FLEXIBLE PROCESS PLANNING SYSTEM CONSIDERING DESIGNERS' INTENTIONS AND MANUFACTURING CONDITIONS

E. Arai, H. Wakamatsu, and A.Tsumaya
Dept. of Manufacturing Science, Graduate School of Eng., Osaka University
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
{arai, wakamatu, tsumaya}@mapse.eng.osaka-u.ac.jp

Abstract
This paper describes a flexible process planning system considering designers' intentions and manufacturing conditions in production process. The mechanisms of this system are achieved by the following methods: recomposition of minimum convex polyhedrons decomposed from total removal volume into feasible manufacturing features sets, selection of desirable manufacturing feature sets based on technological design requirements with respect to designers' intention, determination of desirable machining sequences, and evaluation of the efficiency of each candidate of process plans. This system can generate multiple process plans according to manufacturing conditions by changing desirable manufacturing feature sets or their machining sequence.

Keywords:
process planning, flexibility, manufacturing feature, function, designers' intention

1 INTRODUCTION

Automatic generation of a process plan from a solid model of a part is normally divided into several activities such as: selection of machining operations, selection of tools, selection of fixture systems, sequencing of the machining operations, evaluation of the machining time and cost and so on. A process plan should consist of the most suitable manufacturing feature set and the optimum machining sequence for specification of a part and the current manufacturing condition. Most of existing manufacturing systems perform fixed process planning which often provide "fixed plans" for production. Those plans are applicable only if no failures and disturbances occur during production process and no alterations of facilities exist in workshop. Moreover, in some cases, because manufacturing feature interpretations are predefined in a fixed way, only small number of plans can be generated as candidates. In addition, it is not guaranteed that those output process plans are the most efficient and the most accurate for manufacturing. Because a great deal of useful embedded information in a part model is ignored, determined sequences often do not satisfy required functions. For solving this problem, the flexibility of process planning and effective way to create more candidates is required.

In this paper, a flexible process planning system considering designers' intentions and manufacturing conditions in production process is proposed. Firstly, a procedure to generate manufacturing feature sets, which are referred to as MF sets, is explained. Secondly, a method for determination of machining sequence based on the functional and technical requirements of a product is proposed. Finally, the effectiveness of our proposed method is demonstrated.

2 SYSTEM ARCHITECTURE

Specifications, functional requirements, and designers' intentions require the design solution to have some specified geometrical conditions and technological information. Such conditions and information are called as "technological design requirements" in this paper.

A process plan depends on both technological design requirements and manufacturing conditions. In general, requirements for part production can be divided into two: technological design requirements of the part and requirements with respect to manufacturing conditions. The former corresponds to the necessary condition for production and it is independent of manufacturing conditions. In this paper, feasible MF sets and their sequences satisfying technological design requirements are generated at first. They are stored in a planning system. After that, the most optimum process plan including kinds of tools and their paths is determined considering manufacturing conditions. If some failures occur in a factory, an alternative plan can be derived immediately without changing the original MF set and its sequence. If errors affect the original set or its sequence, for example, if one machining cell breaks down and the rest cells in service can not process the original set, alternative sets or sequences stored in the system can be selected.

In order to realize such flexible process planning system, the following functions are required: generation of multiple MF sets satisfying technological design requirements, generation of feasible machining sequence for each set, and determination of the optimum process plan. The goal of this system is obtained through the following main steps shown in Figure 1. The input to the system is a blank part model and a product model, which includes geometrical conditions and technological information with respect to required functions and designers' intention. It starts with extraction of total removal volume, which is referred to as TRV, that is followed by two other important procedures: feature interpretation and feature sequencing. This creates the optimum plan by comparing machining times of each candidate. The manufacturing feature recognition is executed based on judging the number of the open faces of the feature, by retrieving and modifying the familiar cases from database, case-based reasoning decides machining conditions including tools, cutting conditions, tool path and so on for individual features [1]. The decided information in every feature plays a crucial role in evaluation of process plans. The above procedures are to be repeated on the occasions which production was stopped by referencing to the machined stock as new blank material and the new-generated process plan can be used to restart the manufacture with minimal lost time.

