



Development of Flexible CAPP System Based on 3D CAD Model of Product to Support Agile Machining Operation

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Doctoral Dissertation

**Development of Flexible CAPP System
Based on 3D CAD Model of Product
to Support Agile Machining Operation**

迅速な機械加工を支援する製品の 3 次元 CAD モデルに基づく
フレキシブル工程設計システムの開発

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ABSTRACT

Since the automation has been acknowledged to maintain the competitiveness of metal cutting industries, several studies have been performed to meet the requirement for automating the process planning. On the other hand, the evolution of current machine tools automation technology has been able to perform a thorough analysis intelligently on actual machining and shows the possibility of actualizing the manufacturing cycle virtually. The recent Computer-Aided Process Planning (CAPP) technologies already have the capability in optimizing all the combinatorial computation that involves knowledge, resource, and aspect of the machining process. However, the generated process plan mostly limited to specific condition, specific machine, and other specific conditions. More studies are needed to fill the gap between the design and manufacturing stages to support the challenge in realizing the fast and robust CAPP system. Moreover, eventually, to also actualize the CAPP system virtually and work autonomously side by side with the succeeding process to support the manufacturing cycle.

The recent CAD technologies also already have the capability of recognizing design shape suitable and perform several advanced analysis regarding the shapes, but still are difficult and not practical to link to the machining process. This research proposes a CAPP system which able to construct machining process plan (MPP) generatively. The proposed system is built within the CAD environment. The process of MPP generation considers the dynamic of feature development during machining stages. The MPP is developed to be the feeder for supporting the machining operation plan (MOP) generation which considers a flexibility of shapes in an intelligent framework of machining tool within the shop floor.

This research is divided into four main task. The first task is to elaborate several past research to give a broader view of related aspects, e.g. features, logics and example of developed CAPP system. The knowledge management, real-time process planning and flexible process planning are believed to be the aspects to support the MOP generation within an intelligent framework. The second task is to elaborate the establishment of new feature unit which is needed for supporting the development of MPP generation system. Previous research has been able to show the sequencing of machining process based on the total removal volume (TRV). TRV constitutes the volume of the workpiece which needs to be removed to produce the required shapes. In this research, a volume in the process (VIP) is introduced as the new TRV feature-based unit. The VIP is intended for showing the dynamic and unique representation of the straightforward decomposition of TRV definition. The first prototype of MPP generation system based on proposed feature unit is also elaborated.

The third task is to develop an MPP generation system which considers several flexibilities in deciding the best configuration. The prototype which has been explained previously is evaluated to show the performance of the generated MPP based on its total process time. The total process time is consist

of machining time, tool changing time, direction changing time and setup time of the corresponding MPP configuration. The fourth task is to show the capability of linking the CAD and CAM stage by enabling the MOP generation based on the corresponding MPP. An MOP generation system which based on case-based reasoning (CBR) is discussed and elaborated. The previous machining case is used for defining the new machining parameters for the corresponding MOP. The enrichment of VIP into its primitive removal volume (PRV) and actual removal volume (ARV) is also performed to support the MOP generation system. By treating two different kinds of VIP may accommodate each stakeholder, the process planner and operators, to have more comprehensive analysis to consider another aspect, e.g. the setup of the product and machining parameter optimization, based on PRV and ARV. These are also a way to managing the machining knowledge for further use. Additionally, the feasibility to incorporate the aspect of design tolerance is also shown to maintain the flexibility of the MPP. Finally, the significance, contribution, and any potentials findings of this research are reported.

Keywords: Virtual manufacturing, intelligent machine tool, CAPP, machining process, machining operation, CBR

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Chapter 1 Introduction

1.1 Research Background

Process planning is becoming an important issue in integrating the product design and manufacturing stages to accelerate product development. The product can be modeled in any detail, and later on, machining processes need to be generated accordingly for shaping the blank material. A rich variety of product shapes might exist, and mostly the actual machining processes considerably depend on personal skills in determining the best cutting methods. Consequently, the conventional practice which happens to be responsible for a production plan generation in the later stages has resulted in the need to project the production plan into the earlier stages of product development. The awareness of decision-making in the design stage has a significant effect regarding energy and cost requirements and the sustainability of the product lifecycle [1]. For this reason, several automation technologies within each manufacturing role, i.e., design and manufacturing, are constructed and proposed to smooth out the information transfer regarding the production plan.

Automation technologies have a significant influence in increasing manufacturer's productivity. In particular, in metal product manufacturing industries, several automation technologies have created enormous enhancements in the computer-aided environment. In the design stage, several Computer-aided Design (CAD) technologies have had a significant influence on the design process. A product can be designed in a straightforward manner in a 3D virtual environment using CAD software. On the shop floor, several Computer-aided Manufacturing (CAM) technologies have had a significant influence on the metal removal process. The machining center, which is a multi-functional and numerically controlled machine tool, has evolved from only performing manual cutting processes to performing unmanned cutting processes [2]. Regarding the efforts to build the linkage between design and manufacturing, Computer-aided Process Planning (CAPP) technologies have had a significant influence to integrate these stages. Each design convention needs to be translated into a manufacturing convention in engineering the product. To link information between CAD and CAM systems, CAPP is considerably promising as an automated decision support system for planning the related product manufacturing process. Figure 1-1 shows three scopes regarding CAPP development for the metal removal process: CAD, CAM, and CAPP itself. CAD is the input to CAPP, and CAM is the output from CAPP.

CAD researches have been conducted since three decades in recognizing product designs with rule-based pattern recognition [3]. Marchetta et al. [4] investigated the usage of artificial intelligence methodology to recognize manufacturing features. These manufacturing designs will contain an amount of knowledge, namely formal, tacit, product, process, compiled and dynamic [1]. This knowledge needs to be transferred carefully into machining operations. Previous studies have gained an optimal solution to recognizing shape or manufacturing features. However, the lesser research investigates the linkage to CAM solution using the result of feature recognition and shows the practicality of the outcomes.

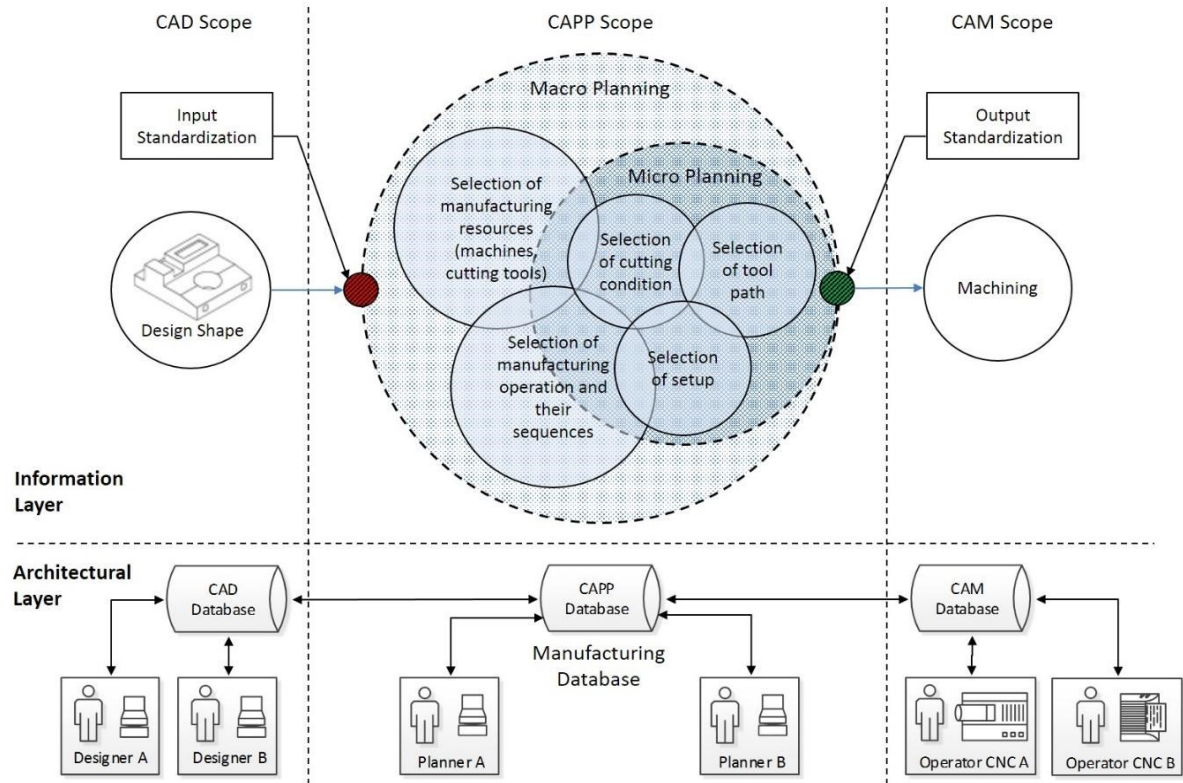


Figure 1-1 Review scheme on CAPP systems development.

The term of planning was introduced in the 1950s as the trend in modeling human intelligence increased (Feigenbaum and Feldman (1963) in [5]). In 1965, computer-aided systems started to be used to assist in the selection process for new designs (Niebel (1965) in [6]). Since then, several CAPP systems have evolved to become more suitable for various manufacturing environments. Another related Computer aided (CA)-x system also occurs in detailing the scope of a CAPP system task. Since 1984, there have been 12 review papers that were published, with nine of them explaining the CAPP development, and the rest explaining, particularly, the involvement of expert system in CAPP development.

The first review paper published in 1984 described process planning as a tedious task that strongly suggested being automated because of some factors such as high labor and equipment costs, decreasing the availability of trained process planners, and the competition between industries to achieve higher productivity [7]. The gap that occurs between the design and manufacturing stages is believed to be caused by the lack of process planning knowledge possessed by the operators in each phase. Therefore, the need to interface CAD and CAM was noticed, which also initiated extensive research in process planning.

In 1988, Ham and Lu [5] reported that the major emphasis on the global perspectives of fundamental issues was in developing computer-based planning systems for various manufacturing tasks.

The CAPP system has been suggested to have short- and long-term goals. These goals must be defined clearly and need to be structured carefully in its development. A narrow-focused planning systems that are isolated from other planning systems must be avoided. The potential role of artificial intelligence (AI) techniques is highly recommended for dealing the need for an integrated planning system, which is categorized as a knowledge-intensive problem. Since human intelligence can be captured and applied in a machine, several prototype systems based on expert systems are being built in the areas of planning and control [8]. Extracting domain knowledge for this type of system has been found to be a difficult task that needs strong management commitment and support.

In 1989, Altung and Zhang [9] discovered 156 existing CAPP systems, for rotational, prismatic, or sheet metal products. In Computer-Integrated Manufacturing (CIM) concept, CAPP is believed to play a key role to integrate CAD and CAM systems. Many approaches have started to interface CAPP with CAD extensively, instead of with CAM. Although it has limited results, the application of AI is strongly recommended for continuous monitoring of actual production experiences and feed-backing information to the planning system. A single database technology needs to be constructed to record all activities from the design stage through the post-process planning phase to generate an integrated planning system. Portability of the CAPP system has also been started to be considered in responding the variety generation of computing technology devices.

In 1991, Shah et al. [10] discussed the task of defining a process plan by its product definition or feature. By this time, several product modeling approaches had been discovered, e.g., design by feature, parametric modeling, and so on. The product is modeled using a CAD system that integrates with the CAPP system to generate a numeric control (NC) program. This integration has decreased effort in transferring information that regards the technical consideration of machining features. With this capability, machining information can be incorporated into the early design stage. However, at this time, the automatic generation of an NC tool path, except for simple 2½-D parts and axisymmetric parts, is still in the experimental stage.

By 1993, the rapid development of personal computers influenced CAPP usage in small- and medium-sized companies [11]. It has been noticed that CAPP is also helpful in assisting with assembly planning problems. One of the important fields were to provide a shared database between CAD and CAPP. The NC programming was predicted would become a sub-function of specific CAPP systems. Development towards integrated CAPP and NC systems has moved in different directions, either by extending CAPP downward or NC systems upward.

Within the same year, ElMaraghy [12] discussed more broadly the development of CAPP. CAPP is seen as essential for achieving CIM implementation. Types and levels of process planning activities have also been distinguished clearly from a high level to a more specific planning environment. Further, the Standard for the Exchange of Product (STEP) model data has been recognized for standardizing a model product term for the vertical and parallel operation. The flexibility of the process

plan is one of the most significant aspects of realizing real-time events. Several developments, e.g. dynamic process planning and distributed process planning, have been shown to enhance the flexibility. Although most process planning tasks are automated, human judgment must still be involved in the CAPP systems loop.

In 1995, Kiritsis [13] selectively gathered 52 papers related to the development of knowledge-based expert systems for process planning. It was explained that knowledge consisting of domain-related facts cannot be well defined analytically. Even if it can be formulated, the number of alternative solutions is still significant, and extensive computation is needed. This problem can be caused by the lack of well-established knowledge engineering. From all gathered papers, fully automated CAPP systems clearly did not represent an efficient process planning system.

In 1996, Leung [14] drew attention to a process planning problem that has emerged in various systems and it is hard to compare to other subjects. Variant CAPP is considered to be revitalized by combining generative concepts to form the basis of the next-generation process planning system, e.g., retrieval of process plans based on similarity and automatic adaptation of process plans. Time efficiency in defining a process plan also means that issues of process plan optimization, integration with product design, and production planning and control will be significantly different. The emergence of AI technologies is considered for combining multiple tools to determine the best process plans and to apply these techniques appropriately at a practical level.

In 1997, Cay and Chassapis [15] identified the value of CAPP in concurrent engineering and CIM. Several studies have discussed the usage of CAPP at an early stage owing to its capability to support a collaborative environment. It is expected that in the future, agent-based distributed engineering systems will provide a basis for the integration of concurrent product development activities. Optimization, parallel machining, and tolerance analysis are other approaches that have been reported to gain more attention in developing CAPP systems.

In 1998, Marri et al. [16] classified CAPP systems based on their general features, product planning capabilities, and implementation environments. At this time, CAPP systems only offered partial solutions and were isolated from other manufacturing functions. CAPP systems needed to be enhanced to consider the shop floor status of machines to make the system real time and dynamic. Most CAPP systems are not capable of coping with the uncertain nature of the shop floor. Intelligent CAPP systems are going to play a significant role in the modern manufacturing industry [17].

By 2009, Xu et al. [6] classified the process planning research for determining the level of focus in a certain domain and the impact of particular technologies. The Genetic Algorithm (GA) has been identified as the most popular tool for solving process planning problems. Their review showed that CAPP systems will be enhanced to become more collaborative and distributive to meet the needs of globalized manufacturing trends, i.e., the usage of STEP data models and support for an Internet-based environment. The next generation CAPP is also predicted to be able to create a capability-adjusted

process plan based on actual resource capabilities instead of only being based on nominal resource information.

On the other hand, the evolution of current machine tools automation technology has much difference since Computer Numerical Control (CNC) was firstly adopted [18]. A lot of automated cutting process could have been done by only instructing machine through the NC programs. However, this practice could no longer be satisfied because of the occurrence of the computer intelligence issues for the future. The traditional machine tool is found to evolve into either multi-tasking or machining center which has multiple axes to handle several machining operation in one machining environment [2]. In order to realize the intelligence requirement of the machine tool, Shirase et al. [19] proposed a Digital Copy Milling (DCM) system that can perform the cutting process without preparing the NC programs for the first time. Various researches have been conducted to escalate the intelligence of the DCM. Additional supporting researches by Shimada et al. [20] and Hirooka et al. [21] to enhance the DCM to control cutting conditions to avoid tool breakage, cutting load adaptation, and whole rough cutting conditions. Shinoki et al. [22] also showed that past cutting conditions could be used for defining ongoing cutting conditions. For database support, Igari et al. [23] proposed an updatable database to manage the patterns of cutting conditions and promisingly to be automated by efficient querying processes. Although the cutting processes and conditions can be defined instantaneously by the DCM, all cutting processes need to be structured orderly according to a flexible environment. Therefore, a CAPP system is required to provide machining process information continuously and robustly into the DCM systems. The availability of CAPP system might enable the entire system to run autonomously right after the designer dispatches the 3D workpiece model.

1.2 Statement of the problem

The customization era enforces the metal cutting industry to become responsive and agile. In realizing product, the knowledge has emerged into the uniqueness of machining style operations and makes a difference point of view between planner and operator in designing the machining process. Since the operator is the primary actor instead of the planner to realizing a product, their knowledge should also be considered in the process plan. The occurrences of different viewpoint need to be managed or eliminated to create smooth information transfer. Especially when dealing with different resources environment availability, such as sequence, machine tools and other. The smooth information transfer between the planner and the operator will reduce the time to realize the machining process.

The recent CAD technologies have the capability of recognizing suitable design shape, but still are difficult and not practical to link to the machining process. The recent CAPP technologies already have the capability in optimizing all the combinatorial computation that involves knowledge, resource, and aspect of the machining process. However, the generated process plan mostly limited to specific condition, specific machine, and other specific conditions. The most important thing is the process plan is not native from the operator point of view which will be the expert to realize the product on the shop

floor. The phenomenon creates another additional time to adjust the generated process plan into a suitable machining operation parameters. Moreover, the existence of a rigid machining feature definition during the process plan generation also limit the flexibility of the process plan.

Furthermore, the agile environment of competition between manufacturers has been a great influence on the adjustment of practices on the shop floor. The intelligent machine tool is next requirement in NC machine tools [24]. The intelligent machine tool is designated to be able to generate all information for the entire machining operation by itself. The intelligent machine tool performs machining operation actively, adaptively, and flexible. In order to achieve the intelligent machine tool, the corresponding real-time process planning applications are also required. The advantages of information technology can be used to view or even interrupt the process plan in the real-time machining environment. As mentioned earlier, an interface to enable machining with rapid planning was introduced by Shirase et al. [19]. They demonstrated machining without the need for NC programs. Several enhancements also have been shown by Shirase and Fuji [18] to maintaining the reliability of this approach to perform the actual machining by proposing the Autonomous and Intelligent Machine tool (AIMac) framework . As a result, CAPP must be built in an agile environment by considering the capability to easily reconfigure the process plan.

1.3 Research Objective

By considering the problem which has been stated previously, this research will have four following objectives:

1. To show the prominence and map the requirement of future development on CAPP technologies towards the flexible environment. The state of the art of the current development of CAPP system is needed to be shown to describe more clearly about the practical aspect in realizing the machining operation.
2. To propose an alternative methodology in acquiring machining process plan (MPP), which is less depended to the so-called machining feature, to support the requirement of a flexible MPP in an autonomous operation of succeeding process.
3. To propose a corresponding method to manage the flexibility of MPP by considering the machining environment.
4. To propose a corresponding methodology to manage the feature creation based on the need to preserve machining knowledge for machining operation plan (MOP) generation.
5. To propose a corresponding methodology to manage the flexibility of MPP by considering the design requirements.

1.4 Thesis Structure

This thesis consists of six chapters. Figure 1-2 depicts the entire flow of the thesis. The first chapter is used for showing the current issue on flexible MPP generation. The second chapter is constructed for elaborating each related elements and aspects within the development of CAPP system regarding the MOP generation. Former researches, which are related to the development stages of CAPP system, are shown. The broader view of related aspects, e.g. features, logics and example of developed CAPP system are also shown. The second chapter is intended to achieve the first of research objective.

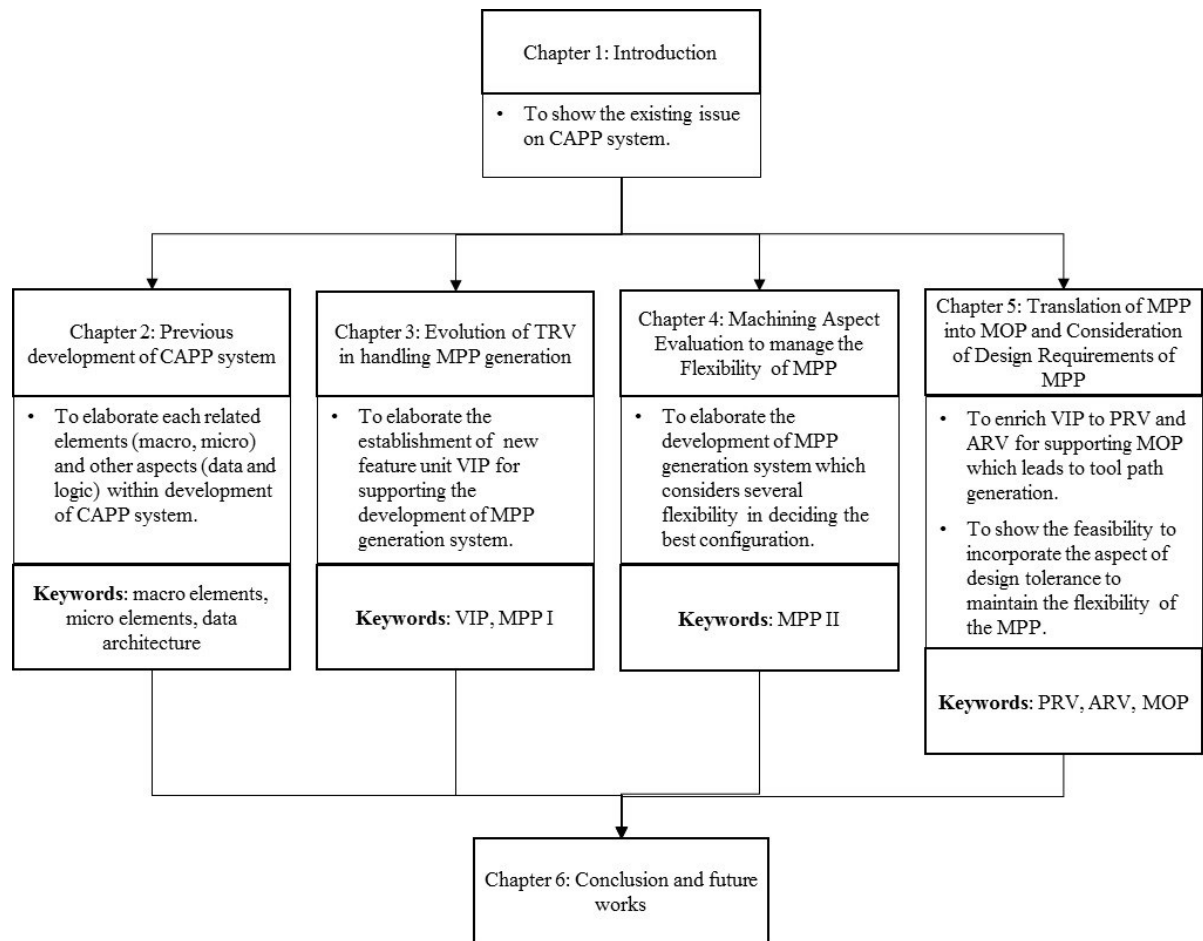


Figure 1-2 Thesis construction and related task.

