to computer T_L.

2. cutting speed(V_C), optimal feed rate(f_z), and machining time(t_m) (Halevi and Weill, 1995)

$$V = \frac{3700}{HBN^{0.6} * a_r^{0.3}}$$ for basic milling operations

$$V_C = 0.89 * V$$ for basic milling operations

$$f_z = 0.8 * f\left(\frac{D}{60}\right)^{1.2}$$ for basic milling operations

where

$$f = \frac{20.25 R_a^{0.4}}{HBN * a_r^{0.3}}$$

$$t_m = \frac{(L_P + T_L) * pitch}{V_C * f_z}$$

3. feed(f) and machining time(t_m) for drilling operations(H_D: hole diameter, H_L; hole depth) (Halevi and Weill,1995)

$$f_1 = \frac{2.83 H_D^{0.6} R_a^{0.5}\left(1.09 - 0.04\frac{H_L}{H_D}\right)}{HBN} \quad if\ D \geq 8mm$$

$$f_2 = f_1\left(\frac{H_D}{20}\right)^{0.4} \quad if\ D < 8mm$$

$$V_C = \frac{3.38 H_D^{0.4}\left(\frac{160}{HBN}\right)^{1.6}}{f^{0.6}}$$

$$where\ f\ is\ either\ f_1\ or\ f_2$$

4. feed (f) and machining time(t_m) for reaming operations(Halevi and Weill, 1995)

$$f_3 = \frac{0.1}{(H_D - H_R)^{0.1}}\left(\frac{220}{HBN}\right)^{1.4}\left(\frac{H_D}{3}\right)^{0.62}$$

where H_R is a hole diameter after a reaming operation

$$f_4 = f_3\left(\frac{R_a}{3.125}\right)^{0.3} \quad if\ R_a \geq 1.575\,\mu m\ \ and\ \ H_D \geq 8mm$$

$$f_5 = f_3\left(\frac{R_a}{3.125}\right)^{0.3}\left(\frac{H_D}{20}\right)^{0.4} \quad if\ R_a \geq 1.575\,\mu m\ and\ H_D < 8mm$$

$$f_6 = 0.67 f_3\left(\frac{R_a}{1.575}\right)^{0.15} \quad if\ R_a < 1.575\,\mu m\ and\ H_D \geq 8mm$$

$$f_7 = 0.67 f_3\left(\frac{R_a}{1.575}\right)^{0.15}\left(\frac{H_D}{20}\right)^{0.4} \quad if\ R_a < 1.575\,\mu m\ and\ H_D < 8mm$$

$$V_C = 27\left(\frac{220}{HBN}\right)^{0.7}$$

$$t_m = \frac{\pi H_D H_L}{V_C f}$$

$$where \quad f \text{ is one of } f_4, f_5, f_6, \text{ and } f_7.$$

5. feed(f) and machining time(t_m) for grinding operations(Halevi and Weill, 1995)

$$\frac{V_w}{V_s} = 4\sqrt{R_a \frac{D/2}{X^2}}$$

$$f = 2\sqrt{R_a D}$$

$$t_m = \frac{L_p}{V_w f}\left|\left(\frac{W_p}{D}+1\right)\right|^{+}$$

where
V_s = rotational speed of a grinding wheel
(in general, 28m/sec $\le V_s \le$ 33m/sec)
V_w = worktable speed
D = wheel diameter
f = feed
X = distance between major grains of a wheel = 1mm
t_m= machining time
L_p = grinding length

5.5 Generative Process Planning System Modules

The following three modules have been developed for a generative process planning system in this study:

1. Feature data selection: this module adapts the results from the feature recognition algorithm for a user to specify the features to be machined. The user can conform the dimensions, tolerances, and surface roughness values for the specified features on the windows.
2. Primary data management: this module manages the primary data such as the range of surface roughness for the processes, geometric tolerances, and tool data. A user can modify the data through a window.
   a) process data : required surface roughness and geometric tolerances for features
   b) tool data : tool diameters for mill, grinder, drill, and reamer
3. Generative process planning: this module generates the routing sheet for the features selected from the feature data selection module by using the decision making process, which include the following steps:
   a) displaying selected features
   b) generating a machining sequence
   c) modifying the selected machining sequence
   d) determining machining parameters
   e) generating the routing sheets

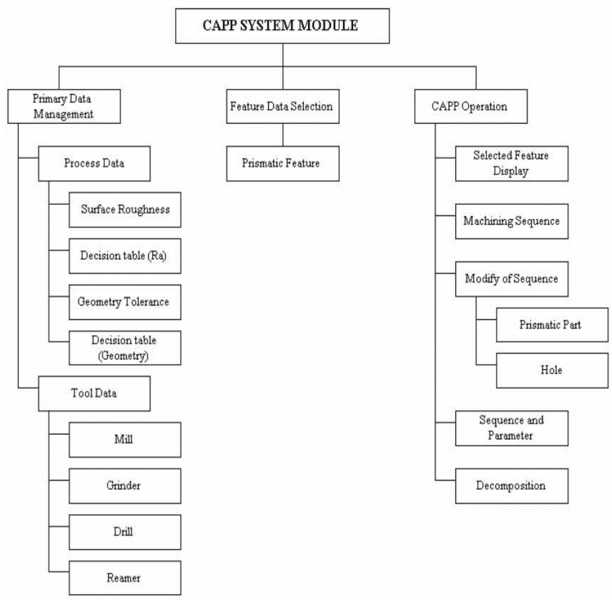


Figure 11. Process planning system modules.

5.6 An Example

A slot feature shown in <Figure 12> has been applied for the developed generative process planning system. The steps required for the feature are described below.

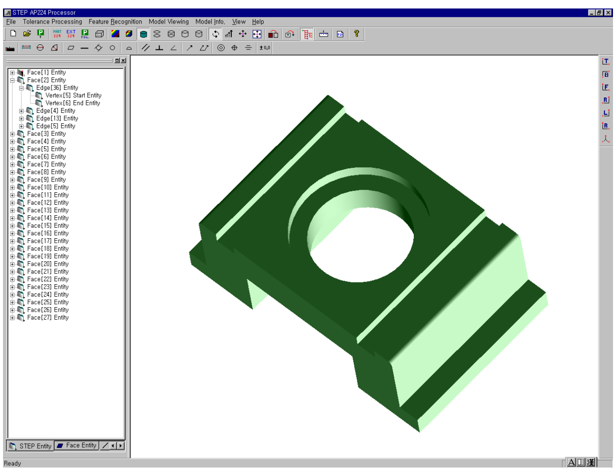


Figure 12. A slot feature applied for the developed planning system.

1. Feature data selection(<Figures 12 and 13>)
 • get the feature information from CAD drawings.
 • convert the information to STEP AP203 file information.
 • convert the information to STEP AP224(*.stp) file information through the automatic feature recognition process.
 • add feature dimensions, dimensional tolerances, geometric tolerances, and surface roughness to the converted STEP AP224 file information.
 • specify or check the features for which the routing sheets are to be generated.

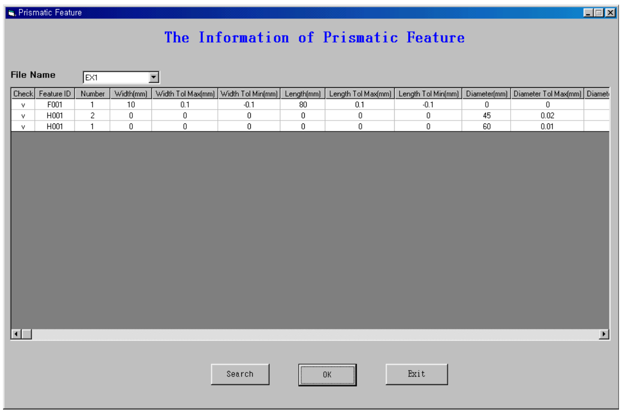


Figure 13. Feature data selection.