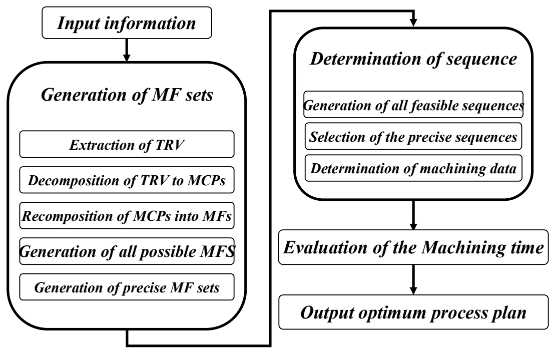


Figure 1: Flow chart of proposed process planning system

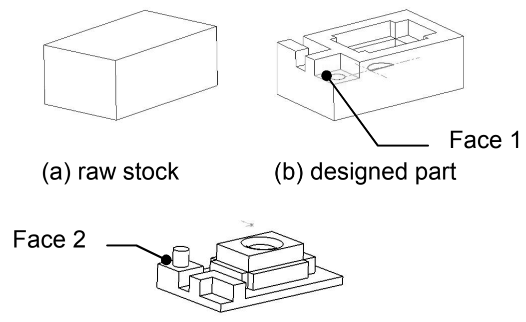


Figure 2: Example of TRV extraction

2.1 Feature interpretations

Design features can be defined as sets of geometric entities representing certain shape or functions while MF stands for portions of a workpiece that can be generated with metal removal processes. The finished part can be created from the stock by removing a MF set.

In the actual factories, the unexpected failures in production process always cause time-consuming rearrangement of production facilities or redesign of parts. To realize the flexibility to those possible disturbances, a sufficient number of feature interpretations are required during process planning. However, fixed plan methods decide MF sets in a fixed way and limit the number of feasible MF sets. Furthermore, some MF sets do not satisfy designers' intentions. To overcome this fault, our system offers multiple feature interpretations, which are represented in the form of MF set through the following four steps.

Extraction of TRV

Process planning starts with the extraction of the removal area composed by planar surfaces and cylindrical surfaces in this system. The removal area, that is, TRV is computed through difference between the raw stock and finished part. Some parts with complex shapes usually offer TRV composed of more than one removal volume. These volumes are defined as SRV (Sub Removal Volumes) and they are handled respectively. In our proposed system, TRV can be recalculated even if a part is in manufactured. This implies that when a failure or a disturbance stops machining process, process plans can be derived from a new TRV, which is generated by subtracting from half-way machined stock. Designers add some geometrical conditions such as parallelism and technological information such as surface finish, that is, technological design requirements, into elements of a part to represent their intentions. These descriptions are attributed to corresponding entities of TRV as constraints. In the system, it includes surface finish, parallelism, flatness, straightness, concentricity, and cylindricity. Figure 2 shows an example of the extraction of TRV composed of four SRVs. Face 1, one of faces in the part model and its corresponding face in TRV, which is denoted as Face 2, share the same attributed information.

Decomposition of TRV into MCPs

For generating enough feasible MF sets to adapt to diversified manufacturing conditions, each SRV is decomposed into minimum convex polyhedrons, which is referred to as MCPs. They are recomposed into multiple sets of manufacturing features in the next step. In this system, decomposition is performed by cutting planes that are generated referring to all planar faces in each SRV. Every planar face belonging to SRV is extended enough to split SRV. Cylindrical faces are not considered to create cutting faces. Then, system randomly selects one cutting face to bisect a SRV. If the SRV is intersected with this cutting face, several new volumes which have one or more created faces are generated. At the same time, some faces attributed with constraints information in the SRV are split into several small faces in separated MCPs. The information is to be inherited from parent faces to new-created faces for delivering technological design requirements to later steps. The above procedure is repeated by using another cutting face until all cutting faces are used.