The third chapter is constructed for elaborating the establishment of new feature unit which is needed for supporting the development of MPP generation system. The new feature unit is based on total removal volume (TRV) concept of a product. The first prototype of MPP generation system based on proposed feature unit is elaborated. The results of the experiment are also shown. The fourth chapter is constructed for elaborating the development of MPP generation system which considers several flexibility aspects in deciding the best configuration. The prototype which has been explained in chapter

three is escalated to show the performance and ability in conducting further analysis for making a decision. These chapters are intended to achieve the second and third of research objective.

The fifth chapter is used for showing the enhancement of the developed system to be able to generate the corresponding MOP, which leads to tool path generation. In this chapter, the enrichment of TRV is shown as the effort in dispatching the result of MPP into MOP. Another work from related research is combined to show the successive step of MOP generation based on the enriched TRV. Additionally, the feasibility study to incorporate the aspect of design requirement is also proved to maintain the flexibility of the MPP. These chapters are intended to achieve the fourth and fifth of research objectives.

Finally, the sixth chapter is used for concluding the entire research goals. The significance, contribution, and any potentials findings of this research are reported. Hence, possible future research directions are described.

Chapter 2 Previous Development of CAPP System

2.1 Introduction

This chapter discusses the conducted research of each CAPP task, particularly, for metal removal processes. As mentioned in Chapter 1, two advanced computer-aided technologies, CAD, and CAM, have been extensively used to help manufacturing companies operate from product design to product machining. In daily operations, CAD is used for creating several product designs and CAM is used for defining machining conditions based on the given product shape. Furthermore, CAPP emerged to respond to the need of smooth information transfers between CAD and CAM [25]. The CAPP coordinates the product design and the MOP, e.g. preparing cutting tools, sequencing cutting processes, job scheduling, and cost analysis for the corresponding MPP [26], [27]. Previous papers on CAPP review have explained the prominence and emergence of several methods to solve process planning in general. The research and development for each task of CAPP which related to machining operation have not yet been discussed. Previous research of CAPP has already shown its utility to help in several areas that need process planning; however, it is still difficult to explain particular area owing to the generalized concept of process planning for the actual machining operation.

2.2 The CAPP system milestone

Currently, process planning systems have two major divisions [16], the variant and the generative type. Variant process planning (VPP) system defines the machining process based on previously stored machining process information. VPP is more suitable for parts that have the large-order scale and low variation in shape. The other approach, generative process planning (GPP) system synthesize the required machining process for a given and put into series of machining process by using the available machining knowledge. Instead of exploiting similar previous machining processes, GPP mostly generates the machining sequence from scratch. This happens because each given part has a unique shape. GPP is mostly suitable for dealing with parts that having low order scale with a high variation of shape. However, the drawbacks in applying these two kinds of systems practically have triggered other approaches, a semi-VPP or a semi-GPP. Each process planning system, VPP or GPP, will be complimentary for the semi- process planning systems.

The milestones of CAPP system development can be summarized in Figure 2-1. In 1970, the first GPP system was proposed to assist with the machining process on a single spindle lathe. Later in 1973, further development of a multiple spindle lathe was proposed. In 1976, the first VPP system called CAM-I was proposed for a lathe. At this time, a different study also introduced a user-interactive CAPP system. The following year, a CAPP system called APPAS was proposed for a milling machine. The CAPP system can also be modularized to decrease the effort for generating a process plan. Moreover, efforts were taken to integrate CAPP with CAD. Since the introduction of the concept of Flexible

Manufacturing Systems (FMS) around 1980, CAPP systems were developed to be compatible with FMS. CAPP is also designed to be compatible with micro-computing devices.

By 1990, several approaches had been introduced for integrated CAD-CAPP systems, e.g., feature-based modeling and design by feature. Considerable research was conducted later to increase the flexibility of CAPP systems. To reduce the computation time for generating a process plan, CAPP was designed to be distributed across several computing devices. Integration between CAM and CAPP has also been introduced to improve flexibility in generating a process plan. In 1991, CAPP contributed to realizing the concept of concurrent engineering. In 1999, an agent-based framework was introduced to help CAPP systems distribute CAPP tasks whereas centralizing the process plan. Between 2004 and 2009, several CAPP systems that complied with the STEP-NC standard were proposed. The compatibility issues were raised by the popularity of the CIM framework and the need to exchange consistent information between manufacturers. The increase of computer network usage drove researchers to develop CAPP systems that utilize the internet. In response to the need to reduce energy consumption, CAPP has also been proposed to be an environmentally conscious system. Several optimization methods also contribute to solving process planning problems with multiple objective criteria. However, a practical CAPP system is yet to be developed for designing an autonomous machining system.

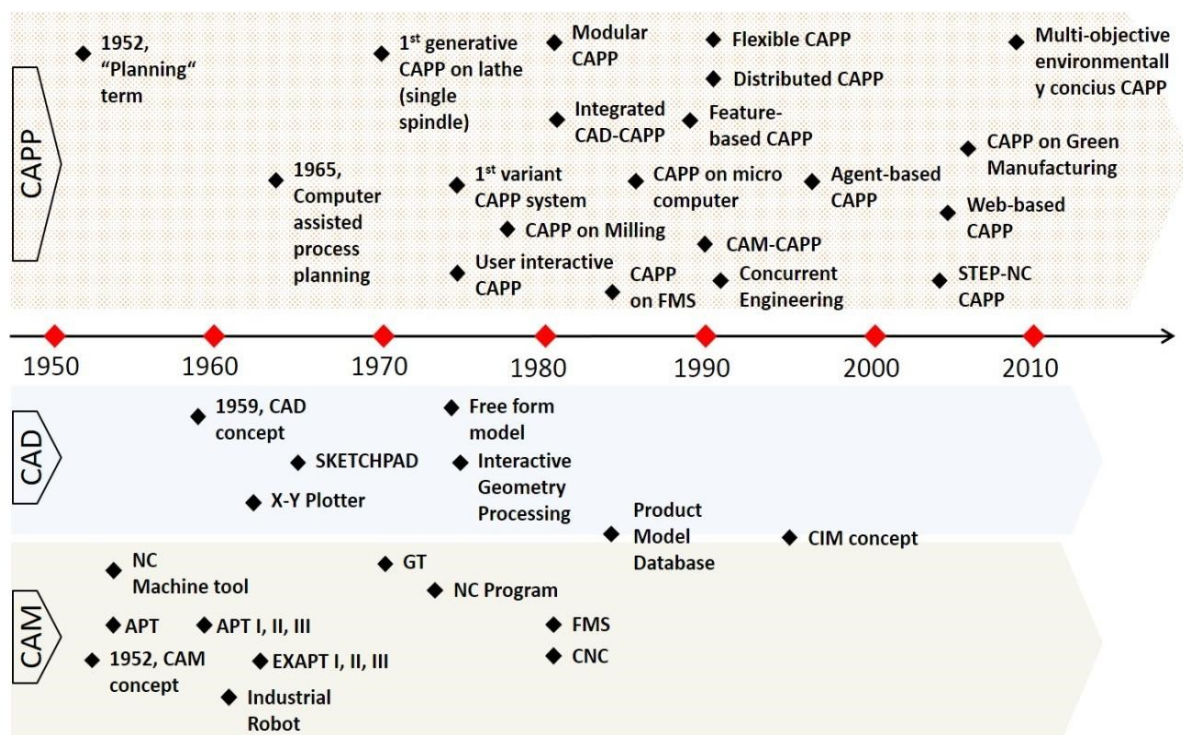


Figure 2-1 Milestones of CAPP research.

2.3 Importance of feature and its definition

The feature links the physical and geometric aspects of a workpiece or an assembly of workpiece [28]. Moreover, features are the most important form or unit in succeeding further analysis on CAD models as depicted in Figure 2-2. Regarding the machining operation, the features will define which MOP is suitable for the corresponding machining shape in process planning scope.

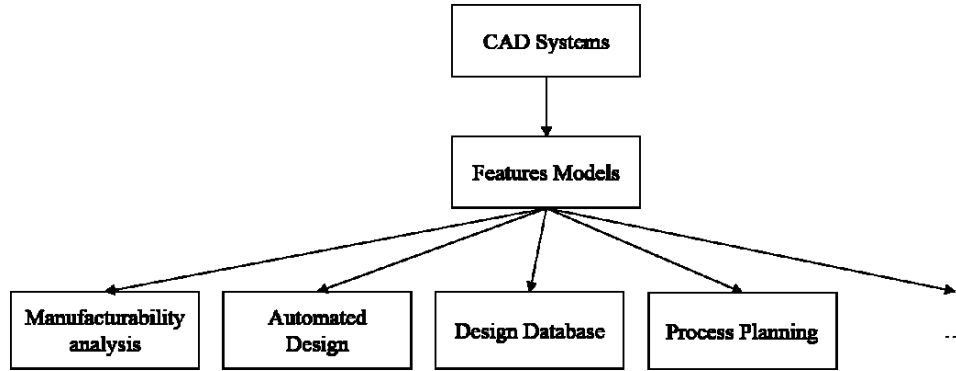


Figure 2-2 Features as a link between design and downstream applications [29].

Nasr and Kamrani [25] defines the feature as the common form which can be used by technicians or operators for associating various attributes and information of a product. Erve and Cals (1986) in [30] defines as one of the characteristic of the workpiece in defining geometric shapes and can be associated with a particular machining process. Moreover, it may be also used for fixturing or measurement purposes. In this study, the feature is determined by the shape of a product which will correspond to a particular machining operations or to be called machining feature (MF) in the series of manufacturing activities. The following points show other existing definitions of MF:

1. MF is a collection of geometric entities which is connected each other, and the entire of it might correspond to a particular machining method or process in shaping the geometry [25].
2. In the feature-based machining, all forms of machined shapes can be classified as MF [31].
3. MF can be defined as a part of the workpiece which has been produced by a series of metal cutting techniques (Choi, Barash and Anderson (1984) in [30]).
4. MF contains information of a volume which need to be removed or to be machined (Anderson (1990) in [30]).

2.4 Classification of feature

In general, the classification of features will always depend on the particular application and can be further described as in Figure 2-3. Table 2-1 shows classification of features based on several different perspectives within the study of a CAD model. The features of the CAD model can be identified and classified based on four aspects, namely the features as supporting information, features as a depiction

phase of the manufacturing process, features which have a different configuration and the corresponding profile of the feature itself.

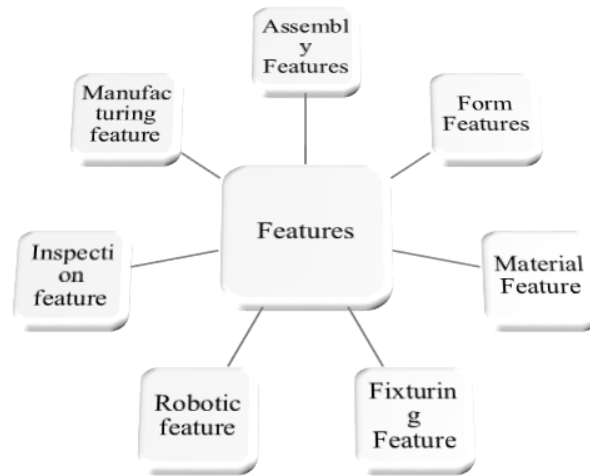


Figure 2-3 Types of features [25].

Each aspect in Table 2-1 may have a particular type of features. For example, three kinds of features might appear as MF in a CAD model based on the aspect of configuration, elementary features, compound features and functional features. The elementary features can be interpreted as a primitive feature. The compound features can be interpreted as a feature caused by a combination of two or more MF. While the functional features can be interpreted as MF that provide other information such as the characteristics of the relevant features, e.g. threaded holes.

Table 2-1 Classification of MF based on several perspectives [25].

Aspect	Type of features	Characteristics
1. Information support requirement	Form features	Size, shape
	Precision features	Tolerances, surface finish
	Material features	Material type, material grades, heat treatment, etc
2. Applicability of the features in different phases of manufacturing	Design features	Center line, radius, function of the features
	Process planning features	Starting surface, manufacturing method
	Assembly features	line, radius, tolerance
3. Configuration of the feature	Elementary features	Hole, step, etc.
	Compound features	Stepped hole
	Functional features	Screw thread
4. Profile of the features	Prismatic features	Slot, pocket, etc.
	Cylindrical features	Hole, fillet, arch, etc.

2.5 Features in CAM cycles

As mentioned earlier, a significant portion of the processing might be accomplished on a CNC machine tool. As a part to implement the process plan, the NC of part program is generated automatically by CAD/CAM [32]. The CAD/CAM system dispatch the NC program directly to the machine tool using a telecommunications network. By utilizing this arrangement, the designing process, NC programming, and the determination of machining parameter production are all implemented by a computer. Figure 2-4 shows a typical CAM cycle in a feature-based environment. Steps 1 to through 4 show the details the feature extraction procedure in which the geometric information of the part design has to transfer to some the format that can be used by CAPP system. Then, steps 5, 6, and 7 responsible to generate a process plan which contains all required information to manufacture the part. Finally, steps 8 and 9 are responsible for generating NC code.

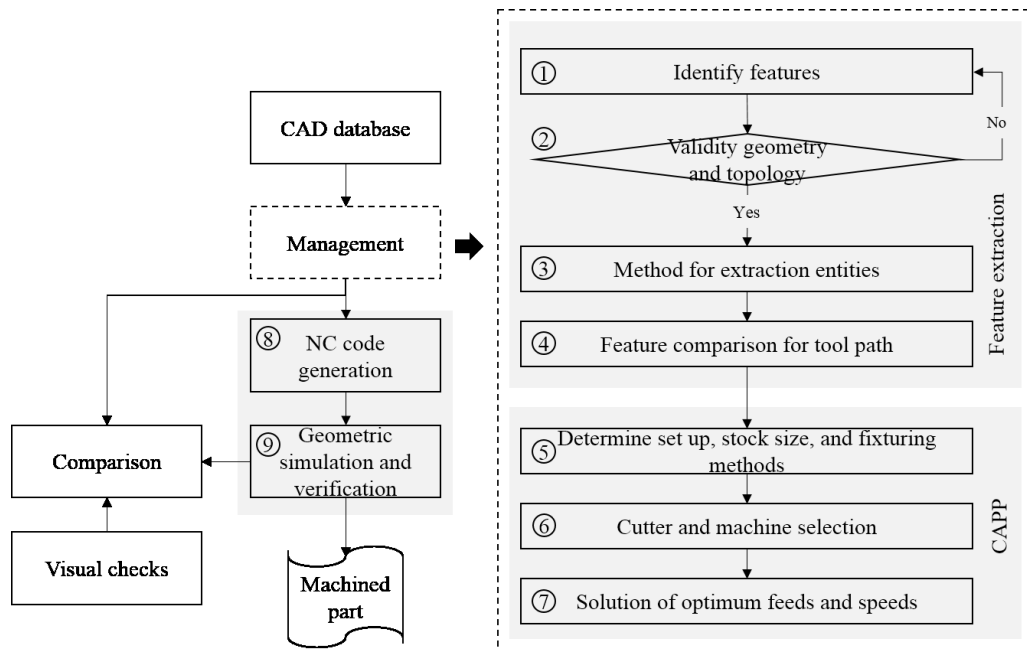


Figure 2-4 Feature-based design environment [32].

Automatic MF recognition for machining is essentially used for searching a solid model for machinable volumes that passes certain manufacturability criteria and provides global and local relationships of the corresponding MF [3]. Figure 2-5 shows the universal scheme of an automatic feature recognition which may be performed by constructing geometric models first; then a computer program processes will continue to discover the features automatically. Shah and Mäntylä [28] classifies recognition feature automatically into two parts, the machining region recognition, and pre-defined feature recognition. The division is based on consideration of the need for a pre-defined features or not to generate tool path to form a feature.

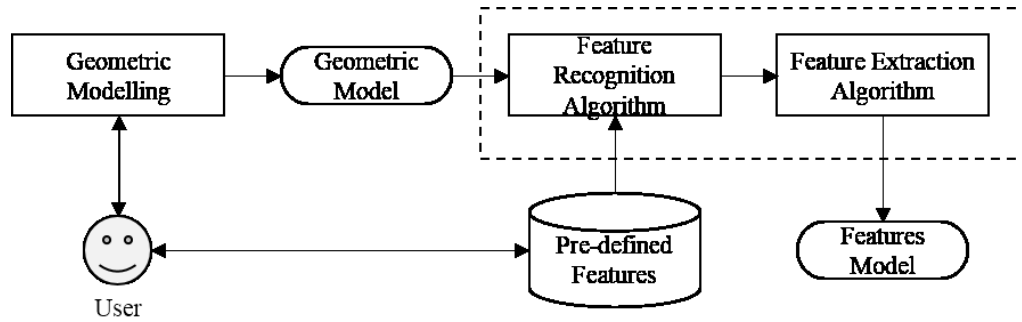


Figure 2-5 Automatic MF recognition scheme [28].

Machining-region recognition method is only intended to determine the machining area. The machining areas are not necessary to be defined as a particular feature. The main reason is, at the end of the process, the machining toolpath may be generated without the need to know what kind of features which is well describing the area. The method of recognition machining region can be classified into three categories, namely sectioning, convex hull decomposition, and cell decomposition [28].

The methods of pre-defined feature recognition aim to determine the machining area and also the particular features characteristic. The methods of pre-defined feature recognition will match any areas that must be carried out machining with a pre-defined features. Some key aspects underlying each feature recognition techniques based pre-defined feature recognition, namely [33]: matching, growing entity, volume decomposition, and recognition from Constructive Solid Geometry (CSG) trees.

As elaborated by Shinoki *et al.* [22], MF might have several topologies as shown in Figure 2-6. These MF are seen only to perform a machining process based on a finish or target shape. There are three drawbacks can be comprehended. First, the feature definition will depend on its topology. Secondly, the management of the feature creation will become more tedious work to do, since whenever each time a new topology occurred, then it needs to be included as a new feature definition in the pre-defined features collection. Lastly, the freeform surface feature will be hardly defined by only its topology. In other words, this practice might lead the MPP system to be working more like a VPP system instead of a GPP system.

2.6 Elements Configuring Computer-aided Process Planning

This section describes an automated system for design and manufacturing stages. By referring to Figure 1-1, there are three scopes involving CAD, CAPP, and CAM. In CAPP, two interfacing points represent the relations with CAD and CAM. The CAPP scope considers two types of planning: macro and micro. Macro planning consists of manufacturing resources and machining operation selection. Micro planning consists of cutting condition selection, setup selection, and tool path determination. Each of these planning elements will be explained in later sections. This chapter will discuss the accessible

studies until 2012 and describe the development of each planning element. Table 2-2 shows the development stage of each planning element from 1970 until 2012.

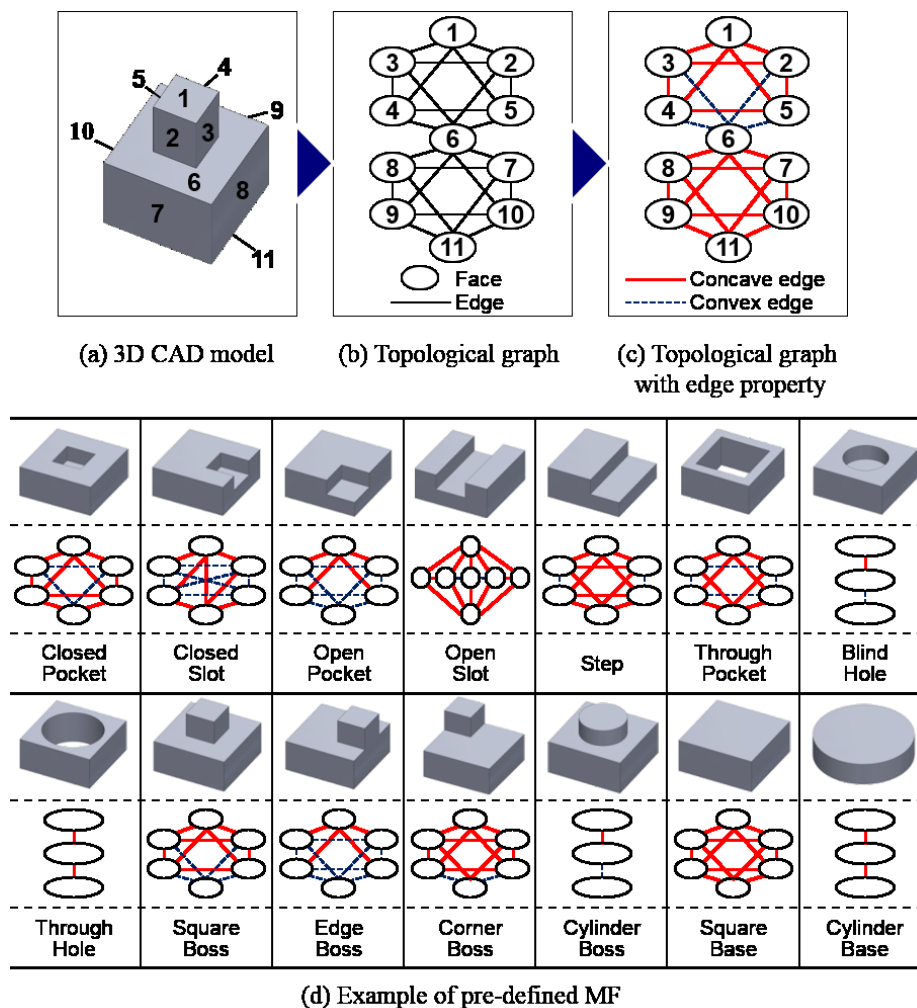


Figure 2-6 The examples of predefined features and its topography [22].