2. Generative process planning
 • sequencing for the selected features by using the decision tables and machining allowance determination algorithm(<Figure 14>).
 • checking if the machining sequences are well suited for the shop floor. If it is not suitable, then the sequence is modified by changing surface roughness and tolerances(<Figure 15>).

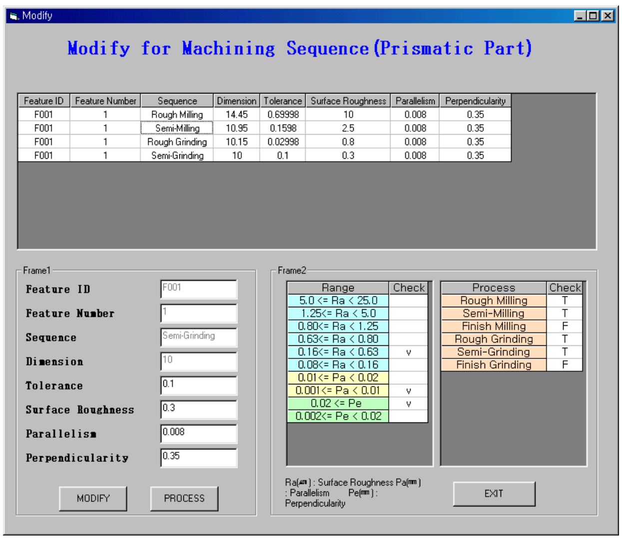


Figure 15. Modifying machining sequences.

 • termining the machining parameters and tools with the machining conditions(<Figure 16>).
 • displaying the routing sheets(<Figure 17>).

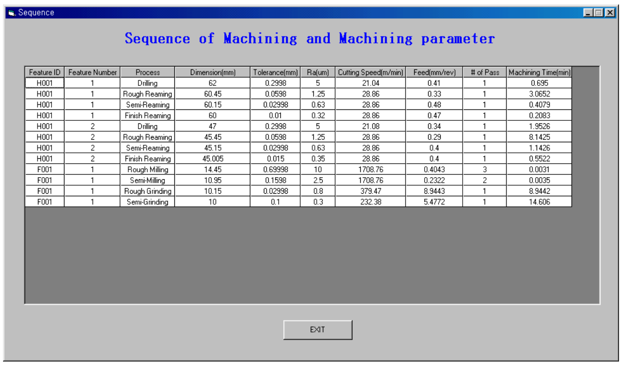


Figure 14. Machining sequence and machining parameters.

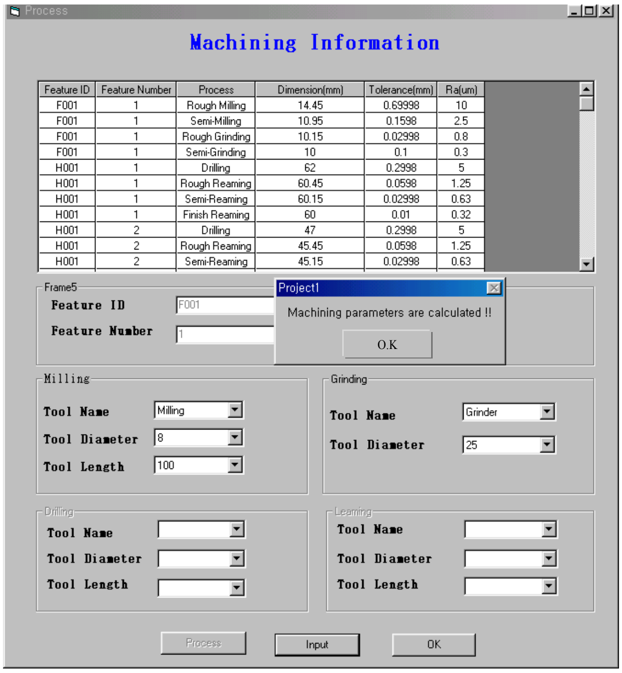


Figure 16. Machining parameters and tools.