Generation of desirable MFs

Each MF removed with a single machining operation is a combination of MCPs. Because the tool condition and cutting conditions are not changed until tool exchange, if MCPs attributed with the same technological design requirement are machined at one time as one MF, they have the same accuracy in general. In this paper, MFs satisfying technological design requirements is defined as "desirable MFs". The system gathers the MCPs with the same technological design requirement, and combine them into one desirable MF. For example, Figure 3(a) shows an example of recomposition considering geometrical condition. When a certain flatness is required to a highlighted face of a part shown in Figure 3(a-1), a highlighted face of a TRV shown in Figure 3(a-2) also must satisfy this requirement. If MCPs are recomposed as represented in Figure 3(a-4), the highlighted face is not machined at one time. It implies that the machined face may not satisfy the required flatness. Therefore, recomposition of MCPs with the same requirements as shown in Figure 3(a-3) is desirable. Another example is illustrated in Figure 3(b). A slot of a lower part is designed so that an upper part moves along it smoothly as shown in Figure 3(b-1). It corresponds to the guide function in this paper. The information with respect to this function is attributed to highlighted faces of the extracted TRV as shown in Figure 3(b-2). Then, recomposition shown in Figure 3(b-3) satisfies the guide function, that is, the upper part can move smoothly along the slot because it is machined at one time while recomposition shown in Figure 3(b-4) may not satisfy it. Therefore, recomposition shown in Figure 3(b-3) is eliminated from desirable candidates.

Let us consider the case where the MCPs with the same requirement are separated as shown in Figure 4. If they contact with the same MCP without any requirement each other, they can be recomposed as shown in Figure 4(d). The case where MCPs have multiple requirements must be also considered. In this paper, the following precedence constraints are introduced to determine how to recompose them.

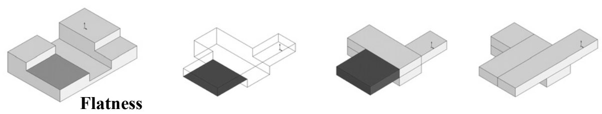
(a) Datum-related is prior to non-datum.

(b) Functions-related is prior to accuracies-related.

(c) In the cases of the same type of requirement, high accuracy is prior to low accuracy.

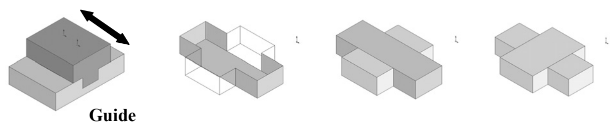
(d) Rough cutting-related is prior to finish cutting-related.

Applying the above procedure, non-desirable MFs, which do not satisfy technological design requirements, are eliminated.



(a-1) (a-2) (a-3) (a-4)

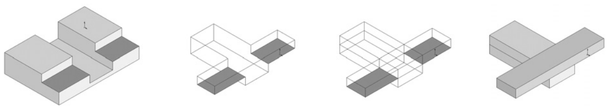
(a) recomposition considering required quality



(b-1) (b-2) (b-3) (b-4)

(b) recomposition considering required function

Figure 3: example of MCPs recomposition



(a) (b) (c) (d)

Figure 4: Recomposition of separated MCPs with the same requirement

Recomposition of remained MCPs to MF sets

Uncombined MCPs without any requirement are recomposed to obtain several sets of MFs. Merging these MCPs in different ways leads to different MF sets. MCPs generated through decomposition are grouped into distinguished horizontal layers according to their geometrical position. MCPs whose top faces perpendicular to z-axis are included in the same horizontal plane are defined as the same level MCPs. Because tool properties such as length and strength restrict the size of machinable MFs, recomposition is to be executed level by level to avoid creation of MFs which can not be machined in the tool approach direction. A procedure to recompose in one level is as follows ;

(a) Gather all remained MCPs in the same level and give them ID numbers to differentiate them from others.