2.6.1 Model convention used for feature definition in defining process planning

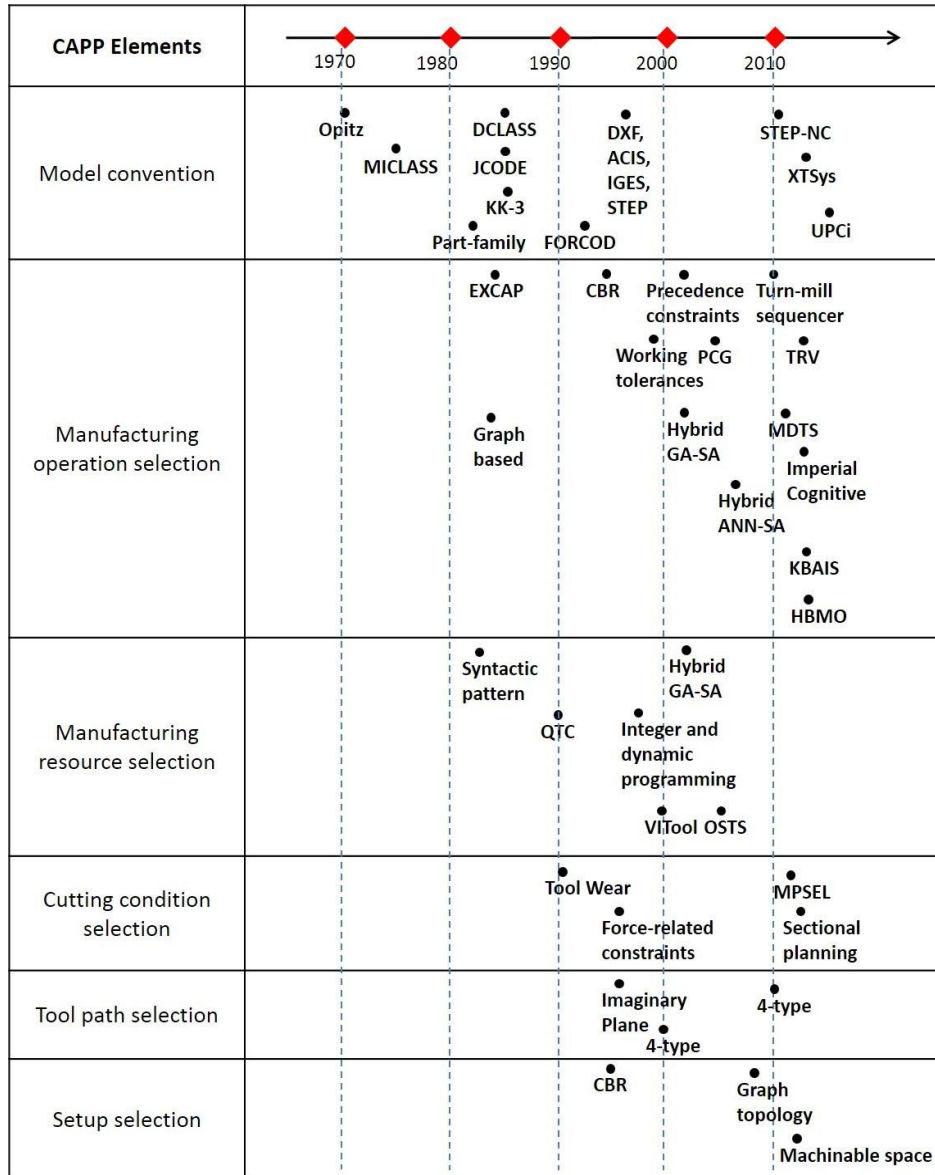
As depicted in Figure 1-1, there are two interfacing points connected to CAD and CAM. These points will constitute a model convention from this point forward. In order to integrate the CAPP smoothly, several modeling conventions have been established. Two main modeling convention base categories were identified previously, namely, the coding scheme, the CAD, and CAM interface.

2.6.1.1 Coding scheme

A coding scheme is the easiest way to accommodate a VPP system-type input, and their existence is influenced by the innovation of the Group Technology (GT) production system. Commonly occurring strings of features can be grouped or formatted together as a “macro feature” or “macro” to

facilitate the coding. The concept can even be extended to link common established Automatically Programmed Tool (APT) features if an APT-based geometry system is desired.

Table 2-2 Former research on CAPP elements.



The OPITZ coding system is one of the earliest examples of a coding scheme [34]. Furthermore, the MICLASS system [35], the DCLASS system [36], the JCODE system [37], the KK-3 system [38], and the FORCOD [39] are examples of coding schemes that were invented to code or design products. Figure 2-7 shows the application of these coding schemes in supporting particular VPP systems. Previously mentioned coding schemes can also be used for GPP system and can be applied as semi-GPP systems [9]. Semi-GPP may also utilize several coding schemes, e.g., part family coding in ACAPS [40].

Further, it is believed that as cellular manufacturing concepts are introduced, many other coding schemes are constructed to meet specific needs of manufacturers.

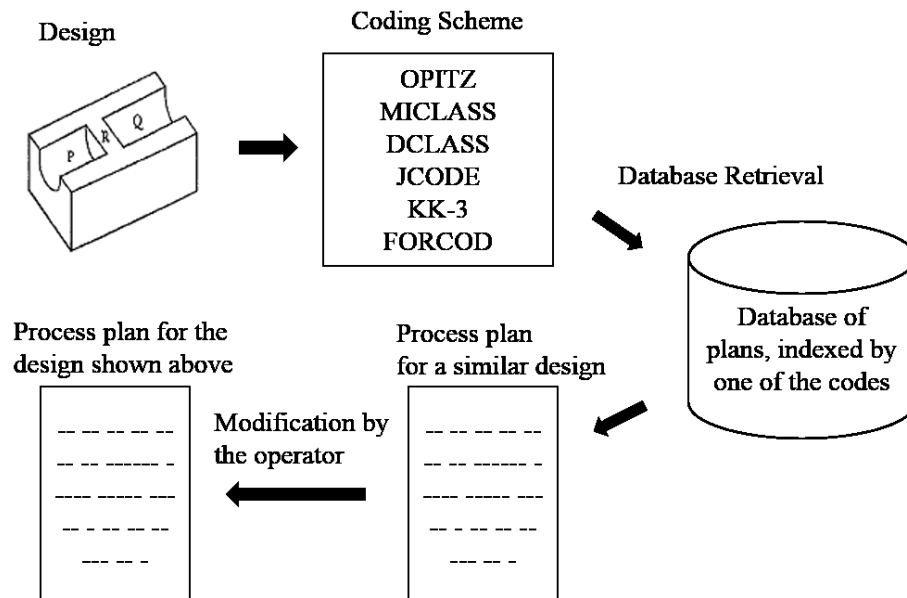


Figure 2-7 The application of coding scheme in VPP system.

2.6.1.2 Interfaced CAD and CAM

In order to decrease knowledge transfer efforts, a planning module emerged to be integrated into the design module. In short, CAPP was designed to interface CAPP with CAD natively to simplify the planning process. This approach amplifies the generative process planning to be more capable of generating a solution. The first simple approach is to extract information directly from the digital file format of a CAD model. Drawing Interchange Format (DXF) and Initial Graphic Exchange Specification (IGES) are examples of digital formats that can be read to obtain detailed product information.

Three types of models are used for feeding the CAPP module. First, the surface models, namely Bezier, B-spline, NURBS, beta-spline and Ferguson [25]. These are the best approaches for representing free-form surfaces. Second, the CSG model that comprises a collection of primitive geometric transformations by a binary tree and are represented by Boolean operators. The third is the B-rep models. In B-rep, a product is represented by its boundary, faces, edges, and vertices. By using a B-rep model, each parameter within the model can be manipulated to generate the process plan. Another study also combines two or more modeling approaches to generate product information. CSG, B-rep, and another solid modeling method can be illustrated in Figure 2-8.

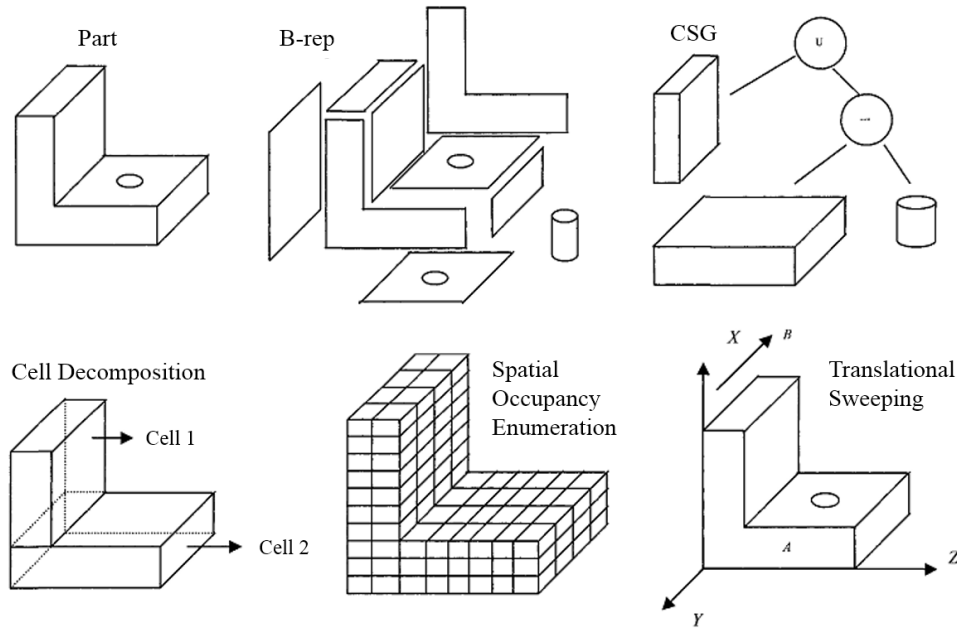


Figure 2-8 Basic types of solid modeling representation [25].

The most popular approach is to model a product by using its “features.” The integration direction will be more CAPP “upward.” The definition of a feature is established to simplify the planning process. This definition can be used early in the design stage. This approach is also known as the “feature-based” or “design by feature” process. As a requirement to integrate CAM into the CAPP scope, a model called “manufacturing features” is introduced. The determination of feature creates the possibility to induce the machining consideration earlier in the design stage. Automatic feature recognition is conducted to determine the information to be processed in the CAPP module [41]. The involvement of manufacturing features will be explained further in section Chapter 3.

Methods for extraction of geometric features from CAD models can be divided into internal and external approaches. Internal approaches use an application protocol interface (API) in the CAD software by which the part was designed. External approaches use a neutral data format, e.g., ACIS, IGES, and STEP or an ASCII file [3]. These files are then translated into a suitable form to represent features in process plans.

As opposed to the concept of features regarding the machinable volume, Nakamoto et al. [42] introduced the use of total removal volume (TRV) of blank material to represent the machinable volume. TRV constitutes material that needs to be machined from the blank material. Regarding practical use, any kinds of material shape should be considered. Therefore, the material that needs to be removed could vary depending on the input. In this case, feature definition is not sufficient to represent the machining process requirements.

Previously mentioned MF or “manufacturing feature” has gained popularity since being introduced in 1989. Several definitions of MF arose, and the definition process turned into a free-for-all. In order to accommodate the compatibility, STEP was introduced to curb the terminology. STEP is also suitable for standardizing product information between manufacturers. STEP-based applications are emerging in all industrial domains [3]. STEP is capable of describing a part’s geometry, topology, and tolerance relations with other parts, various attributes, and contingency for appropriate assembly. The recent development STEP-NC has also bridged CAPP with CAM in stating product information for computer numerically controlled (CNC) machining.

Yan et al. [43] proposed a reverse engineering system to extract machining information from machining operation data. The machining elements that belong to the feature are recognized by the Boolean relations of their cut contours and Z levels. Once the elements of a feature are recognized, the operation sequence of the machining feature will be known. In a practical situation, NC part programs are finalized on the shop floor. Nearly all of the machining information except setup information is included implicitly in part programs. However, the part programming standard (ISO 6983) is limited to providing a corresponding CAPP-CAM integration. The consequence of this is that there are many part programming dialects that create limited portability between CNC machines. Furthermore, it is considerably difficult to extract machining knowledge from part programs.

Safaieh et al. [44] proposed a novel methodology to achieve interoperability between CNC machines for manufacturing asymmetrical components. The Cross-Technology Interoperability System (XTSys) for CNC machine was developed to cope with interoperability problems. XTSys can recognize tools, operations, and features in NC code and store this information in a standardized database. XTSys is also designed to read machine code written in any language, e.g., G&M codes, STEP-NC, and Heidenhain language, for input and output. Zhang et al. [45] proposed a universal process comprehension interface (UPCi) to capture and reuse manufacturing knowledge from shop floor part programs based on its G&M codes. A meta-model of an NC program can be generated based on particular G&M scheme. By using the meta-model, cutting tool and product geometry information can be used to recognize features.

2.6.2 Selection of a manufacturing operation

Selection of a manufacturing operation will continue the previous process in accepting the model convention of a product. A selected manufacturing operation corresponds to each task that needs to be accomplished to realize the designated product. In a regular way, the process will take the first element that needs to be defined. Later, a selected process will succeed the next step in detailing the process, e.g., selection of the machine tool, cutting tool, cutting condition, and so on.

The first method for solving the manufacturing operation problem is a production rule. The production rule is made by gathering knowledge from a previous or designated process. A simple rule is to capture the knowledge of the planner for the selected removal shape. Because the problem of the

selected operation quality has become worse, the knowledge of the shop floor operator is considered in the process selection. Davies and Darbyshire [46] proposed the EXCAP system that uses the IF-THEN logic to select a suitable operation for rotating components.

As the feature-based planning method is involved, the manufacturing feature is also related 1:1 to the machining process. The correspondence implies that each manufacturing feature is already designed for a particular machining process or, in other words, each machining process will generate specific manufacturing features. Therefore, triggered by this requirement, several studies have been conducted to achieve efficiency in gathering manufacturing features. For example, the syntactic pattern, state transition diagram, decomposition approach, knowledge-based approach, CSG approach, and graph-based approach are proposed to recognize features earlier in the process.

Champati et al. [47] proposed a Case-Based Reasoning (CBR) approach to sequence machining operations. The previously stored machining knowledge can be retrieved by their similarity-of-features relationship and tool approach direction. Similar previous machining processes can be selected and modified to meet the current requirement. The modified machining process is then stored to enrich the machining knowledge base.

Tseng and Kung [48] proposed an evaluation methodology for multiple machining sequences to achieve dedicated working tolerances. The sum of linear tolerances and geometric tolerances is used to evaluate alternative machining sequences. In this approach, the best axis for machining the products can be defined for each machining sequence that uses 3-axis machine tools.

Ciurana et al. [49] proposed a graph theory to simplify capturing manufacturing information. All gathered manufacturing processes are retained as precedence constraints, but it is simpler than the Ho and Moodie [50] approach. Each node corresponds to a particular machining operation. Each node is categorized as an emitter, receptor, or intermediate operation. In this classification system, operations are grouped into several classes that represent the importance of the operations. Operations can be easily reduced or simplified by using the given sequence of manufacturing operations while still considering the technological restrictions between operations.

Shakeri [51] proposed a simple heuristic approach and presented a numerical example for generating a process plan. The system consists of two modules, a Precedence Constraint Generator (PCG) and an operation sequencing and tool selection (OSTS) module. The PCG module is charged with generating the predecessor–successor relationship based on three constraints, *z*-axis limitations, *x/y*-axis limitations, and technological constraints. The result from the PCG module is analyzed in the OSTS module using the minimum tool changes criterion.

Zhu et al. [52] proposed a methodology to sequence the machining process for a turn–mill machine tool. The milling feature is extracted first by applying a Boolean arithmetic calculation. By using a part's open faces, Nakamoto et al. [42] was able to recognize the categories of milling features.

Apart from the cutting tool types, the turning operation is sequenced by using the diameter location on the turning axis. The product axis, which extends from the tool post to the chuck, is sectioned together in order to acquire the corresponding sequence based on its diameter. Hole features parallel to the product axis can also be recognized, and the specific machining process can be planned.

In addition to the feature-based approach, Nakamoto et al. [42] and Morinaga et al. [53] proposed the concept of TRV to determine the required machining process. TRV is acquired by subtracting the finished part from the input material. The generated TRV shape constitutes the material that must be removed from the given shape. The TRV is divided into cells before it can be decomposed into any different machining shape. Nakamoto et al. [42] consider all possible machining process configurations to calculate the best solution. Morinaga et al. [53] only examine the configuration created from any concave shape of the TRV. This improvement decreases the number of candidates while keeping a convergence solution.

Multiple approaches to enhance the basic methods for simplifying machining features have also been popular. Reducing the number of solutions and combining them into sequences of machining processes remain as the challenge in practical application. The constraints of each machining process are generated for simulating the manufacturability of the product. Horowitz and Sahni [54] proposed a topological ordering algorithm to generate an optimal manufacturing sequence based on a given graph of previous constraints.

Li et al. [55] proposed a hybrid GA and Simulated Annealing (SA) optimization methods to solve the sequence of the machining operation. Several alternative operation sequences are generated and optimized by considering the lowest total spending cost for machine, tooling, set-up, tool changes, and machine changes. GA is used for the first phase to generate the solution, and SA is used as a compliment to perform a better-localized search of the GA solution. This hybrid GA-SA utilization has shown to be efficient and produces better results in achieving multiple process plans.

Zhou et al. [56] proposed a hybrid Artificial Neural Network (ANN) and GA optimization methods to generate a global optimal process plan. A back propagation ANN model was built and trained to make decisions on alternative machining methods and their selection probabilities. By utilizing feasibility studies of precedence constraints for each process, the GA can obtain an optimal process plan candidate based on the selected machining schemes and corresponding operation precedence constraints.

Lian et al. [57] proposed systems that used the Multi-Dimensional Taboo Search (MDTS) algorithm for optimizing a process plan. This method assumes that the process plan is determined by operation dimension and parameter dimension (machine, tool, and tool access direction (TAD)). Existing approaches prioritize to obtain optimal solutions in the operation dimension, i.e., the optimal operation sequence. Parameter dimensions are optimized to adapt to the operation dimension. Each dimension is treated equally, and different dimensions are optimized. Computational comparison of

MDTS with GA, SA, Taboo Search (TS), and Particle Swarm Optimization (PSO) shows that the proposed MDTS is superior for solving process planning problems.

Prakash et al. [58] proposed a selection of operation sequences that was based on Knowledge-Based Artificial Immune System (KBAIS) method. Artificial Immune System (AIS) method is incepted with a knowledge-based (KB) system that is constructed from tacit and explicit knowledge from a personal operator experience. The proposed KBAIS system uses knowledge-based initialization, selection, and hypermutation instead of randomization. These methods can converge faster than a simple AIS.

Lian et al. [59] applied the Imperialist Competitive Algorithm (ICA) to generate an optimal process plan with various flexibilities. The total manufacturing cost criterion proposed by Li et al. [55] was also used for evaluating the solution. Several manipulations using a mutation technique is believed to generate unfeasible solutions, so a constraint-handling algorithm was adopted to modify unfeasible solutions into reasonable ones. The results showed that the algorithm performed significantly better than previous algorithms, e.g., GA, SA, TS, and PSO. By considering the same flexibilities, Wen et al. [60] implemented a Honeybees Mating Optimization (HBMO) to select the optimal process plan. HBMO can achieve a considerably similar result to ICA in some cases by considering the same total manufacturing cost.

2.6.3 Selection of manufacturing resources

Several manufacturing resources need to be defined before the machining process starts. There are at least two main resources that need to be defined, the machine, and the cutting tool. Liu and Srinivasan [61] used syntactic pattern recognition to select machine tools to manufacture a part. A set of semantic primitives shape is seen as a picture. If the syntax of the corresponding picture matches the grammatical specifications, then the picture can be classified as a particular pattern.

In the knowledge-based reasoning approach, several Quick-turnaround Cell (QTC) systems have been built. Chang [62] developed a QTC in which machining operations with the same TAD are aggregated as a setup. Tool changes were also minimized based on the clustering techniques by Chu and Gadh [63]. Li et al. [55] proposed tool change cost as one criterion to optimize the solution of the process plan. Several alternative resource scenarios to support the corresponding operation sequence are analyzed using a hybrid GA-SA approach.

Chen et al. [64] proposed integer programming and dynamic programming approaches to optimize cutting tools for a 2½D machining operation. Tool cost is used as the objective function to evaluate the problem. These two approaches are compared, and it was shown that dynamic programming outperforms integer programming in identifying the minimum required cutting tools. However, dynamic programming requires longer computational time.

Baker and Marupoulos [65] proposed a vertically integrated tooling (VITool) systems to add the capability for designing product by considering cutting tool requirement and availability. Tool selection consists of a five-level hierarchy. Sequentially from the most detailed, they are machine operation, component, multi-batch/single machine, multi-machine, shop floor, and tool stores. Each level contributes to calculating tool requirements in order to accomplish the machining operation. As another complement, Shakeri [51] proposed the OSTS module to minimize tool changes in a manufacturing sequence. An operation matrix is established to show the efficiency of the module. Several rules of thumb are created to help the system maintain its objective of minimum tool changes.

2.6.4 Selection of cutting condition

Cutting condition means the parameters of machining that need to be set before or during the machining process. The earliest studies related with this CAPP element mentioned that all parameters need to be set up before machining starts. Otherwise, it will encounter a fatal error and severe problems. This procedure for machining has changed subsequently to provide online adjustment of the cutting condition. The adjustment lead to a safer and more reliable machining process. Although this matter is considered only in the CAM area of research, CAPP should also recognize these requirements.