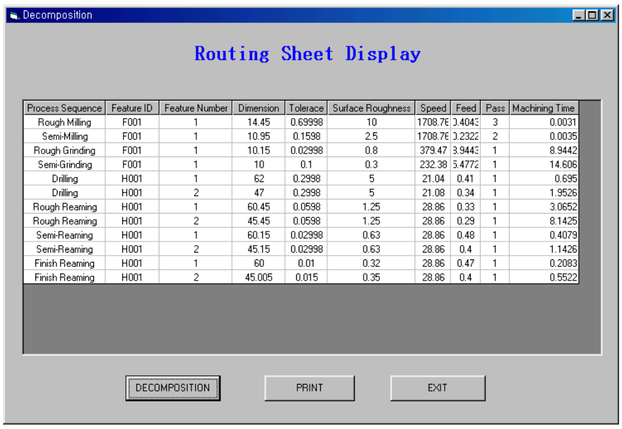


Figure 17. The routing sheet.

6. Conclusion

A new generative process planning system has been developed on the basis of a feature recognition kernel, **IF**^{2}. The design information is stored in the form of STEP AP203 and converted into STEP AP224 format (*.stp) through the feature recognition algorithm. This effort has been made not to loose the text based information which is critical to develop a useful process plan. Dimensions and tolerances, geometric tolerances, and surface roughness specified on the features are the critical factors to select the reasonable machining processes, setups, number of operations, and machining parameters. We have been experienced that many feature recognition algorithms lost such text based information during recognizing the features. In this study, the STEP frame has been accepted to follow the standard and to eliminate the cases of loosing the data.

IF^2 kernel generates both floor hints and axis hints at a time, group them by setups, assigns a heuristic strength to each hint, sums up all hint's strength in each setup, and ranks the setups. More importantly, **IF**^{2} produces an interpretation that promises the minimum cumulative machining cost with the smallest number of setups. At the hint generation stage, **IF**^{2} computes and classifies all possible setups for a part by using tool axis directions, ±**x**, ±**y**, or ±**z**, in a 3 axis machining operation. This optimal interpretation is obtained by the **A*** algorithm by which the optimal path from a start state to a goal state is determined in search space. Each state means a feature and the optimal machining sequence or setup sequence can be produced by this interpretation. Finally, the manufacturability of the sequence is verified by both the available tool sets and feature dependency with the check of optimality.

Decision tables are utilized in many areas in which various input variables exist to produce many different outcomes. The tables provide direct decisions for users. In this study, various processes can be selected to machine either prismatic parts or holes on the basis of surface roughness, dimensions, dimensional tolerances, and geometric tolerances as input variables. Another progress made in this study is the use of the empirical data from various machining data handbooks for selecting machining processes, operational allowances, and machining parameters. The empirical data are also used for converting the surface roughness values to the geometric tolerances such as perpendicularity, parallelism, angularity, and concentricity. Finally, a process plan to be generated by developed software is to minimize the machining time.

Our efforts still have a number of problems to be solved. The **A*** algorithm gives an optimal interpretation by considering tool axis, tool size, and feature dependency. Even though the algorithm minimizes the number of setups, the sequence may not be realistic because the machinability of a material must be satisfied. The machinability of a material is defined by the surface roughness, tool wear, and power consumption. More geometric tolerances such as straightness, flatness, roundness, cylindricity, etc. must be adapted for more applicable system.

These problems will be solved if more empirical data are gathered and formulated for establishing accurate relationships between surface roughness and tolerances.

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