(b) Choose MCPs in random and combine them with other MCPs along x- or y-axis so that the combined volume is convex. This combination is repeated until any combinable MCP can not be found in the x- or y-direction. The ID of temporarily volumes and that of the final volume corresponds to the lowest ID number of its components. During this process, the system checks whether generated features are recognizable shapes or not. In this system, cylindrical column features and rectangular block features are available to be handled.

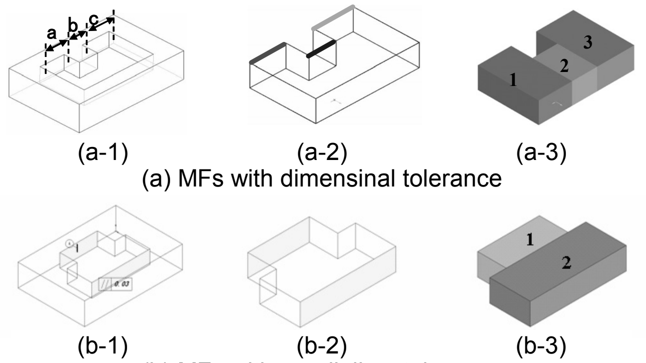
(c) The above procedures are applied to all levels. Finally, numerous desirable MF sets can be obtained as the output.

After that, individual MFs in each MF set are recognized and the machines, tools, cutting conditions and so on are determined by case-based reasoning [1]. The useful information created or inherited from the original product model is attributed to each MF. This information includes feature name, nominal dimension, dimensional tolerance, location, special characteristics, surface accuracy, and various types of geometrical tolerances.

2.2 Determination of machining sequence

One of important and difficult activities in process planning is determination of machining sequence which affects the quality of a part and the efficiency of its production. For producing the part, there are more than one of desirable MF sets available to be chosen. Moreover, for each MF set, there are many machining sequences of included MFs. However, consideration of all possible MF sets to determine the optimum process plan is rather time-consuming because the huge number of alternatives exists. The constraints with respect to technological design requirements should be considered to eliminate improper machining sequences before generation of possible process plans. Because the most of conventional systems focus on creating sequences based on part geometry alone and do not utilize other information such as designers' intentions, the final sequence plan often do not satisfy requirements, or are relatively time-consuming. In this paper, desirable machining sequences are also derived according to technological design requirements. Due to tools' restrictions in length and hardness, machining of MFs which are too large in the tool approach direction should be avoided. Therefore, in this paper, sequencing is executed in each level. The solution of one MF set begins with recreating ID numbers to identify remained MFs in one level and sorting all these MFs in this level to generate all possible machining sequences as candidates. The vast number of feasible sequences are derived through this mean. Without consideration of technological design requirements, it would be possible for a level composed of *n* MFs to be processed from one of *n* factorial sequences. An obvious choice would be to represent a sequence as a string, whose elements are ID of features in a level of this MF set. However, in actual, this number of alternatives is reduced by requirements. Desirable machining sequences of each level are extracted from them. Finally, combinations of desirable machining sequences in each level are picked out for machining time evaluation. In this paper, the following constraints are mainly considered: cylindricity, flatness, dimension tolerance, concentricity, and surface finish. The MFs satisfying the same requirement are to be continually machined. So, strings described by the correctly sorted numbers, whose order represents machining sequence, are delivered to the next step. Then, the decoding process is applied, translating each code into the string of the features. At last, some rough process plans consisting of a desirable MF set and its desirable machining sequence are provided for optimum plan determination. Figure 5 shows examples of machining sequence determination considering requirements. In Figure 5(a), extracted TRV can be separated into three MFs illustrated in Figure 5(a-3) considering dimensional tolerance as shown in Figure 5(a-1). Then, these three MFs are attributed with the dimensional tolerance. This requirement may not be satisfied if they are machined in the following order: MF1->MF3->MF2 or MF3->MF1->MF2. This implies that these sequence are not desirable. In Figure 5(b), MF1 possesses the datum of a parallelism tolerance in MF 2. Therefore, sequence MF1->MF2 are selected as the desirable sequence.