The earlier work by Chang [62] on tool wear made a huge impact by considering tool life in setting up the cutting condition. Tool life is defined as the total cutting time of a new tool before reach a definite flank wear. The tool life definition is based on Taylor's tool life equation. In this research, machining optimization is considered for two types of operation, single-pass and multi-pass. Single-pass operation assumes the depth of cut will be fixed, but in the multi-pass operation, the depth of cut becomes a decision variable.

There are three values in the cutting condition that need to be addressed: cutting speed, depth of cut, and feed rate. Boogert et al. [66] proposed to maximize the depth of cut first, and then, the cutting speed. Later, the feed rate is temporarily set to the minimum values to avoid violation of force-related constraints. This practice ensures that when the feed rate and cutting speed are determined, and reductions are required to satisfy force-related restrictions, the depth of cut never violates these limitations. Adoption of the cutting force model constants should be performed by maintaining a feedback system measure the initial cutting force and adjust the related parameters for a given cutting process.

Gupta et al. [67] proposed an integrated model for process planning and parameter selection for a lathe. In their research, the choice of a suitable depth of cut for turning is determined by its manufacturing cost. The model used the existing expert system, Machining Parameter Selection (MPSEL), to list all possible machine and tools that can be used for a turning operation.

Hirooka et al. [21] proposed a regional planning of the cutting condition. Several zones with different surface roughness are assigned a predetermined instruction in the CAD model. Each zone can

have a different cutting condition. The best possible cutting condition to conduct overall machining is defined based on the zone created before the machining starts. Although only 3-axis machining operations were used for the experiment, the regional planning is also believed applicable in multi-axis or multi-tasking machines.

2.6.5 Selection of tool path

Due to the limitations of 3-axis machine tools, prismatic parts are characterized by only 2½D machining operations. The tool path boundaries can be extracted using the feature parameters, and they intersect the feature model with an imaginary plane if it has a complex shape [66]. The second method is also known as the slicing technique. Several slices are moved until it reaches the designated depth of the features. Then, the boundary created on the imaginary plane is offset with a fixed or variable step size. Two main types of tool paths can be used: contouring and zigzag. Yan et al. [43] identified four types of tool paths from NC programs for milling: unilateral zigzag, bilateral zigzag, inward contouring and outward contouring.

Kubota et al. [68] applied four types of tool paths, contour line, scanning line, drilling, and center drilling for multi-tasking machine tools. A contour line is assigned for the closed pocket. A scanning line is assigned to any feature except a closed pocket. A drilling path is assigned for through-hole or blind-hole features.

2.6.6 Selection of setups

Champati et al. [47] proposed the CBR approach to initiate a setup needed in products. The previous machining process similar to the given shape will be retrieved and sequence by its setup. Originally, six setups are required to be initiated if all faces are assumed to require a machining process. The features that require particular setup will be aligned with the previous initiated six setups.

Lee et al. [69] proposed a simple method that minimizes the setups by using a set of graphs. At first, topological relationship of features is given. By sorting the topology, the pairwise relations are converted into a set of graphs with partial ordering of simple features. For each setup, only one tool approach direction is allowed.

The use of a visibility map has been introduced by Woo et al. [70] for estimating the cutting tool access requirement of particular workpiece shapes. The visibility map is represented as a visibility cone in Figure 2-9. Afterward, Kang and Suh [71] introduced a binary spherical map (BSM) approach as a further enhancement of the visibility map. The BSM is constructed by projecting several points which represent the visibility area onto a virtual sphere. The sphere represents entire tool motion travel in the multi-axis machine tool. The smallest travel distance of the cutting tool can be achieved by evaluating several ring intersection of any feasible tool motion with those points on the BSM. Lee et al. [72] proposed an evaluation methodology, called the Preliminary Manufacturability Evaluation System (PMES), which incorporates the visibility cone into a workspace analysis. PMES can find the optimal

workpiece orientation and configuration of the machine tool. Moreover, Anotaipaboon et al. [73] introduced a similar method to the visibility cone by considering a set of the cutting tool contact points and the cutting tool orientation. In order to define the workpiece orientation, a least-squares optimization procedure is executed for finding the minimum kinematics error during axes rotation. The workpiece orientation may be used for defining the setup position.

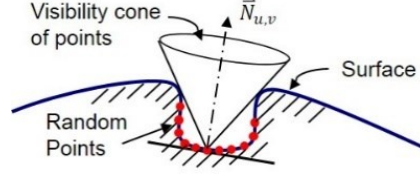


Figure 2-9 Visibility cone.

Apart from the previously mentioned studies, Nishiyama et al. [74] introduced a machinable space for positioning the workpiece. The machinable space is used for exposing the actual machining space that can be used for machining. The example of machinable space, with a maximum 420 mm X travel, 210 mm Y travel, and 400 mm Z travel, is shown in Figure 2-10. Figure 2-10 also shows a condition in which the mounting table is tilted to its maximum B-axis rotation (until colliding with the spindle).

To create the machinable space, several points, as depicted in Figure 2-11a, are calculated using a transformation function in Equation (2-1). In Equation (2-1), t_{Bx} and t_{Bz} are the offset points to the center of the B-axis centroid in the X- and Z-axes, respectively, which are calculated from the center of the mounting table. The entire machinable space can be constructed by considering several angle rotations, as depicted in Figure 2-11b. The setup position can be determined by putting the workpiece in the multi-overlapping area to have a better accessibility as illustrated in Figure 2-11b.

$$\begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta & t_{Bz}\sin\theta - t_{Bx}\cos\theta + t_{Bx} \\ 0 & 1 & 0 & 0 \\ \sin\theta & 0 & \cos\theta & -t_{Bz}\cos\theta - t_{Bx}\sin\theta + t_{Bz} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_T \\ y_T \\ z_T \\ 1 \end{bmatrix} \quad (2-1)$$

2.7 Manufacturing information in the CAPP data architecture

Several machining processes can be repeated and modified several times. These activities produce a large amount of data that needs to be stored properly. All these data have to be evaluated in order to select the sequence of operations that will make up what is known as the route sheet [49]. Instead of storing all the historical machining process data directly, it should be considered to keep only the essential data structurally.

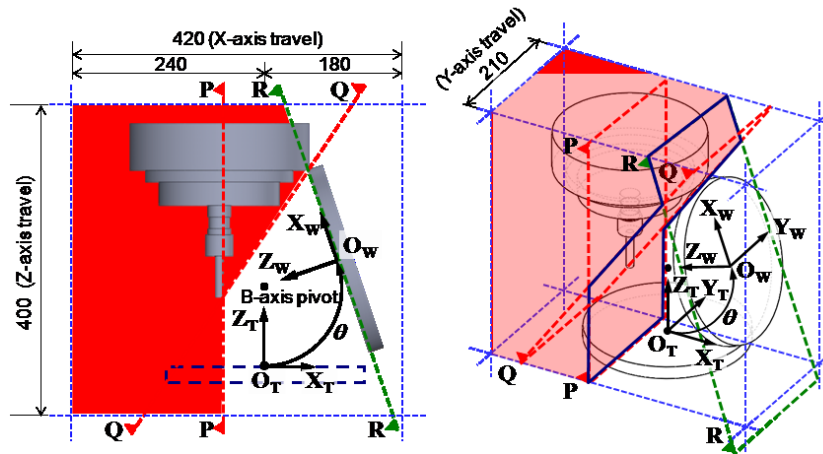


Figure 2-10 Example of the machinable space of a maximum table rotation by the B-axis [74].

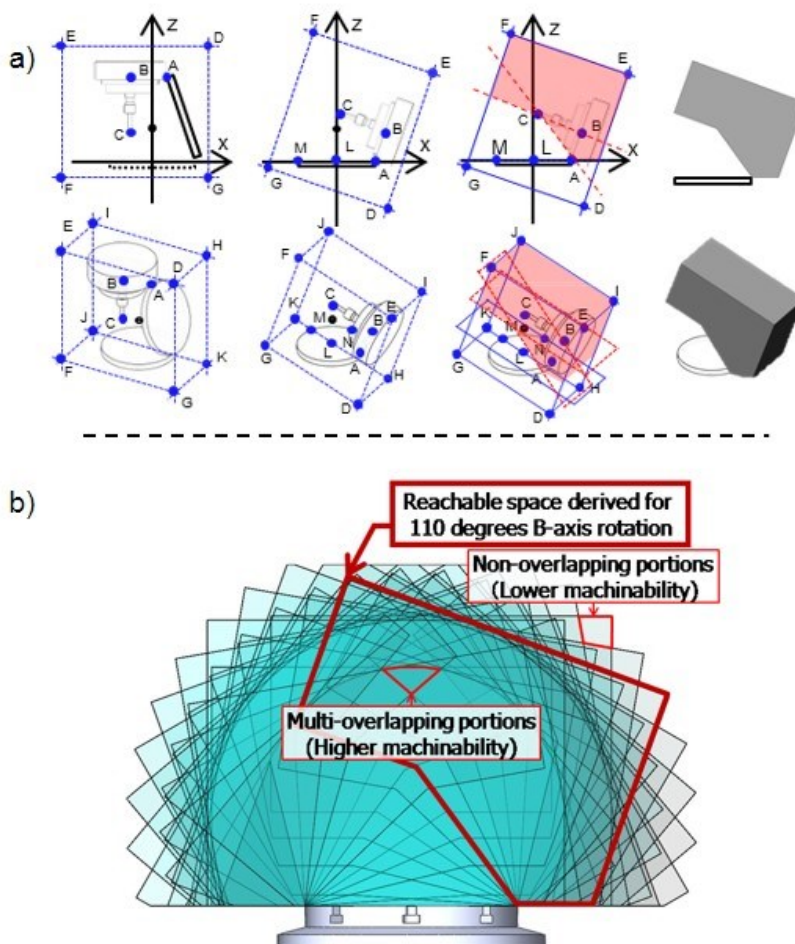


Figure 2-11 Machinable space. (a) Determination of machinable space vertices; (b) Total machinable space [74].

2.7.1 Knowledge structuring

Madurai and Lin [75] described the generic relation between feature model and the corresponding related aspects of MPP. Feature model is consist of features. Features are constructed by the corresponding process. Each process is supported by the cutting tool and particular machine tool. These relations can be described as the relation of feature taxonomy, process taxonomy, tool taxonomy and machine taxonomy in Figure 2-12.

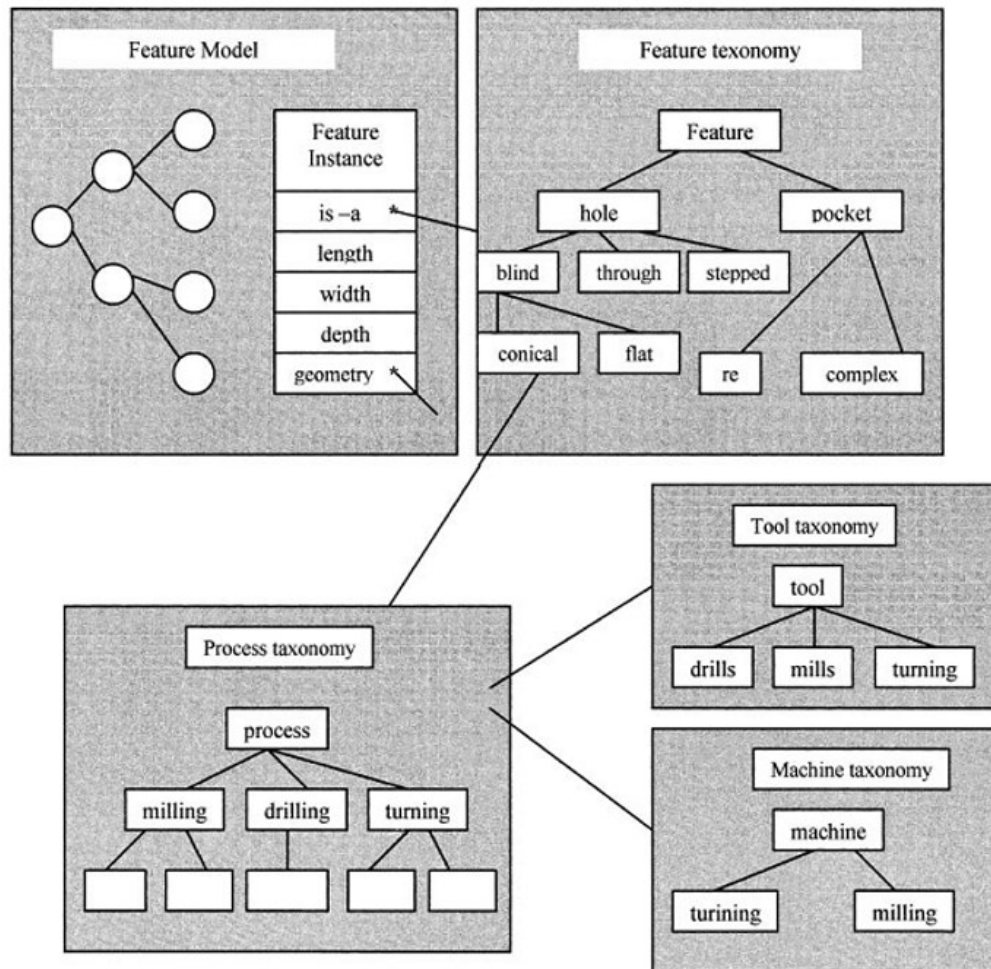


Figure 2-12 Feature-based manufacturing knowledge repository [75].

Ho and Moodie [50] proposed a network representation to describe flexibilities of machining operations. As shown in Figure 2-13, there are three types of nodes in the network: starting, intermediate, and ending. The starting and ending nodes do not contain any operational information, but only indicate the starting and ending of the machining process of the part. An intermediate node represents an operation. It contains alternative machines, cutting tools, and the TAD that can perform the operation [59].

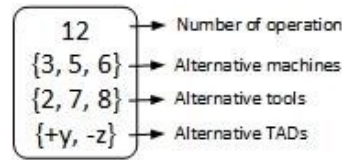


Figure 2-13 Node in network representation (reproduced from [59]).

Yan et al. [76] proposed a system to extract machining information from machining operation data. In an NC program, operations are divided by tool change code M06, positioning code G00, reference point return codes G28–30, end program code M30/M02, change feed rate F, and spindle speed S codes, or changing cutting mode. This information can be extracted as structured information as shown in Figure 2-14.

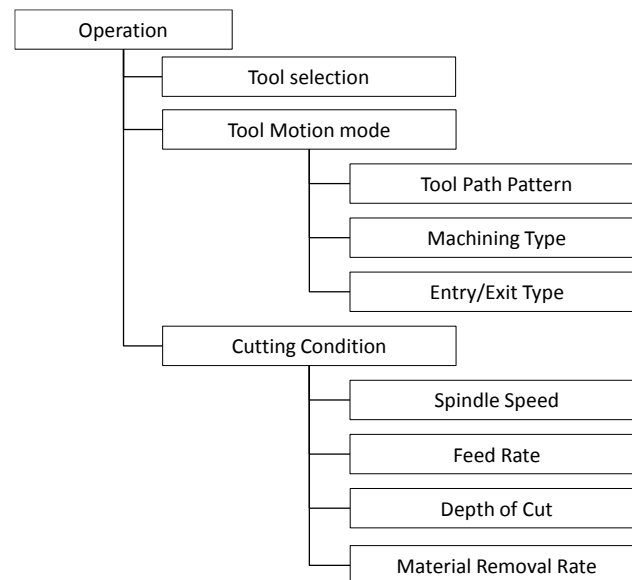


Figure 2-14 Machining operation structure (reproduced from [76]).

Feng [77] structured the model of machining process planning activity by using an ICAM Definition (IDEF0) diagram. The model is developed as part of an effort to integrate manufacturing software systems. The model consists of five main steps of the basic element of process planning (A0) level: generation process sequences; operations; shop floor routing; control programs, and; validation of plans and programs. In Figure 2-15, the interfaces between other subsystems for exchanging information have been shown to provide clear information handling for each task. The input, control, resource, and output data identified in the activity model are shared by and exchanged among different CAPP systems, CAD systems, production simulation systems, and production scheduling systems.

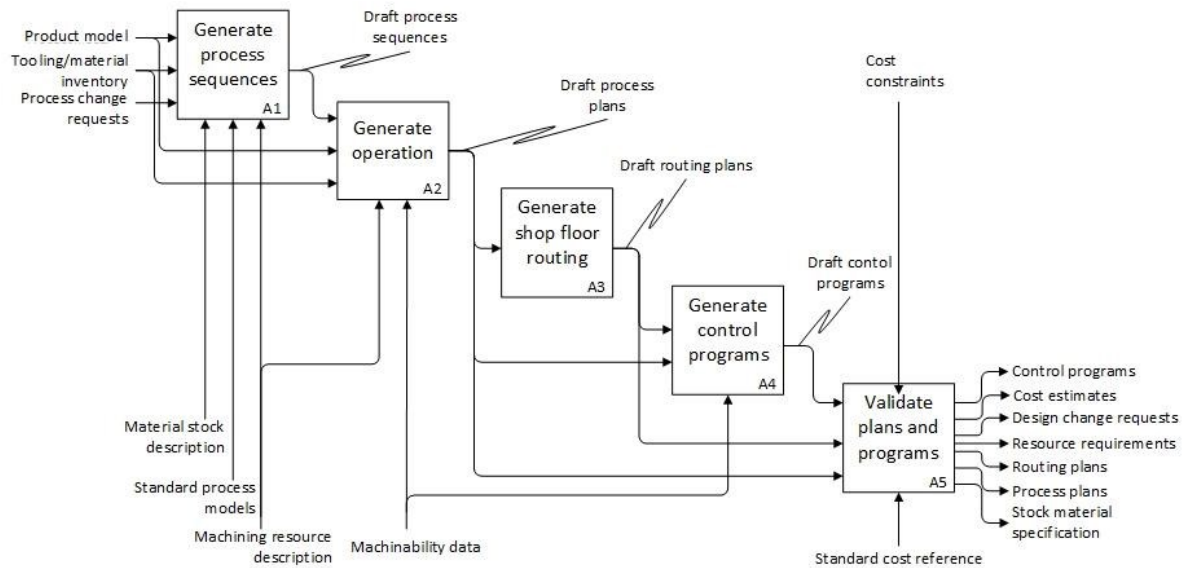


Figure 2-15 A0 level in IDEF0 of machining process planning (reproduced from [77]).

Zhou et al. [56] proposed an Integrated Product Information Model (IPIM) that is built based on the STEP modeling methods. As shown in Figure 2-16, IPIM is a software representation of geometry, features, knowledge, technology, and other management data that describes a product throughout its lifecycle. IPIM data can also be exported to a neutral file that can be imported by other application systems for the product lifecycle.

Igari et al. [23] proposed an updatable machining database of an actual NC machining data. The machining database is stored according to ISO 14649 machining working steps. The machining working steps are acquired from analysis through ISO 6983 NC data. There are two type data items: process plans and operation plans. A process plan stores a machining feature type and its corresponding machining operation. An operation plan stores a machining strategy, tool type, and their cutting conditions. In addition, a decision tree representing the process plan is generated.

2.7.2 Logic reasoning

Champati et al. [47] proposed the Thematic Organization Packets (TOP) scheme to store knowledge about intersections of several previous machining processes. Four kinds of intersections are considered: reference, clamping, opening feature, and good manufacturing practice. Based on these TOP elements, relationships between features are indexed. These indexes of various relationships among features are used to provide machining knowledge of manufacturing shapes.

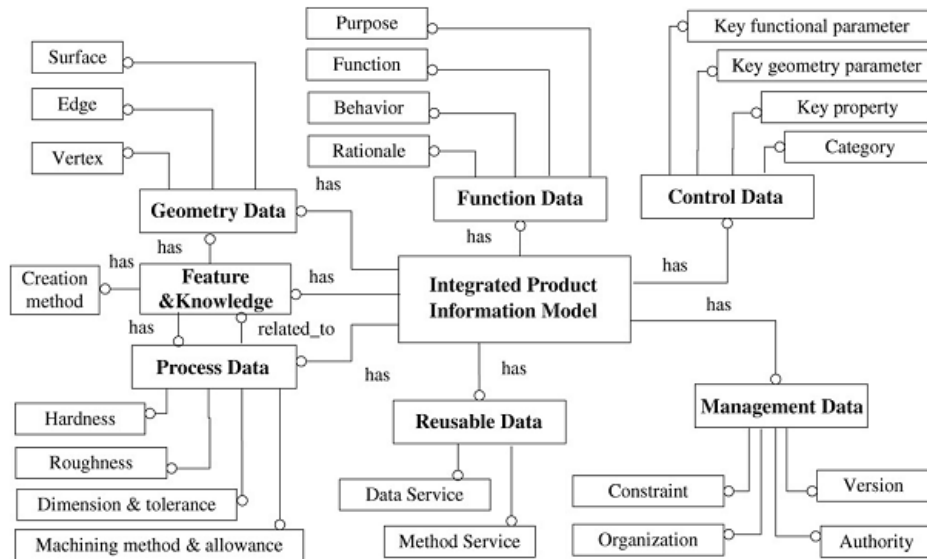


Figure 2-16 IPIM product information model [56].

Tanaka and Kishinami [78] proposed an abstract model of a machining operation to capture the general and fundamental characteristics of a machining process. The abstraction is based on the characteristics of the machining process and the machined shape. The abstract model of the machining operation is based on the relationship between the characteristics of the machining process and the machined shape. It was shown that an abstract model of operation planning can be obtained by reversing the abstract model of the machining operation.

Nakamoto et al. [42] proposed a simple heuristic approach to categorizing free-form, hole, and prismatic features. Hole features are the first features to be separated. The rest of the features are free-form and prismatic. Each feature is matched to a pre-defined feature based on the availability of its opening faces. Later, cutting tool and tool path selection are also determined from the pre-defined feature database.

Igari et al. [23] proposed a decision tree to manage data in a machining database. The machining database has been explained previously. The machining database is converted into a decision tree for easy accessibility. Data items are diversified into several homogeny subclass data sets based on process plan attributes. In order to generate an operation plan for a requested process plan, an IF-THEN rule is used to produce a machining strategy and tool type. The cutting condition is regressed from selected nearest neighbors in the machining database.

2.8 Full-Scale CAPP system

Van Houten [79] proposed the first well-known generative process planning system called PART. The system consists of modules for particular tasks in succeeding process plans. The modules are executable programs that communicate via a relational database. The CAD interface module accepts

solid product models from external CAD systems and converts them into ACIS models. In this model, manufacturing features are extracted. In the end, NC programs and production-related documents are generated by the NC output module. The whole scheme of the PART system is shown in Figure 2-17.

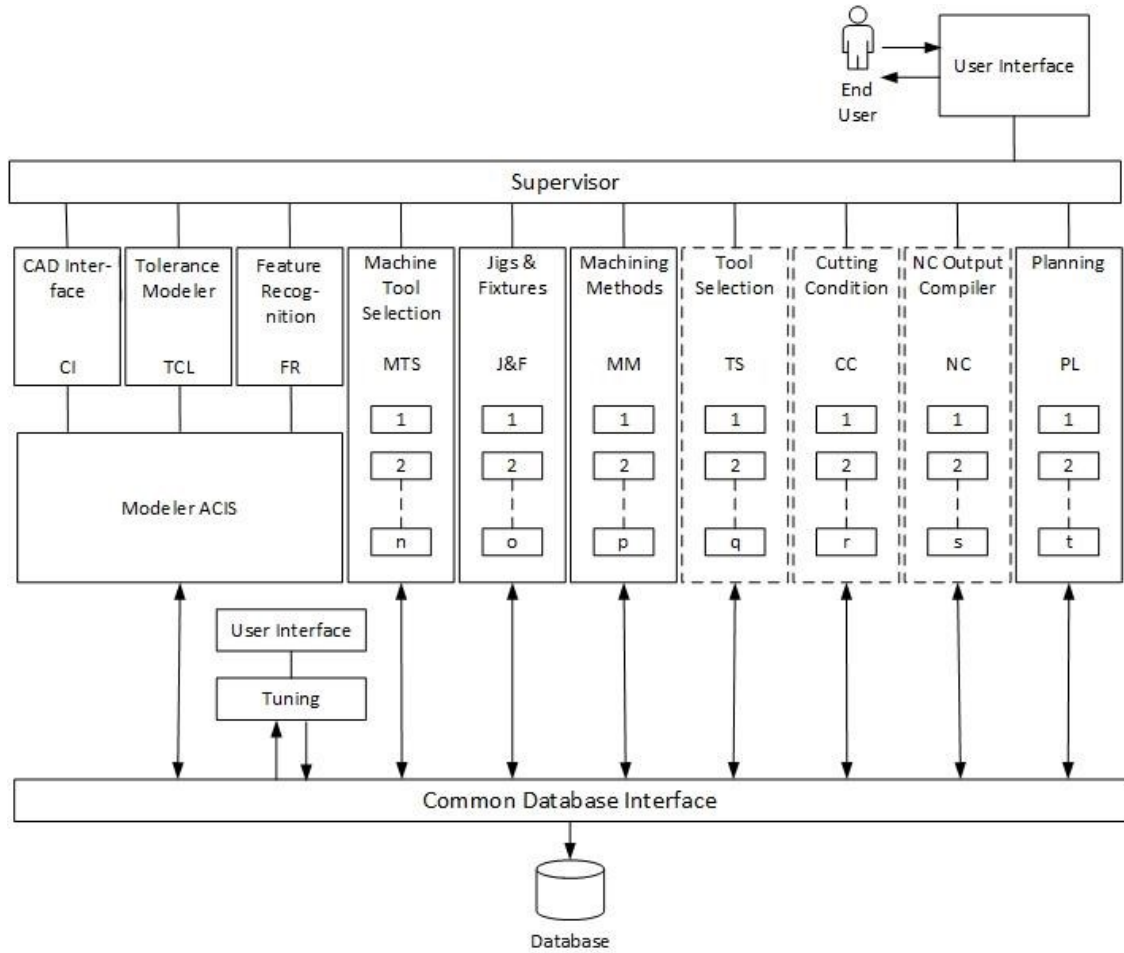


Figure 2-17 PART reference scheme (reproduced from [79]).

Regarding the bottom-to-up approach, it is believed that process plan only can be finalized on the shop floor. It is because the availability can only be defined in the actual machining or shop floor [36]. Yamazaki et al. (1997), which is cited in [18], proposed to include process planning within the TRUE-CNC architecture. TRUE-CNC is a feature-oriented CNC controller. Here, machining operation proficiency and machining know-how are captured, analyzed, and used for generating new operation plans.

To support machining knowledge elaboration, Yan et al. [43] proposed an Autonomous Machining Process Analyzer (AMPA) system to extract machining know-how data from NC programs. The system was developed as a component of TRUE-CNC. The input includes an NC program, tool data, and a blank product model. The output is the extracted machining know-how data, including

machining elements, machining features, and machining operation data. The data extracted by the system are exported automatically into the machining know-how database through the Open Database Connectivity (ODBC) interface shown in Figure 2-18.

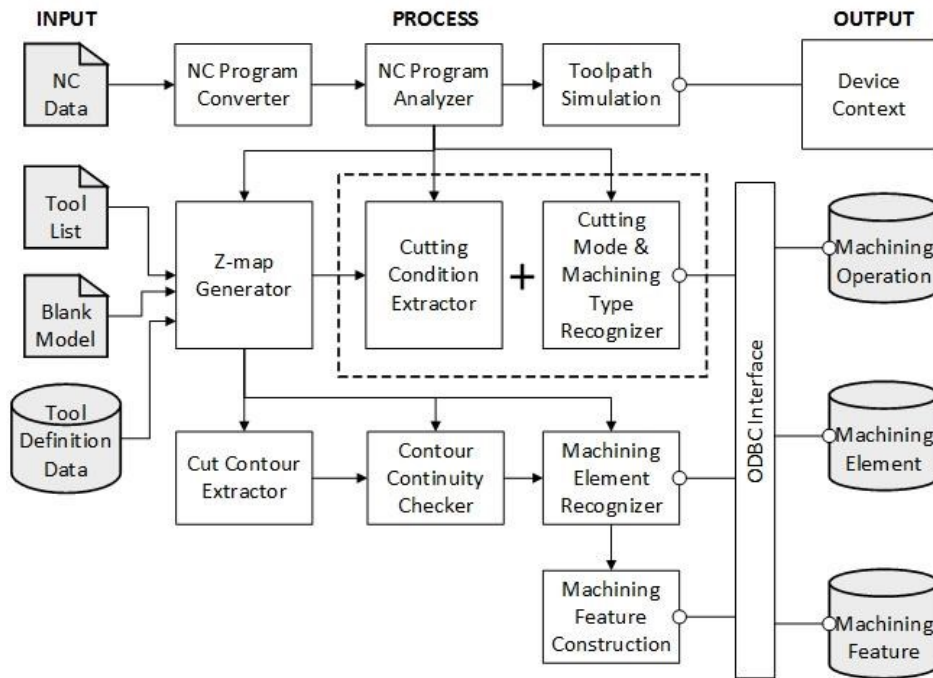


Figure 2-18 Block diagram of the AMPA system (reproduced from [43]).

Interoperability between CNC machines must also be considered to reduce dependency in a particular machine tool. Specific part knowledge could be obtained by analyzing the NC program. By capturing knowledge from an NC program, a part can be manufactured without depending on a particular process or resource. XTSys was proposed by Safaieh et al. [44] to analyze an NC program semantically and transform it into STEP-NC-compliant manufacturing data. The system consists of a semantic adapter, manufacturing dictionary, and manufacturing process data as shown in Figure 2-19.

2.9 Conclusion

Recent CAPP technologies are found to be capable of solving combinatorial problems that involve knowledge of machining resources. However, generated machining process plans are still limited to particular conditions and are not native to machining operations. Structurally, machining process plans can be divided into two main processes: generating process sequences and generating operation conditions. To comply with the requirements of these two processes, the full scale of CAPP systems has evolved into several kinds of information architectural designs. Thus, the practicality and flexibility of machining operations will be the primary issues that need to be covered by future CAPP systems.

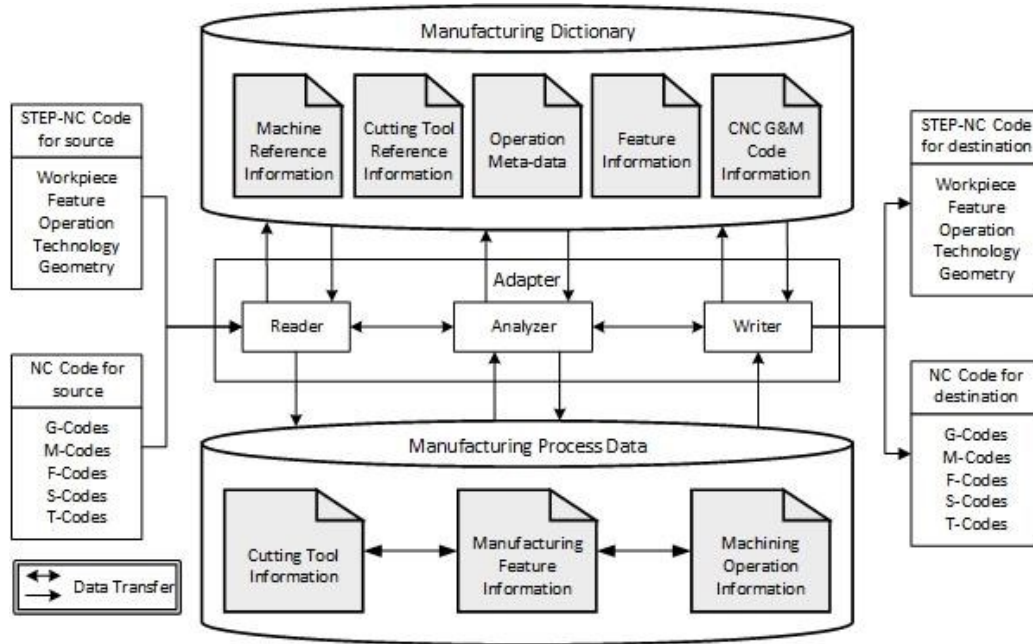


Figure 2-19 XTSys structure to support interoperability between machine tools (reproduced from [44]).

As mentioned earlier, a shop floor operator might be involved in finalizing the machining process plan. Though the plan is made by the CAD-CAPP planner, the execution process will always depend on the CAM operator. Hence, an approach to defining the process plan that can contribute the best practices to each role in the manufacturing cycle is still needed as an integrated solution. Technological precedence constraints on the shop floor must also be considered for improving the quality of process plan and also to improve practicality, despite not being mathematically computable. To date, STEP-compliant product information has been enhanced and can be useful in bridging the gap between CAD and CAM. The integration of information is also supported by STEP-compatible CAD/CAM software. However, this will make rigid restrictions and not become a generative process to construct a flexible MPP.

The CAPP has been developing into various kinds of the system to support machining operation. Since the first code system, named with MICLASS has existed, the elaboration of CAPP has been diversified into individual elements of macro planning and micro planning to analyze and determine a proper process plan. Several tools are constructed from heuristic to analytical approaches to solve these elements of CAPP. Many heuristic approaches are available, e.g., CBR, OSTs, and TRV. but still limited to solving a particular problem for a machine tool or a type of product. The ICA approach is believed to be the most promising analytical approach to finding the optimum solution compared to GA, SA, and others. However, more studies must be conducted to apply it in a practical situation.

Machining knowledge is essential. CBR is one of the well-known approaches to managing machining knowledge. In the past, machining knowledge, i.e., machining know-how, has been hidden implicitly. In the CBR approach, this knowledge structure can be simply captured and acquired from an actual machining activity. CBR has been formalized as a four-step process: retrieve, reuse, revise, and retain. Particularly revise and retain processes are quite important to getting a suitable solution and to improving the case database. However, there is no generalized methodology for those processes.

Since Steudel [7] recognized the requirement for automating the process planning, several studies have been performed to fill the gap between the design and manufacturing stages. The research can be classified into two broad approaches: top-to-bottom and bottom-to-up. From the viewpoint of the CIM concept, the top-to-bottom approach can be seen to satisfy the designer, and bottom-to-up approach can be seen to meet the shop floor requirement. No one can determine the better approach from these two approaches. One aspect that is going to be similar in each approach is the knowledge structure. Due to the growth of information technology, these two approaches can be well maintained in one system if there is a flexible knowledge structure. Several studies have been conducted to gather knowledge for recognizing patterns of machining processes. In the meantime, this knowledge must be stored somewhere to secure and maintain it for future use. Object-oriented knowledge modeling within a database was introduced in 1990. However, it is still limited to a particular product and environment.

How to realize a flexible MPP in CAPP is the last important issue. In CAPP for machining operations, the optimum solution is generated by considering five types of flexibilities: machining process, machine to be used, a cutting tool to be used, tool approach direction, and machining sequence. However, in real practice, the linkage between these flexibilities and the actual condition in the machining environment have not yet been made clear. Evaluation of those flexibilities is quite a difficult task, and the priority of those flexibilities changes according to the machining operation and manufacturing environment. Any kind of fault or hurdle needs to be predicted offline or even online so the machining operation can perform continuously without interrupting the entire production plan. Therefore, the room for machining parameter adjustment will need to be provided at the earlier stage of MPP construction.

Chapter 3 Evolution of Total Removal Volume (TRV) in handling MPP generation

3.1 Introduction

This chapter discusses the proposal of the new feature-based unit which will be necessary before the development of CAPP. This new feature-based unit is an alternative solution to support the traditional way of MPP generation based on machining feature (MF). In this chapter, further study of TRV is performed as an effort to establish a feature-based unit which can support the flexible MPP generation. From Chapter 2.5, MF is known as a common method to define a feature in manufacturing. The determination of MF still highly depends on the existence of the pre-defined features which is populated inside an MF database and will need to be periodically managed once the new characteristics of MF are found. The prior CAPP systems are believed to spend enormous efforts during the extraction of MF and matching stages between MF and the pre-defined features [25]. A large number of the database will add another difficulty in extracting the same MF since matching process in a large database of MF definitions will obviously become an exhaustive and time-consuming process [33]. In the case of a GPP system, a sophisticated MF extraction module might also be added on to shorten the querying time for acquiring the correct MF definition. Thus, the associated machining information can be used to thrive the product's machining. By considering the efforts in evaluating the MF, Nakamoto et al. [42] have introduced a total removal volume (TRV) as another promising main feature-based unit which can be used for defining an MPP instead of using MF. TRV is defined as any volumes that need to be removed in shaping the workpiece. Naturally, the MF is decomposed from TRV of blank material. However, by further consideration, the term of blank material can be acquired from any shapes of material as long as it can fit the lateral size of the product as illustrated in Figure 3-1.

In practical cases, the sequence of machining process can be interrupted by failures that can cause the machining sequence to stop at any states (for example, if the tool is broken, electricity stops, and so on). These failures can produce intermediate shapes or might further reject the product as the consequences. These intermediate shapes can also be considered as another type of blank material which needs further machining process. Therefore, TRV can be pictured as irregular shapes or a significantly different form from the common MF, e.g. slot, step, and pocket. Another research by Park [80] has tried to consider a near net shape or intermediate shape as its feature-based unit. This form also can be regarded as another form of TRV, which might act similarly with the target machining volume. Henceforth, it can be inferred that the blank material shape can have a distinct shape and does not have to be the blank square material for the prismatic component and blank cylinder for the rotational component. On the contrary, the traditional MF will depend heavily on singular or composition of primitive features which are the subtracted volume from either blank square material or cylinder.

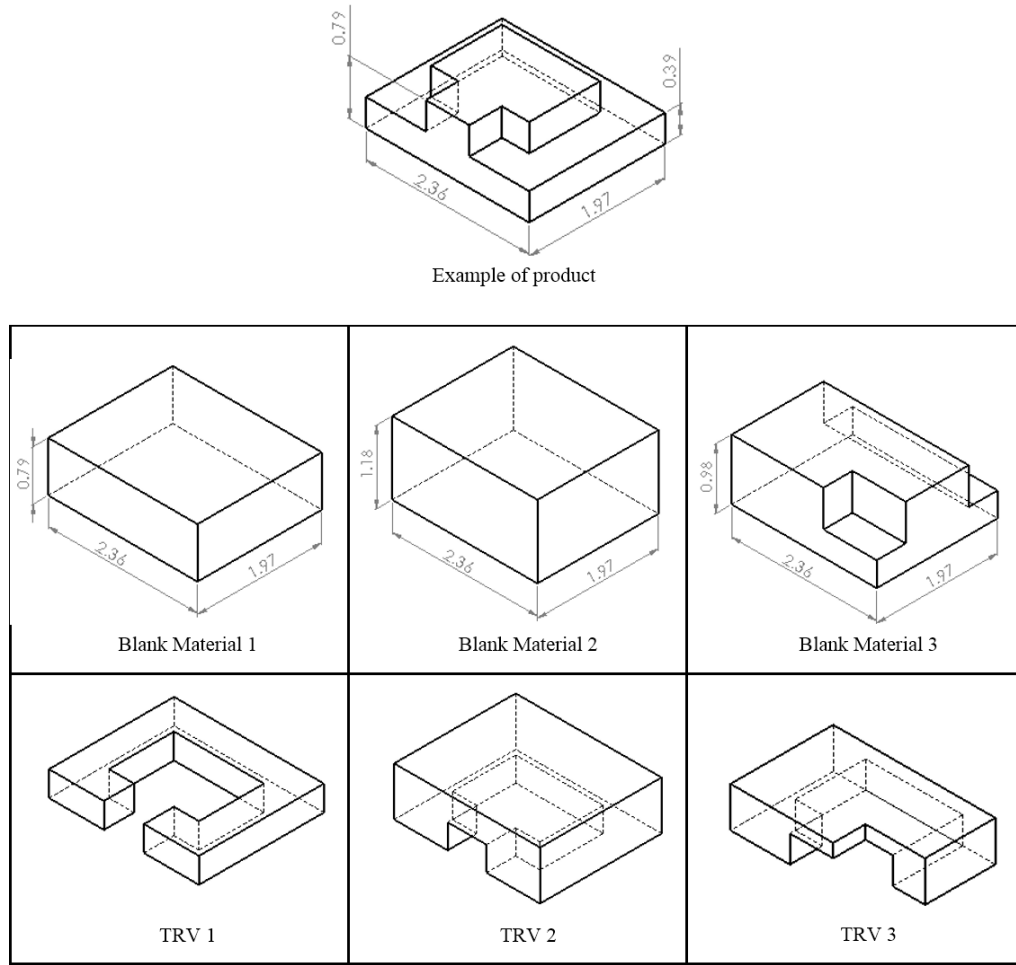


Figure 3-1 An example of the product and the variety of TRV caused by utilizing different blank materials.

3.2 TRV and Volume In-Process (VIP) definition

The first introduction of TRV-based MPP by Nakamoto *et al.* [42] exploited the cell decomposition process to generate the removal volume more naturally from the TRV. The MPP is constructed by ordering the removal volume based on its plane that were paralleled to Y-Z or Z-X planes. A couple of years later, Morinaga *et al.* [53] enhanced the MPP selection by optimizing the selection based on its configuration of plane's cutting tool access direction (TAD). The number of cells which were included in the selection was limited by using only the concave reference of the TRV shapes. From another perspective, the treatment of cells decomposition method might suffer on computational issues once the number of cells is becoming larger [81]. From these drawbacks of TRV, this research investigates further the possibility of utilizing directly the cell's constructor, i.e. reference plane. By this methodology, the cells of TRV will not be generated. Each corresponding decomposition of each reference plane is considered as the small portion of TRV which is defined as volume in-process (VIP). TRV is defined as the subtracted volume between the blank and the product as simply depicted in Figure

3-2. VIP can be illustrated as a single primitive feature as depicted in Figure 3-2 which represents particular machining process.

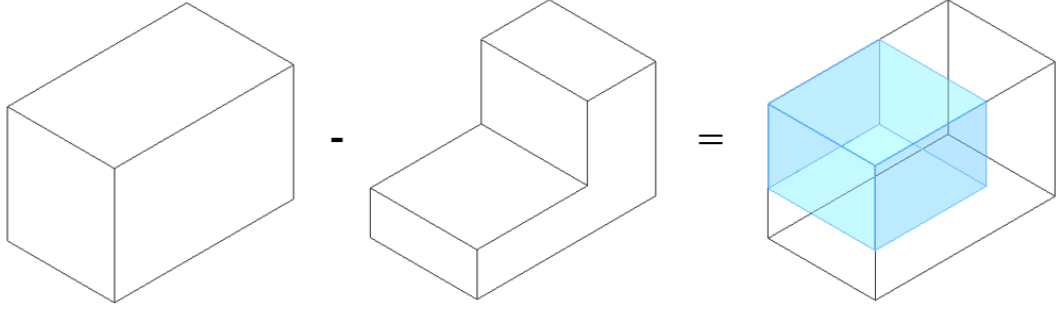


Figure 3-2 Simple illustration of TRV.

In order to analysis the TRV, the entire of the reference plane, P , is collected as the representation of TRV's surface as depicted in Figure 3-3. In the process of decomposition, several VIP might be involved. The TRV can be expressed as in Equation (3-1). VIP is considered as the subset of TRV during the process of decomposition.

$$TRV \equiv \{\cup_{i=1}^m VIP_i, \cup_{i=1}^n P_i\} \quad (3-1)$$

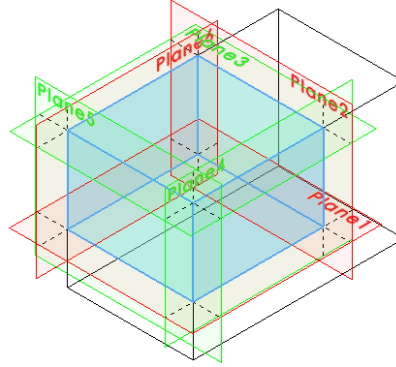


Figure 3-3 Generated reference planes, P , in TRV.