Thus, considering technological design requirements with respect to functions and designers' intensions, desirable MF sets can be generated. Furthermore, desirable machining sequences of these MF sets can be also derived.



(a) MFs with dimensinal tolerance

(b) MFs with parallelism tolerance

Figure 5: Examples of machining sequence considering requirements

2.3 Generation of optimum process plan

By applying our proposed method in the previous sections, appropriate process plans can be derived. They consist of MF sets and their machining sequences satisfying technological design requirements. However, they are not still unique. In this paper, machining time is introduced as the major criterion for evaluation to decide the optimum process plan. Factors affecting the machining time involve selection of tool parameters and selection of cutting condition.

First, procedure to select an appropriate tool and its parameters is explained. In this paper, the relative tool parameters required for machining include tool types, materials, structures, sizes, and tool paths. These items depend largely on the machining methods, dimension of a MF, required machining accuracy and material etc. Different MFs have distinguished attributes, which need different types of tools to fulfill. In this paper, A list of suitable tools for each MF is prepared. According to this list, the tool type can be simply determined. Concerning determination of the tool parameter, it is realized by calculating based on a certain rules clearly illustrated in Figure 6. As the tool diameter varies mainly with status of a MF to be machined, according to this rule, the most suitable and available tools equipped by a workshop can be chosen for the corresponding MF.

The selection of cutting conditions greatly influences machining accuracy, surface quality, machining efficiency, tool life, and so on. Most of the conventional methods to decide the cutting condition are based on if-then database[2]. However, due to its disadvantages of overload on computer and dependence on skilled planner, trial and error can not be avoided, which take extra time and reduce production efficiency. Our system utilizes case-based reasoning system[1] which we had developed to overcome this problem. The structure of this case-based reasoning system is simply mapped in Figure 7. This methodology can correctly take advantage of if-then database to bring suitable solutions for new problems. When a new manufacturing information of a MF arrives, the important features of the new case is extracted as its indexes. Next, the case index contacts with case database and retrieve similar cases base on key features. After receiving extracted case, the case adapter will modify this similar case to fit the current manufacturing requirements and stream it out. Finally, the cutting condition is retrieved from the ultimate case for machining the relative MF. If the depth of cut, feed and the cutting speed from final case are successfully used in removing the corresponding MF, case learner accommodates it as a new standard case in database.

Moreover, for machining MFs, tool path traced on MF is necessary to be figured out. To decide the proper and practical tool path for each MF, this system incorporates the virtual simulated system[3] and save the outlined path data in the attribute of each MF. The tool path can be drawn based on the type of the MF.

After applying the above procedure, estimation of machining time becomes available. The machining time consists of cutting time, tool exchanging time and the time cost when tools travel between MFs. The total machining time in a level of a MF set is calculated with the following equation.

$$T_{level} = T_{remove} + T_{tool\_exchange} + T_{fast\_feed}$$

where T_{level} is the time cost in the process of machining all MFs of this level, T_{remove} is the time spent on removing MFs, $T_{tool\_exchange}$ is time for exchanging tools, and T_{fast_feed} stands for the time used in traveling the tools between MFs, respectively. Until this step, one MF set still possesses more than one appropriate machining sequence which cause different machining time. The calculated machining times of every level in one MF set are aligned as Figure 8. The nodes in the figure show the machining time of every level in every MF set, the two numbers in the node indicate the level number and the machining sequence number respectively, the time spent on traveling tools between levels are taken into account as well. The path with the minimum time in the tree means the most efficient machining flow of this MF set. Compared with other MF sets, the corresponding process plan with the shortest machining time is decided as the optimum plan. Note that other plans, that is, other MF sets or other machining sequences, are stored in the system as alternatives.

2.4 Adaptation to changed conditions

Derived process plans in this paper, that is, desirable MF sets and their desirable machining sequences, satisfies technological design requirements with respect to functions and designers' intentions. Moreover, they are not unique and are independent of facilities in a workshop. It means that according to manufacturing conditions, detailed plans including tool path can be changed with the same MF sets and the same machining sequence. When a facility can not machine one of MFs or can not machine with following the sequence, alternative plans, which also satisfy requirements, can be selected because they are stored in the system. Therefore, the system can derive modified process plans without complete re-planning even if a machining cell breaks down.

3 CASE STUDY

In this section, the effectiveness of our developed system based on a proposed method is demonstrated. The system is implemented by using Visual C++ and Solidworks on Windows XP system. Figure 9(a) shows an example of a part. It is designed with requirements in straightness, cylindricity and the guide function as shown in Figure 9(b). Then, the system extracts the TRV with the technological information written in the attributions of corresponding entities illustrated in Figure 9(c). The TRV is decomposed into a set of MCPs shown in Figure 9(d). Next, they are recomposed and 252 MF sets are finally generated for evaluation. In this large number of MF sets, three alternatives shown in Figure 9(e) are chosen as desirable MF sets considering requirements. After that, the total machining time of candidate plans is calculated and brought to the comparison step. The optimum plan with the shortest machining time is decided and its desirable

MF set and their desirable machining sequence is shown in Figure 9(f). The total machining time is 164.65 sec.

4 CONCLUSION

In this paper, flexible process planning system considering designers' intentions and manufacturing conditions was proposed. A procedure to generate process plans of this system consists of two parts. One is generation of desirable rough plans, that is, MF sets and their machining sequences satisfying technological design requirements with respect to functions and designers' intentions. Such requirements correspond to necessary conditions of part production and are independent of manufacturing conditions. All rough plans are stored in the system as alternatives. The other is generation of efficient detailed plans including kinds of tools and their size, paths, cutting conditions and so on. They depends on manufacturing conditions. When some failures or disturbances occur in a factory during production, the system adapts to it with two steps. First, it tries to alter the detailed plan with the same MF set and their sequence. If it is impossible, the system selects an alternative MF set or machining sequence from stored rough plans. Thus, the flexibility of the process planning system can be realized.

Manufacturing feature	Calculation method (x stands for diameter) — Closed Face — Open Face
Closed Pocket	If l<w, x should be the biggest value fitting the equation x*3<= l
Open Pocket	x is desired to be biggest value available for endmill diameter
Closed Slot	x should be the biggest value fitting the equation x*3<= w
Open Slot	x should be the biggest value fitting the equation x*3<= w
Face	x should be the biggest value available for face mill diameter
Step	x should be the biggest value available for face mill diameter
Through Hole	x should match the diameter of the hole
Blind Hole	x should match the diameter of the hole
Free Form	x should be the biggest value available for ballmill diameter