Each VIP can be defined simply as a feature which consist of solid body, b , the main reference plane, mp , a collection of the new reference plane, p , and a number of open faces, OF . Their relation can be expressed as in Equation (3-2). Open face is defined as the exposed surface of TRV or VIP. The main reference plane is defined as the reference of the machining process. Figure 3-4 shows two different kinds of VIP to handle the similar body of TRV. The removal process can be chosen either by *plane1* or *plane2*.

$$VIP \equiv \{b, mp, \cup_{i=1}^j p_i, \cup_{i=1}^k OF_i\} \quad (3-2)$$

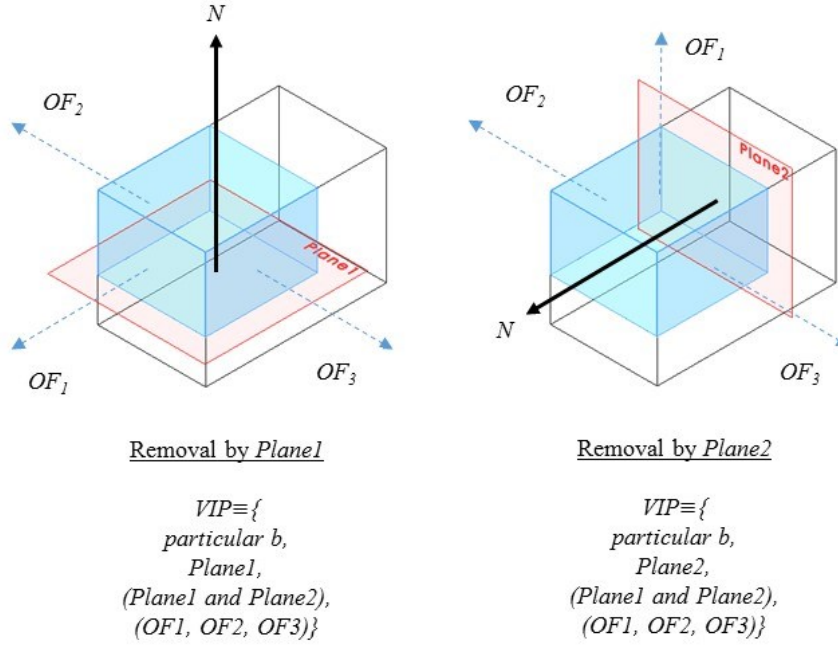


Figure 3-4 VIP feature-based unit.

3.3 Framework of Development

The framework of development is adapted from the common frame of CAPP depicted in Figure 2-4. The first phase framework consists of two main parts as illustrated in Figure 3-5. Each section will be further explained in the following subsection. The first part is responsible for extracting the VIP from TRV. The second part is responsible for determining the machining information of MPP. In this first phase, two characteristics of MPP is determined, the type of tool path and the diameter of the cutter. This chapter is focused on the first part which is the base of the MPP. Further enhancement of the MPP will be explained in Chapter 4 and 5. The detail steps of the proposed algorithm of MPP generation is shown in Figure 3-6.

Both MF and VIP is derived from similar TRV. There are two differences between MF and VIP. The first thing is the MF will need a dedicated extractor engine, as explained previously in Sub-section 2.5 (above). Yet, the VIP can be extracted by using plane manipulation directly on the CAD model. The second thing is the existence of fixed definition from the result of feature extraction. From the typical CAPP modules in Figure 3-5, the fourth process is resulting the fixed definition of MF, e.g., slot, pocket, and hole. However, the VIP is not necessary to have any fixed definition as MF from the beginning. It will only consist of geometry definition, i.e., shape definition. As a compliment, the determination of cutting tool and tool path for VIP is elaborated as further study in Sub-section 3.3.3 (below).

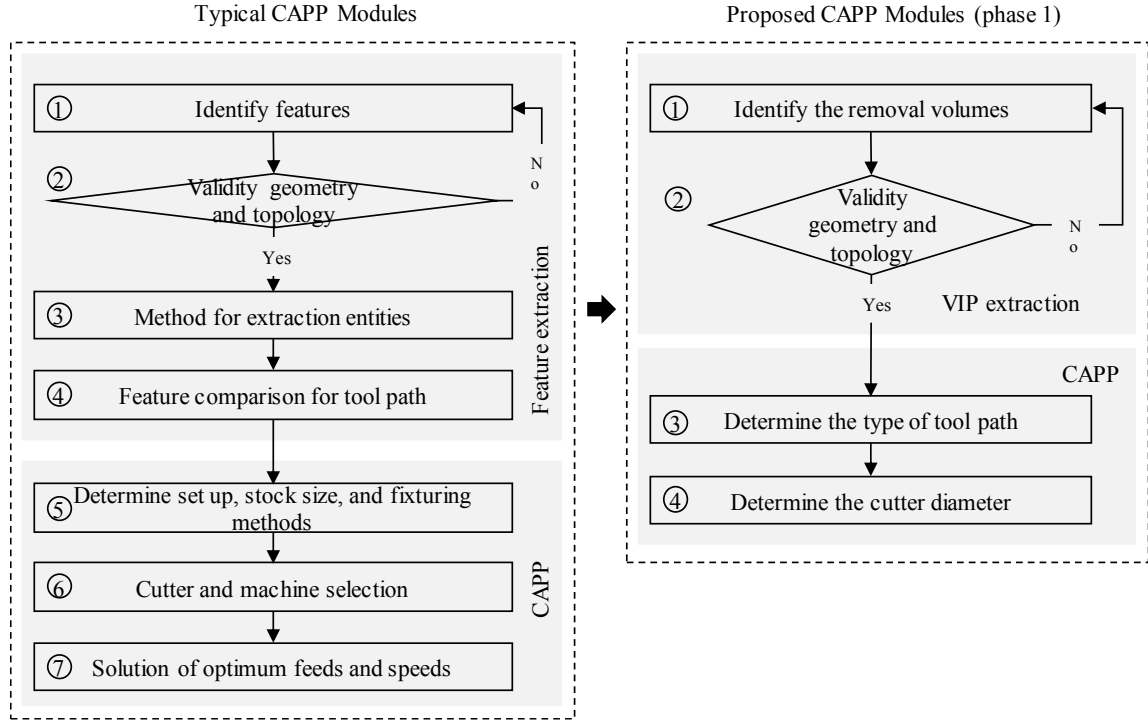


Figure 3-5 The initial framework for CAPP development (phase 1).

3.3.1 Initial TRV preparation

As mentioned earlier, the subtracted volume between the blank and the product will initially set as the body of TRV. For instance, TRV-1, TRV-2 and TRV-3 in Figure 3-1 can be initially set as the TRV. As the guidance in the following subsection, the shape of TRV 2 in Figure 3-1 is used for showing the steps of the proposed algorithm. Each surface in TRV body corresponds to a plane, P . The surface which is located on the outer side of TRV will be excluded from the collection. Only the surface that is located on the surface of TRV and the surface of the product will be included in the collection. As shown in Figure 3-7, $\{P_1, P_2, P_3, \dots, P_8\}$ represent the collection of P in the TRV body. The TRV features are decomposed into VIP by exploiting each P located in the TRV body.

3.3.2 VIP extraction module

In the proposed system, several iterations will be taken to check the entire P on TRV body. Two attributes are established for supporting the iteration. The first attribute is to show the virtual centroid of TRV body. The virtual centroid is acted as a sphere which is located inside the TRV as depicted in Figure 3-8. The sphere centroid is set on the diagonal cross-section of the surface that belongs to the TRV body and the product. From this centroid, the sphere will be enlarged to tangent each P . All P can be ordered from the virtual centroid to the outermost surface of TRV body, based on the distance between the centroid and the tangent point on P .

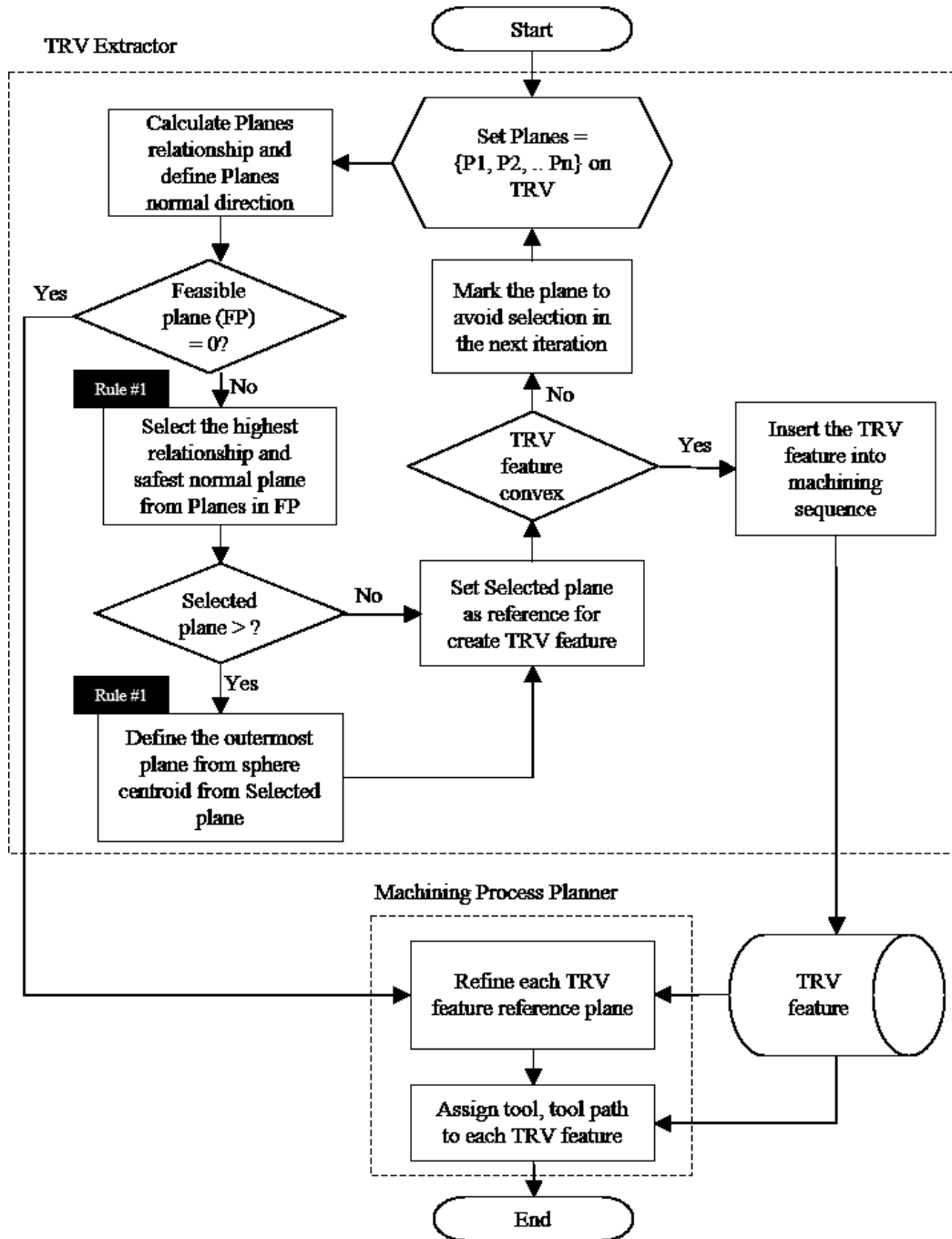


Figure 3-6 Algorithm of MPP generation based on TRV body.

The second attribute is to show the relationship value of between all P . The relationship value, VoP , is expressed in Equation (3-3). In basic geometry, this relationship indicates planes intersection. A plane which has a relationship with another plane will be valued as 1 or 0 if otherwise. This relationship shows the relative importance of each P on the TRV body. In each iteration, VoP is calculated as the reference to extract the VIP.

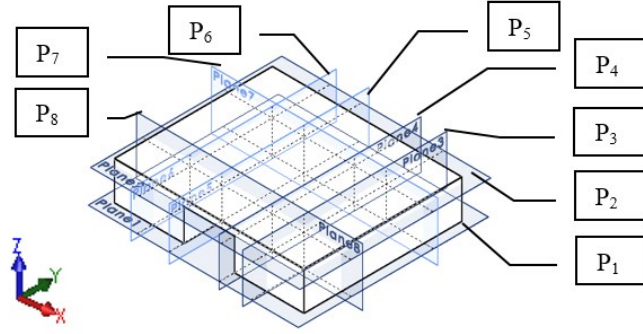


Figure 3-7 Reference planes of TRV.

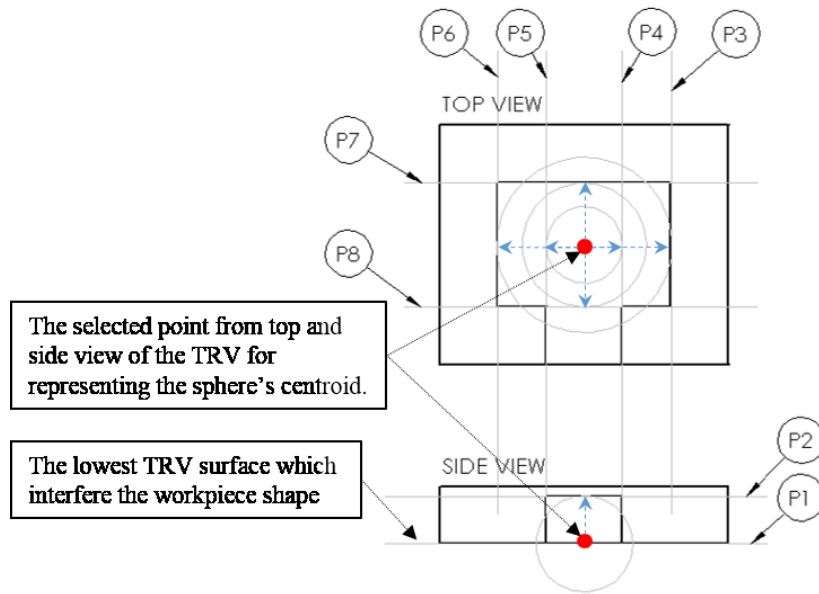


Figure 3-8 Virtual centroid of TRV.

$$VoP_i = \sum x_{ij} \begin{cases} \text{if } P_i \text{ intersect } P_j, \text{ then } x_{ij} = 1 \\ \text{if } P_i \text{ not intersect } P_j, \text{ then } x_{ij} = 0 \end{cases} \quad (3-3)$$

Each VIP is prepared with a collection of p . The collection of p shows all P from TRV, which is having a safe normal direction. The safe normal direction will determine the tool approach direction (TAD) on each P . Each of iteration will apply two following rules:

1. Select P that has the highest relationship and has a safe normal direction from the collection of P . The highest relationship represents the most significant plane that needs to be removed to generate accessibility to another plane. Please note that each P is assumed as the machining plane to remove the corresponding VIP from TRV body. A safe normal direction indicates that the VIP is accessible

without having a conflict with another TRV (workpiece) segment. In Figure 3-9, determinations of VoP are shown. Four planes (P_1 , P_2 , P_7 , and P_8) can be selected as the machining plane candidates for extracting the VIP.

	plane i -th								Rule #1	
	1	2	3	4	5	6	7	8		
1	0	0	1	1	1	1	1	1	6	*
2	0	0	1	1	1	1	1	1	6	*
3	1	1	0	0	0	0	1	1	4	
4	1	1	0	0	0	0	1	1	4	
5	1	1	0	0	0	0	1	1	4	
6	1	1	0	0	0	0	1	1	4	
7	1	1	1	1	1	1	0	0	6	*
8	1	1	1	1	1	1	0	0	6	*

Figure 3-9 Relationship (VoP) matrix.

2. Select the outermost P if the first rule generates more than one machining plane candidates. The attribute of the virtual centroid is used for presenting the order of P on TRV body. As shown in Figure 3-10, P_2 , P_7 , and P_8 are feasible to be selected as the machining plane candidates because each P is located in the outermost and have a different interference axis direction from the centroid as depicted in Figure 3-8. Furthermore, the interference axis direction also explains the safe normal direction on P . If P normal direction goes into similar direction with interference direction, then it can be defined as the safe normal direction on P .

	Rule		
	Rule #1	Rule #2	
	Relationship value	Distance from centroid	
1	6	0	
2	6	10	*
7	6	13	*
8	6	13	*

Figure 3-10 The distance between all selected P from the first rule and its tangent point.

The selected P separates amount of volume from TRV body and is defined as VIP. VIP constitutes a TRV feature which represent the machining volume. Each selected P is used for representing the TAD in machining the corresponding VIP. This study will only consider convex VIP. Any P which generates concave VIP will be marked for preventing re-election in the subsequent iteration. The marked P might be considered after all P are completely evaluated. Figure 3-11 shows an example of one configuration of constructed VIP.

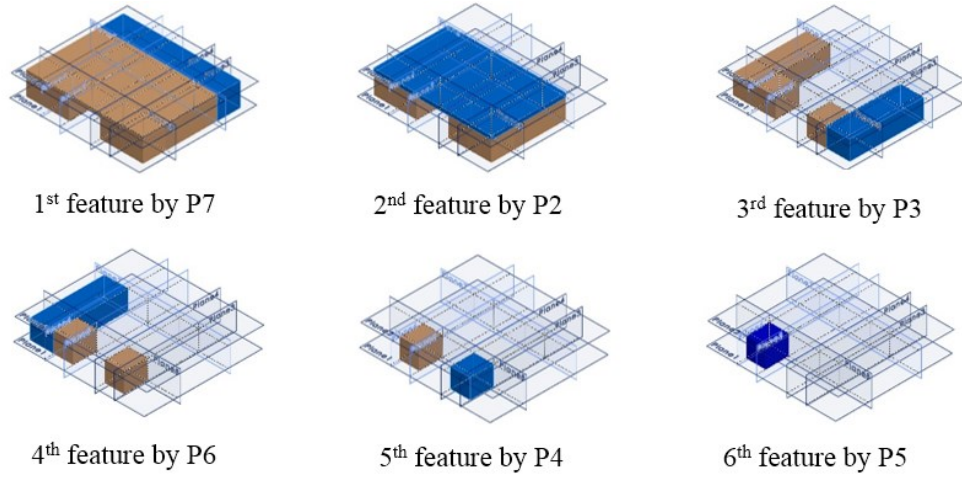


Figure 3-11 Example of constructed VIP (highlighted in dark blue).

The convexity is determined by investigating all outer loops within each face on VIP. All vertices in each loop are evaluated by referring the relative opening of the corner towards the centroid of the loop. A vertex which has a magnitude lower than or equal 180 is defined as a convex vertex. A vertex which has a magnitude greater than 180 is defined as a concave vertex. Any VIP, which has, at least, one concave vertex can be defined as a concave VIP as shown in the right VIP in Figure 3-12. This hypothesis is valid as long as there will be other p which is parallel to mp . The first rule guarantees the P from TRV is selected by also evaluating the safe normal direction. The evaluation of the normal is to guarantee the selected P will not cross another remain P . The left VIP in Figure 3-12 shows the case which the evaluation may fail without the first rule. In the case where the *Plane1* is selected as the mp , although the loop A and B characteristics show no concavity, the N_l is crossing the *Plane2*. Therefore, the left VIP may be falsely defined as a convex instead of a concave VIP.

Figure 3-13 shows all candidates of constructed VIP features from the given TRV 2 in Figure 3-1. After the TRV body is known, P_2 , P_7 , and P_8 are selected by applying both of the rules. P_2 , P_7 , and P_8 are the starting point to configure the entire removal process. However, P_8 will produce a concave shape. Therefore, no other plane will be investigated from P_8 . From each P_2 and P_7 , the remaining P is further analyzed by applying again both of the rules and selected other accessible P for the second removal. Machining by P_2 can lead to P_7 and P_8 . Machining by P_7 can lead to P_2 . These iterations are continued until leaving no feasible P from the last removal state. Eight candidates of constructed TRV features can be generated, respectively from the left tree, $\{P_2-P_7-P_8-P_3-P_6, P_2-P_7-P_8-P_6-P_3, P_2-P_8-P_7-P_3-P_6, P_2-P_8-P_7-P_6-P_3, P_7-P_2-P_3-P_6-P_4-P_5, P_7-P_2-P_3-P_6-P_5-P_4, P_7-P_2-P_6-P_3-P_4-P_5, P_7-P_2-P_6-P_3-P_5-P_4\}$.

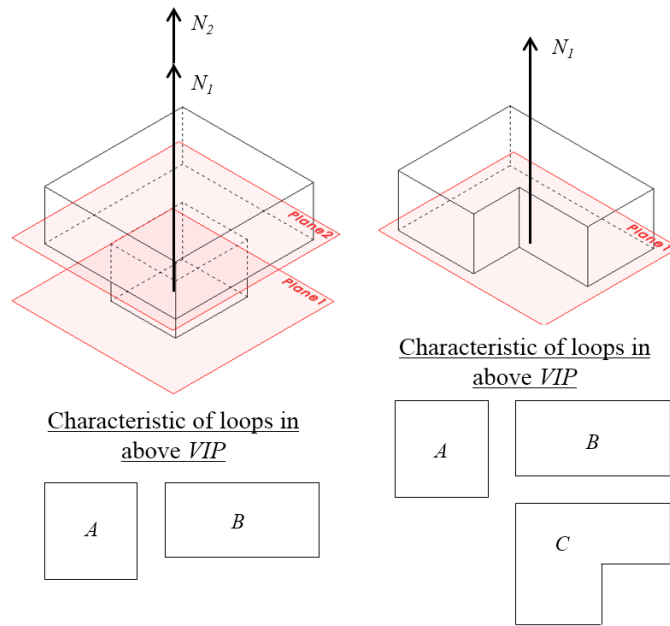


Figure 3-12 Characteristics of the loop in VIP.