Figure 6: Determination of the diameter of tools

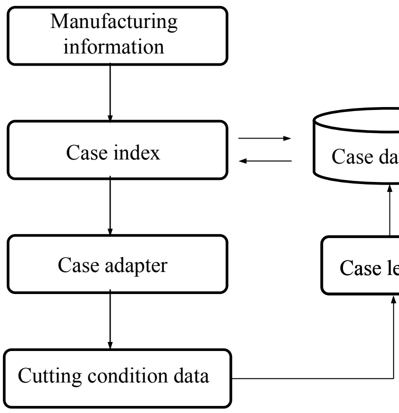


Figure 7: Overview of case-based reasoning system

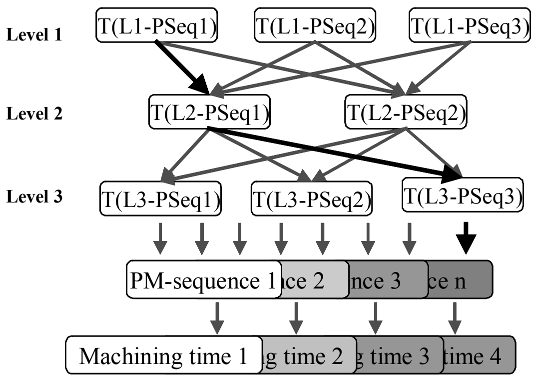


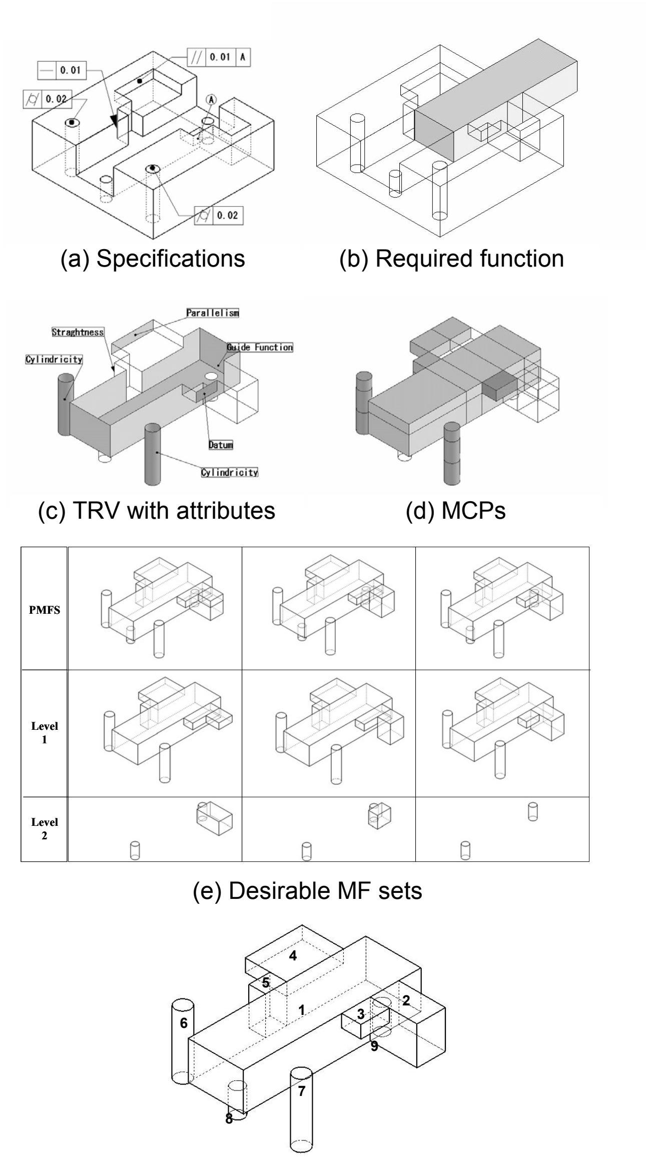
Figure 8: Calcuration of machining time

5 REFERENCES

[1] Shirase K., Nagano T., Wakamatsu H., Arai E., 2000, Automatic Selection of Cutting Conditions Based on Case-Based Reasoning, Proc. of 2000 Intl. Conf. on Advanced Manufacturing Systems and Manufacturing Automation, 524-528.

[2] Arez B., Ridgway K., Al-Ahmari A.M.A., Selection of Cutting Tools and Conditions of Machining Operations Using an Expert System, Computers in Industry, 2000, 42, 43-58.

[3] Nakamoto K., Shirase K., Wakamatsu H., Tsumaya A., Arai E., Automatic Production Planning System to Achieve Flexible Direct Machining, JSME International Journal Series C, 2004, 47, 136-143.



(a) Specifications (b) Required function

(c) TRV with attributes (d) MCPs

(e) Desirable MF sets

(f) Machining sequence

Figure 9: Example of process plan generation