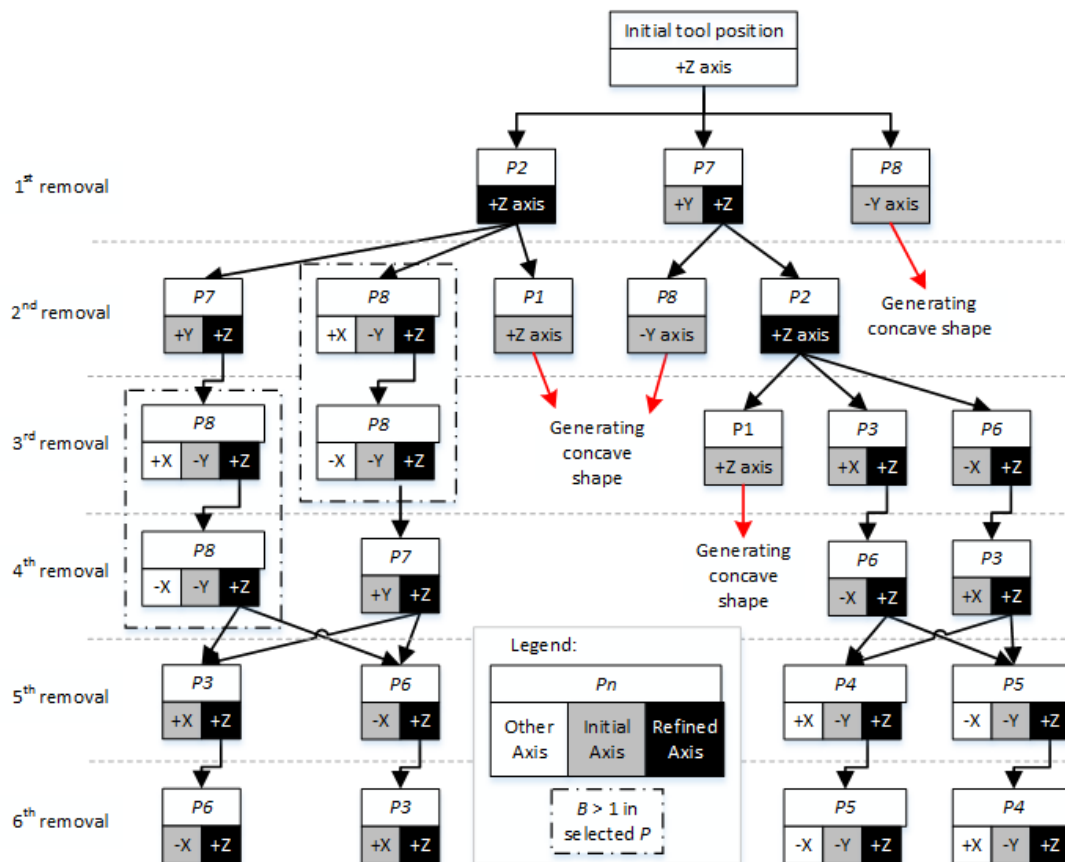


Figure 3-13 The example of constructed VIP.

3.3.3 VIP machining process plan (MPP) module

The corresponding MPP will be determined after all VIP are constructed. The MPP consist of machining plane determination, cutting tool selection, TAD, and tool path determination. This section shows the concept to manipulate the geometry characteristics to get the MPP as shown in Figure 3-14. The VIP consists of a number of vertices and faces. Each vertex and face on VIP feature needs to be specified as an open or a closed entity. The open vertex or face represents the area, which can be accessed by a cutting tool without interfering another VIP body. In the opposite, a closed vertex or face means it cannot be accessed by a cutting tool because another VIP blocked the access to the intended vertex or face.

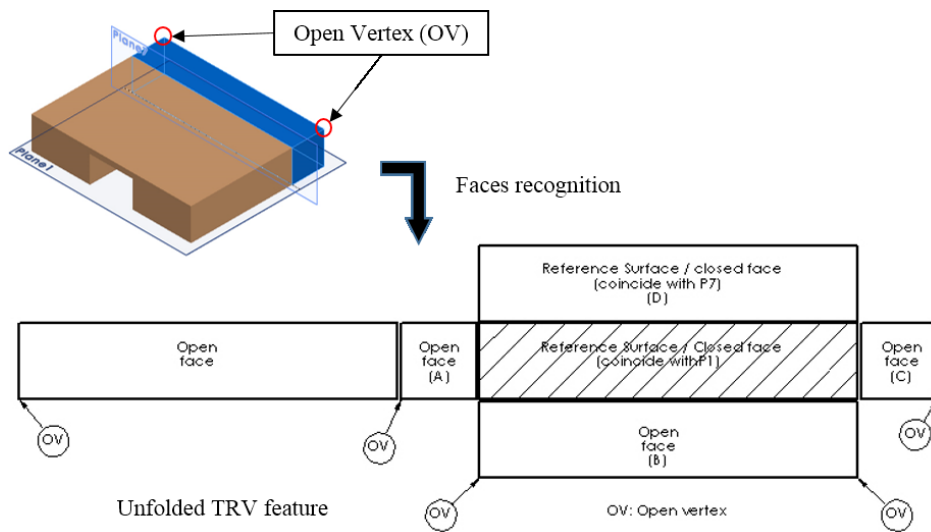


Figure 3-14 Vertices and faces in TRV Feature.

Previously, TAD is defined by selecting the suitable safe normal available on the TRV feature. TAD axis will be the reference for aligning the cutting tool axis. Furthermore, the machining reference direction will need to be defined. For hole feature, the machining reference direction will have the similar alignment with the TAD. For others, machining reference direction will be based on available *OF* surround the reference surface. The *OF*, which has the largest number of open vertex, might be selected as the machining reference direction. As depicted in Figure 3-14, a closed face corresponds to *P1* is selected as the reference plane. TAD is defined as the safe normal on this reference plane. Open face B is chosen as the machining reference direction because having the largest number of the open vertex (which is two open vertices). It also means that the machining process of VIP will be performed from open face B.

The illustration of vertices and faces on TRV feature can be seen in Figure 3-14. The red circles highlight the open vertex. By unfolding the highlighted VIP, it can be known that there are four open faces and two closed faces. These two closed faces are used for reference surface to define the TAD.

Please note that the reference surface corresponds to a machining reference. The shaded surface corresponds to P_1 . It is also defined as the *mp* of VIP. The other adjacent reference surface D corresponds to P_7 . By following the previous elaboration, P_1 is used for constructing the VIP. However, after the VIP is constructed, reference surface which corresponds to machining plane can be changed to manage suitable MPP. By exploiting these vertices and faces in each TRV feature, machining plane is defined as follows:

1. If there are more than one reference surface, then the reference surface that can minimize TAD changes will be selected as the reference surface. Reference surface can have several safe normal axes that could be considered as TAD. At first, the initial TAD is selected based on the corresponding *mp*. In order to simplify the machining process, the system will select the TAD that can minimize changes. In Figure 3-13, although $-Y$ axis is defined as the initial TAD for second removal process by P_8 , the system will select $+Z$ axis as the TAD for the removal process P_8 . This procedure is taken to coordinate the ongoing TAD with the previous TAD ($+Z$ axis) from the first removal process.
2. If there are more than one reference plane, then a reference plane which has the largest lateral surface area will be selected as the new reference plane. This procedure is intended to decrease the total depth of cut needed to complete the removal process of corresponding TRV feature. In Figure 3-14, the reference plane corresponds to P_1 and P_7 have an equal lateral size. In this case, it is not necessary to change the machining plane.

The proposed system considers two types of cutting tools, flat end mill, and ball end mill. Flat end mill will be assigned to reference surface which has, at least, one open face. In case that there is no flat end mill diameter could be fitted in on the open face lateral size, then it will be treated as a reference surface without an open face. Ball end mill will be assigned to a difficult shape, for example, a reference surface without an open face.

Moreover, the proposed system considers two types of the tool path, contouring pattern and zigzag pattern. Reference surface that has open face less than the half number of whole faces on TRV feature will be machined by contouring pattern. Reference surface that has an open face, at least, the half number of entire faces will be machined by the zigzag pattern.

3.4 Experiment and result

The proposed algorithm is validated by manual iteration using Solidworks onto several imaginary workpieces. Each workpiece has suitable machining process plan. A workpiece which has been introduced earlier by Morinaga et al. [53] is also used as one of the trials to evaluate the solution. Ten candidates were constructed for removal process of TRV body. One of the generated MPP (as shown in Figure 3-15) is defined as one of the best solutions in [53] for machining the workpiece. The proposed algorithm can sort three candidates as the feasible MPP as shown in Figure 3-16. Moreover,

unlike in [53], the removal processes for TRV body in Figure 3-16 use only two TAD, $-Y$ and $+Z$ axis. Cutting tool and tool path assignment for each TRV features are shown in Table 3-1.

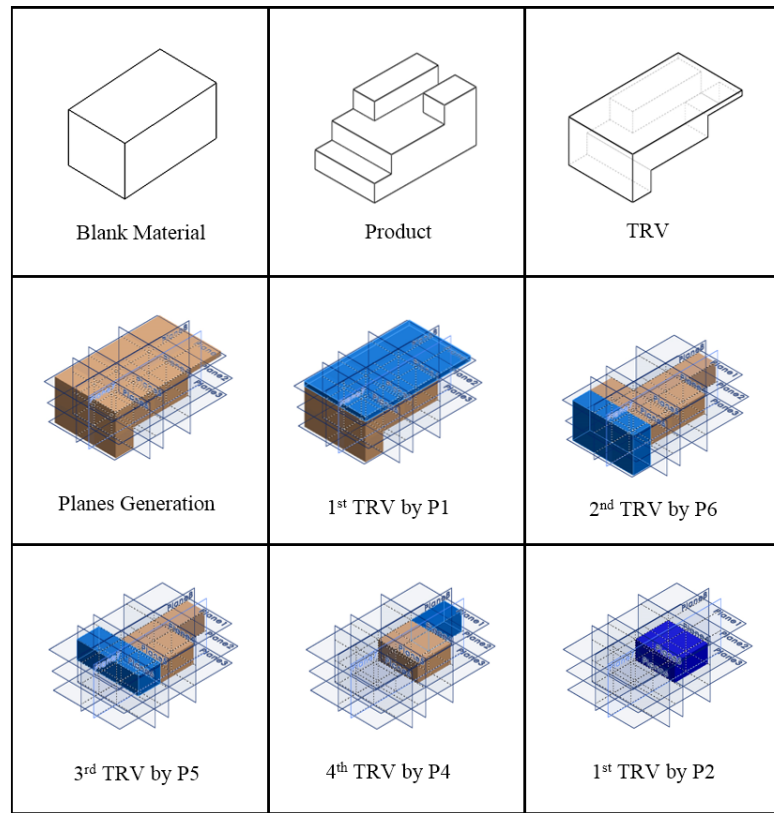


Figure 3-15 Example of constructed TRV features.

Table 3-1 Machining sequence of one candidate for TRV features configuration.

#	Removal Shape	Cutting Tool	Tool path	TAD
1	1 st TRV	Flat end mill	Zigzag	+Z
2	2 nd TRV	Flat end mill	Zigzag	-Y
3	3 rd TRV	Flat end mill	Zigzag	+Z
4	4 th TRV	Flat end mill	Contouring	+Z
5	5 th TRV	Flat end mill	Contouring	+Z

Although the proposed algorithm can successfully reduce the number of candidates, it still needs more enhancements in selecting the best candidate of TRV features. At this moment, minimization of TAD changes is applied to choose the best solution. From the result in Figure 3-16, final machining plan still cannot be selected from three available candidates. These candidates have an equivalent number of TAD changes. If no other constraints required, the best machining process plan can be selected randomly. However, it will be necessary for the future to apply another objective function such as geometric tolerance, minimization of actual cutting time, or minimization of actual cutting cost.

Chapter 4 Machining Aspect Evaluation to manage The Flexibility of MPP

4.1 Introduction

This chapter shows further development of the early concept to realize a flexible CAPP system. The proposed system is focused on forming MPP that can support and feed an autonomous CAM system to determine the corresponding MOP. In Chapter 3, the generated MPP configuration, which consist a set of VIP can be configured by straightforward manipulation of reference plane. However, this configuration still not consider the actual machining aspect. Therefore, this chapter will elaborate the corresponding method to evaluate the MPP configuration by considering the setup and the total process time.

Former CAPP systems exert substantial efforts in extracting and matching machining features according to pre-defined features. These features can be traced to a particular database that keeps the feature definition in the information architectural layer. The matching process and the growing databases of feature definitions no longer meet the requirements of an autonomous system in an agile environment. The matching process in large databases of feature definitions will become an exhaustive and time-consuming process [25]. In this proposed system, two actors are assumed to be involved, the planner and the operator. Each module for CAD and CAPP are established to support these actors' activities as described in Figure 4-1.

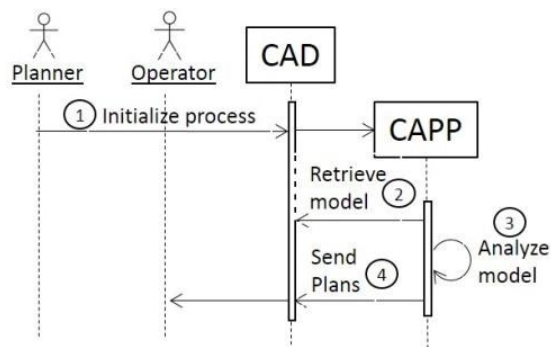


Figure 4-1 Sequence diagram of activity model for planner and operator.

4.2 Framework of development

The second phase framework of development continues the first phase framework of CAPP as depicted in Figure 4-2. The VIP feature-based unit will be used for the base to manage a straightforward machining volume decomposition. Then, several alternative of MPP configurations will be gathered and evaluated. The evaluation is performed by considering the element of setup and total process time of the corresponding MPP. This chapter is focused on how to retrieve the best MPP among others. Further

enhancement of the MPP will be explained in Chapter 5. The detail steps of the proposed algorithm of MPP generation is shown in Figure 4-3.

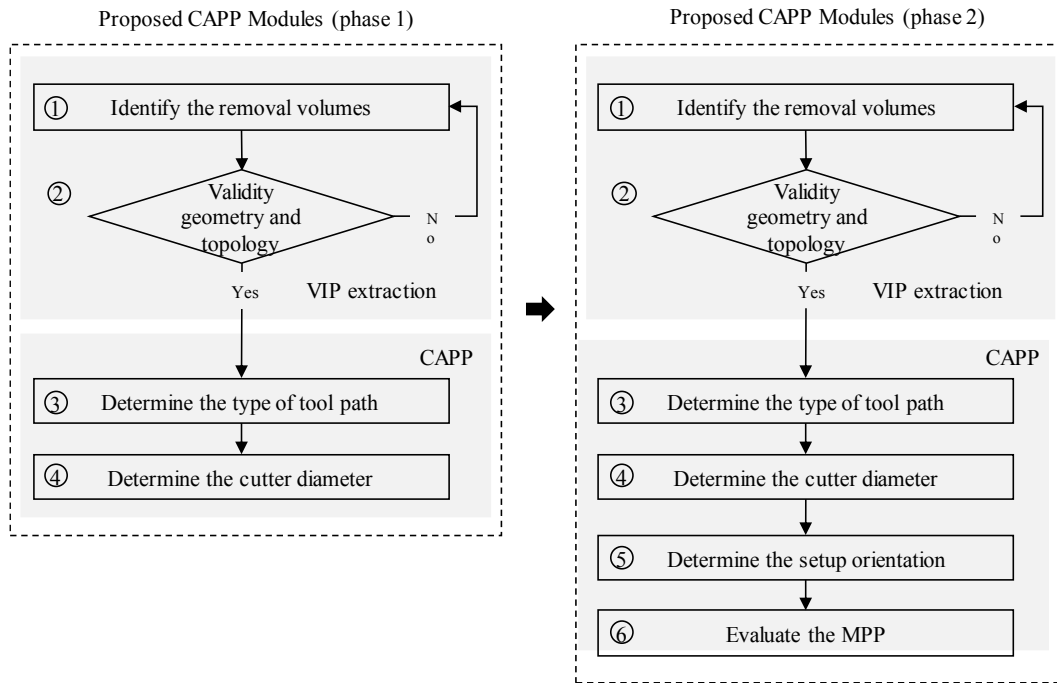


Figure 4-2 The initial framework for CAPP development (phase 2).

4.3 Removal features extraction

The previous chapter has described how the TRV is superior in handling any shape of the blank material. The TRV concept uses backward process planning from the final shape to the initial shape. This concept considers that each finished shape will be processed based on the last intermediate shape, and not from the initial raw material shape. Figure 3-1 has showed a variety of instance of TRV, which was generated by Boolean subtraction process. The reference point can be defined by simply using one of the vertices of the lower surfaces of the raw material and product. In most case, the TRV may consist of multiple bodies as depicted in Figure 4-4.

4.3.1 Multi TRV

A multi TRV body can hamper the iteration process of VIP extraction. This section explains the proposal to improve the main algorithm for supporting the TRV with multiple removal volumes. For example, the iteration process of the initial TRV 2 from Figure 3-1 may give a result of multi TRV body. As depicted in Figure 4-4, P_2 and P_7 may be selected as the removal planes, consecutively, and may generate a multi TRV body. By these instances, the algorithm, which has been explained previously in Chapter 3, needs to be improved to maintain the second rule. Therefore, a different sphere centroids definition for each TRV body are proposed to maintain the consistency of the algorithm.

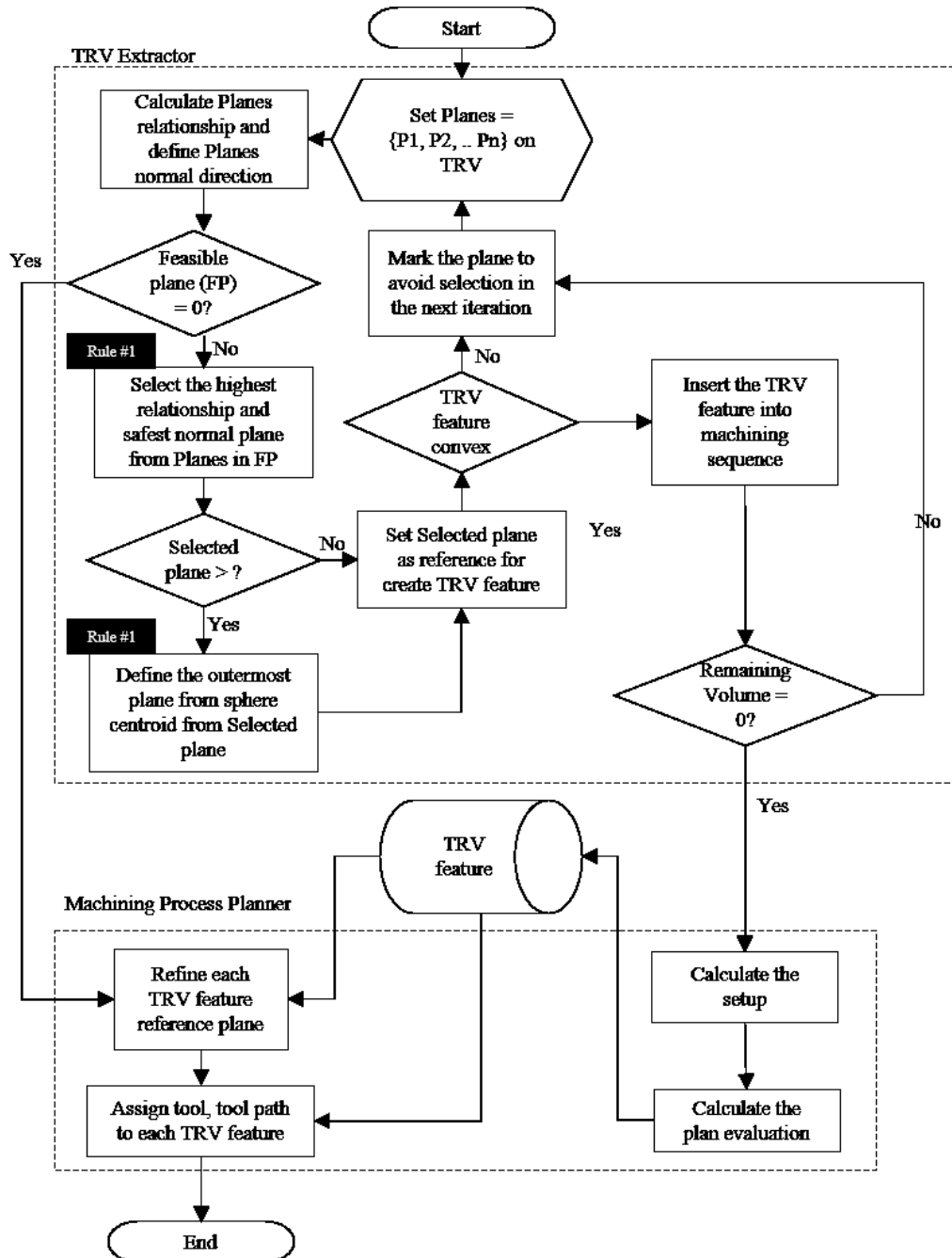


Figure 4-3 Algorithm of MPP generation involving the TRV body.

With a multi TRV, the original sphere centroid is no longer suitable and is renewed for each TRV body as illustrated in Figure 4-5. The new sphere centroid location is determined by using the two following rules:

1. The centroid is positioned on the reference plane that is coincident with one or several faces and not intersecting the selected TRV body. For instance, P_4 and P_5 are selected to hold the centroid for each corresponding TRV body.

2. The intersecting line which is perpendicular to the reference plane from the first rule is drawn from the centroid and should have the least intersections with the other reference planes.

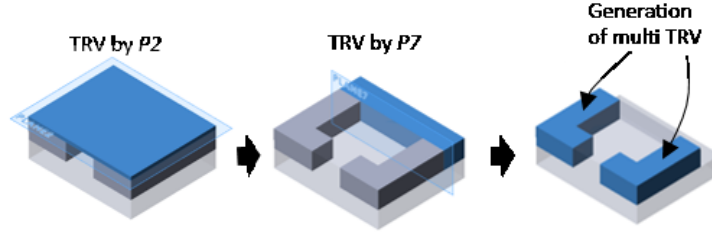


Figure 4-4 Generated multi TRV example in reference plane iteration.

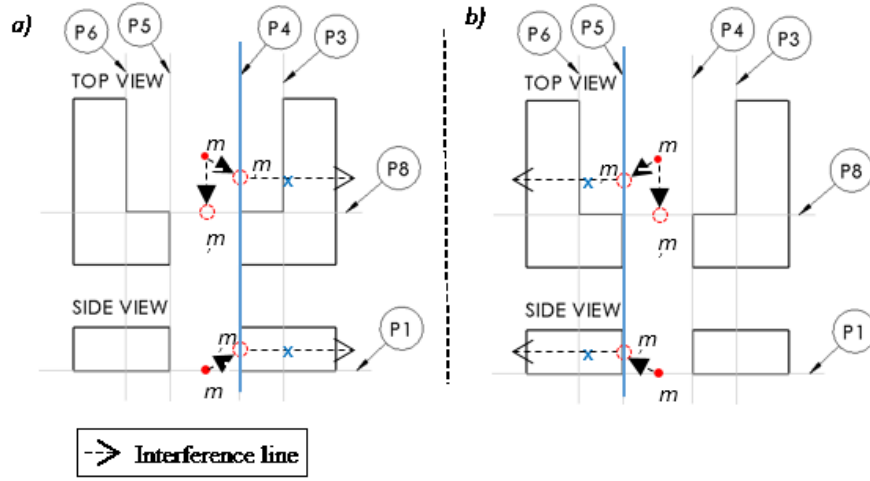


Figure 4-5 Methods for reference point determination of a multi TRV: a) first TRV body; b) second TRV body.

4.3.2 Enhancement of VIP features

This section summarizes the concept to initialize the VIP features to support the setup evaluation process. In order to conduct further analysis, the VIP features need to be enriched with a visibility cone specification, VC . Later on, to evaluate the corresponding setup, the TRV network also needs to be established. The TRV network is used to estimate roughly the position and alignment of the workpiece model.

4.3.2.1 Visibility Cone (VC) specification

The VC can be determined by analyzing the critical points on the VIP as depicted in Figure 4-6. The critical points are analyzed by aligning the tool cone and adjusting the tool cone size. The tool cone is aligned to ensure that the tool cone tip can reach the critical point. There are two kinds of alignments: clockwise, $\overrightarrow{TC}_{cw}$, and counter-clockwise, $\overrightarrow{TC}_{ccw}$. As shown in Figure 4-6, the tool cone is aligned instead

of the machine table to access the critical points. The clockwise rotation is considered as the B-axis positive direction in the [W/cbxy(C)/T] five-axis machine tool configuration [82]. The enhancement will renew the definition of VIP from Equation (3.2) and can be re-expressed as in Equation (4-1).

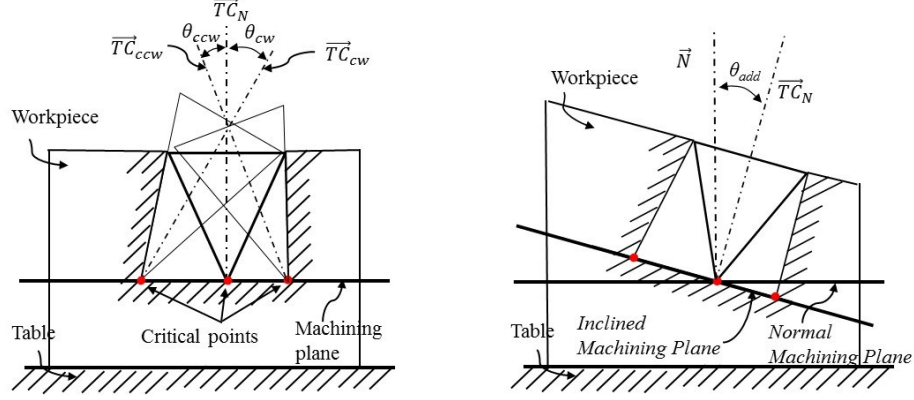


Figure 4-6 Visibility cone in TRV (left), and; inclined TRV machining plane (right).

$$VIP \equiv \{b, mp, \cup_{i=1}^j p_i, \cup_{i=1}^k of_i, VC\} \quad (4-1)$$

Next, the VC is determined by Equation (4-2). The alignments of the tool cone for clockwise and counter-clockwise adjustment are θ_{cw} and θ_{ccw} , respectively, as depicted in Figure 4-6. Moreover, θ_{add} is an adjustment of the VIP if it is in an inclined position as shown in Figure 4-6. If the normal of VIP is parallel to the cutting tool axis (Z-axis), then θ_{add} is 0. Thus, each VIP feature can have its VC specification and recommended tool length, as shown in Figure 4-7.

$$(|\theta_{add}| + \theta_{cw}) \leq VC \leq (|\theta_{add}| - \theta_{ccw}) \quad (4-2)$$

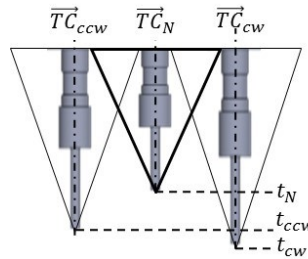


Figure 4-7 Varied recommended tool length based on VC .

4.3.2.2 TRV Network

The TRV network shows the relative position of the TRV center and the VIP feature's centroid. The VIP feature's centroid is denoted by VIP_n and can be expressed by Equation (4-3). The n value indicates the importance of the VIP feature among all TRV features. Thus, the workpiece can be represented as a TRV network with its VC requirements, as depicted in Figure 4-8. Consequently, the definition of TRV from Equation (3-1) can be re-expressed as in Equation (4-4).

$$PM \equiv \{VIP_1, VIP_2, \dots, VIP_n\} \quad (4-3)$$

$$TRV \equiv \{\cup_{i=1}^m VIP_i, \cup_{i=1}^n P_i, PM\} \quad (4-4)$$

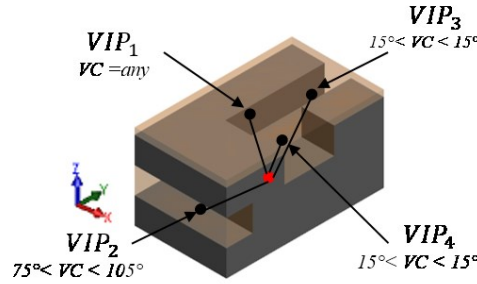


Figure 4-8 TRV network of an imaginary TRV.

4.4 MPP Evaluation

4.4.1 Evaluation function of total process time

After all candidates of the MPP are gathered, the next task is to evaluate the machining time for each plan. Since the tool path has not been considered, the evaluations are based on the decomposed VIP bodies in each MPP. In this study, the machining time, MT_i , is estimated by calculating the machining removal rate (MRR) on the corresponding VIP body. The overall evaluation is referred to as the total process time PT_i and is also improved to consider the setup time, ST_i , for each MPP, as shown in Equations (4-5) to (4-9).

$$PT_i = MT_i + TCT_i + DCT_i + ST_i \quad (4-5)$$

$$MT_i = \frac{TRV_{ij}}{(ad_{ij} \times rd_{ij} \times F_{ij})} \quad (4-6)$$

$$TCT_i = t_{tool} \times NTC_i \quad (4-7)$$

$$DCT_i = t_{DC} \times NDC_i \quad (4-8)$$

$$ST_i = t_s \times NS_i \quad (4-9)$$

where:

PT_i	= total process time for each machining plan i (s)
MT_i	= machining time of corresponding VIP (s)
TCT_i	= tool changing time (s)
DCT_i	= direction changing time (s)
ST_i	= setup time (s)
$TRV_{i,j}$	= total removal volume (mm ³)
$ad_{i,j}$	= axial depth of cut (mm)
$rd_{i,j}$	= radial depth of cut (mm)
$F_{i,j}$	= feed speed (mm/min)
T_{tool}	= tool changing time (s)
NTC_i	= number of tool changes
t_{DC}	= tool access direction changing time (s)
NDC_i	= number of direction change
t_s	= workpiece setup time (s)
NS_i	= number of workpiece setups
i	= number of machining plans
j	= number of configurations in i

4.4.2 Setup evaluation

The concept for evaluating setup is based on the estimation of the workpiece position within the machinable space. A model of an actual machining specification is constructed based on the required tool cone and the improved machinable space. The tool cone is determined by using the spindle diameter, R_s , and the tool length, t , as depicted in Figure 4-9. The tool cone is assumed as the safest allowance for the cutting tool and spindle when traveling within the machining space. For instance, in Figure 4-7, three types of tool lengths, t , are needed: t_N , t_{cw} , and t_{ccw} . To minimize the number of tools required for the corresponding TRV, a suitable tool length, t^* , is selected by using Equation (4-10).

$$t^* = \max(t_N, t_{cw}, t_{ccw}) \quad (4-10)$$

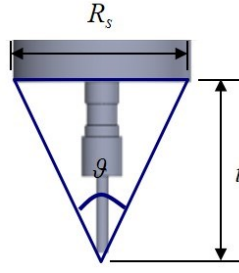


Figure 4-9 Tool cone determination.

By using an approach that is similar to Nishiyama et al. [84], the actual machine tool specification is used for modeling the machining space, as depicted in Figure 4-10. The machining space is limited to X, Y, and Z maximum travel, which are denoted by R_x , R_y , and R_z , respectively. The machine table is limited to the diameter D and can only rotate on the B- and C-axes. If the machine tool is limited to three-axis machining, then only workpiece positioning will be needed, as explained later in this section. In order to analyze the machinable space, three assumptions are established:

1. The cutting tool cone tip is initially aligned with the B- and C-axes.
2. The initial condition of the tool cone and the machine table are defined as the maximum machine table position for colliding with the tool cone. This condition can be achieved by positioning the tool cone to h_0 and the machine table to β_0 , as depicted in Figure 4-10.
3. The C-axis can be rotated 360° .

Previous assumptions ensure the validity of using only half of the machine table for modeling the machinable space. In Figure 4-10, a clockwise rotation of the machine table is chosen as an instance in which h_0 is the maximum travel of the tool cone to reach the center of the table. Further, β_0 is achieved by aligning h_0 with the B-axis. The next rotation angle β_n is determined by Equation (4-11). To construct the machine table region as shown in Figure 4-10, an angle interpolation, β , is needed.

The machine table rotation by β will eventually limit the tool cone to reach h_0 , and shifts the tool cone upward to a new position, h_n . The calculation can be illustrated using Figure 4-11. Two steps are needed for calculating the h_n . In the first step, an imaginary collision point, CP , that occurs between the machine table and the tool cone is calculated by transforming the machine table edge point, EP , using Equation (2-1). The next step is to project the CP by the Z-axis to the tool cone, which is positioned in h_0 .

$$\beta_n = \beta_{n-1} + \beta, \quad n \geq 1 \quad (4-11)$$

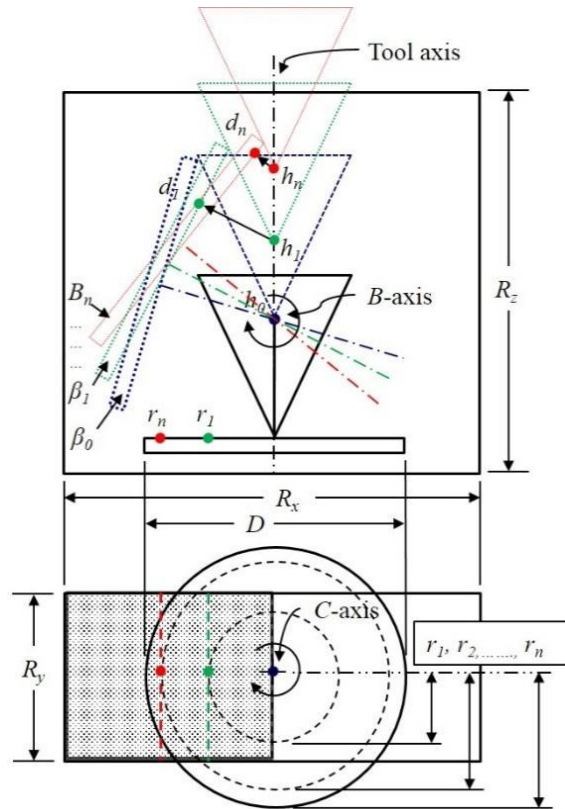


Figure 4-10 Table region determination.

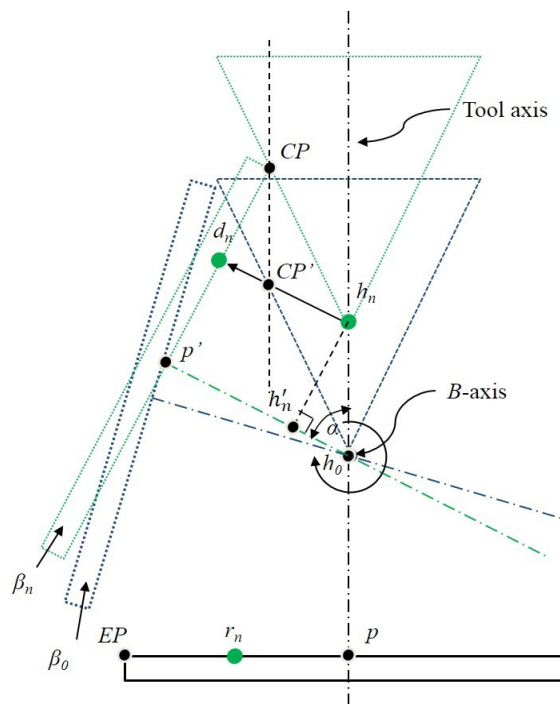


Figure 4-11 Mathematical manipulations of machine table and VC.

Subsequently, the projection point will be defined as another imaginary intersection point, CP' , as depicted in Figure 4-11. At this state, we can ensure that the $|h_0 - h_n|$ line is parallel and equal with the $|CP - CP'|$ line. If the angle, α , is defined by $(180 - \beta_n)$, then the $|d_n - p'|$ distance will equal the $|h_n - h'_n|$ distance, in which p' is a rotated point of the center of the table, p , and h'_n is the projected h_n . As depicted in Figure 4-11, d_n is the maximum travel for the tool cone if the machine table is angled by β_n . Thus, the machine table region, r_n , that corresponds to d_n can be calculated by Equation (4-13). The machine table rotation is repeated until the tool cone tip coincides with the edge of the machine table, or $CP = h_n$.

The last step is to position the workpiece into the advised location on the machine table. The VC specification of the VIP feature is used for positioning the TRV network into the right machine table region. Initially, the network center is aligned with the center of the table, as shown in Figure 4-12. Each location difference, ε_n , between the VIP_n and the required region, $r_n^* r_n^*$, on the machine table is calculated by Equation (4-14). The closest point on $r_n^* r_n^*$ from VIP_n is defined as ap_n .

$$|h_0 - h_n| \cong |CP - CP'| \quad (4-12)$$

$$r_n = |d_n - p'| = |h_n - h'_n| \cong |h_0 - h_n| \sin(\alpha) \quad (4-13)$$

$$\varepsilon_n = \begin{cases} -1 \times |\overline{VIP_n} - \overline{ap_n}|, & \text{if } (\overline{VIP_n} - \overline{ap_n}) \text{ leads inward} \\ |\overline{VIP_n} - \overline{ap_n}|, & \text{if } (\overline{VIP_n} - \overline{ap_n}) \text{ leads outward} \end{cases} \quad (4-14)$$

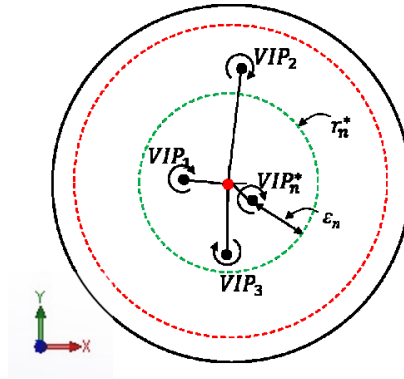


Figure 4-12 Positioning procedure illustration.

Further, several translations and rotations of VIP_n are needed until the entire VIP_n can be put inside its $r_n^* r_n^*$. Each translation or rotation is based on the VIP_n that has a positive value of ε_n , which is denoted by VIP_n^* . After all VIP_n^* values are calculated, the VIP with the lowest n will have the first

priority to be put in its $r_n^* r_n^*$. It is important to note that each translation or rotation by VIP_n^* affects the entire VIP_n position. Moreover, the entire VIP_n must be within the table diameter D .

As shown in Figure 4-12, the positioning procedure will only be on the X-Y axis to avoid putting the workpiece in a 3D rotation that would require further fixturing to secure the workpiece. However, the proposed procedure may generate unfeasible solutions after several rotations and translations by VIP_n^* . Therefore, the positioning will also involve an elevation, Z. Workpiece elevation helps to enlarge the solution space for each VC 's requirement.

On the contrary, if the workpiece machining will be performed on traditional three-axis machining, then the positioning may be done simply by aligning each VC 's requirement with the tool axis (Z-axis). For example, the product in Figure 4-8 needs, at least, two setups. The first setup will be required for VIP_1 , VIP_3 , and VIP_4 . The second setup will be required for VIP_2 . However, an additional fixture might be necessary to support all setups.

4.5 Prototype and Case Study

A sample of the workpiece that is depicted in Figure 4-13 is used for explaining the proposed methodology. From the Boolean operation on the workpiece with a raw material size of $90 \times 56 \times 75 \text{ mm}^3$, multiple TRVs that consist of four solid bodies can be generated. By iterating all the solid bodies in the process explained in Section 4.3, we can resolve the TRVs into three MPP as shown in Table 4-3. The iteration process can efficiently limit the number of candidates that need to be analyzed further by Equation (4-5).

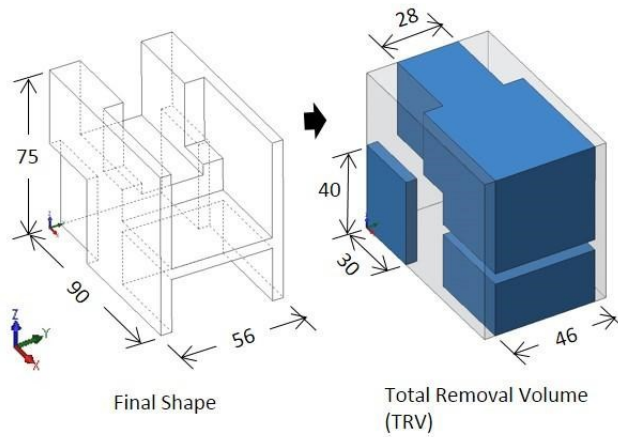


Figure 4-13 The workpiece and its TRV.

In order to calculate the total process time, PT_i , by Equation (4-5), the example of cutting tools and the cutting tool selection rule in Appendix A are used. The values of t_{tool} , t_{DC} , and t_s were given as 10 seconds, 5 seconds, and 600 seconds, respectively. The values of $ar_{i,j}$, and $rd_{i,j}$ in Equation (4-6) were

determined to be 0.25 and 0.1 of the selected tool diameter, D_j . Similar to Morinaga et al. [83], F_{ij} are calculated by Equation (4-15), where f is the cutting feed, v is the cutting speed, and Z_{ij} is the number of cutting edges of the corresponding selected cutting tool. In this experiment, f and v were set at 1 mm and 1000 mm/second.

$$F_{ij} = fv/\pi D_j Z_{ij} \quad (4-15)$$

The MPP candidate results in Table 4-1 show the feasible TADs for each machining sequence (MS). By searching for similar TADs in each MS, we can find a resolution for the cutting tool axis alignment for the workpiece. This cutting tool alignment can be used to determine the number of setups needed for each MPP. In each MPP, the alignment by the +Z and -Z axis for each MS consecutively has the least changes to the cutting tool axis. Consequently, the +Z axis can be selected as the first setup in processing MS1 to MS4 and the -Z axis can be selected as the second setup for the remaining MS.

Table 4-1 The TAD configurations of MPP.

MS	MPP1				MPP2				MPP3					
1		-X		+Z		-X		+Z	+X			+Z	S_1	
2	+X			+Z	+X			+Z		-X		+Z		
3	+X			+Z	+X			+Z	+X			+Z		
4	+X	-X		+Z	+X	-X		+Z	+X	-X		+Z		
5		-X		-Y	-Z		-X	-Y	-Z		-X	-Y	-Z	S_2
6		-X	+Y		-Z		-X	+Y		-Z		-X	+Y	
7	+X			-Z	+X			-Z	+X			-Z		
✓ 2 sequences of TAD in S_1 ✓ 4 sequences of TAD in S_2				✓ 2 sequences of TAD in S_1 ✓ 4 sequences of TAD in S_2				✓ 2 sequences of TAD in S_1 ✓ 4 sequences of TAD in S_2						

The results of the experiment in Table 4-2 show two MPP candidates, MPP1, and MPP2, as the most efficient regarding the total process time. Both of these MPPs will need 12,497 seconds to complete the entire corresponding MS. The details of the configuration of each MPP can be seen in Table 4-2 and Table 4-3.

4.6 Conclusion

In this chapter, an implementation of a new concept of MPP generation based on TRV is proposed. In order to evaluate its effectiveness, a prototype made to work within a commercial CAD-CAM environment was developed. The current development of the proposed system has several advantages, which are as follows:

1. To shorten the definition process of removal volume and simplify the machining features, a new concept for multiple TRV decompositions is proposed. A direct decomposition process by using the

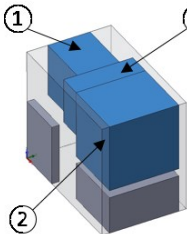
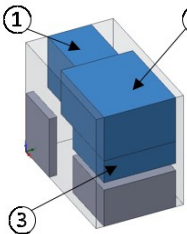
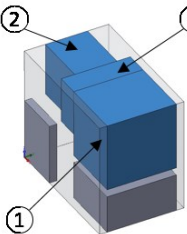
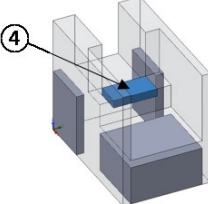
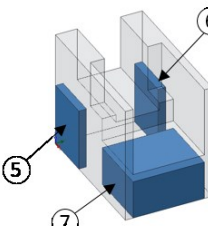
machining plane candidates to form VIP was more efficient in estimating the removal volume than traditional decomposition. The use of machining plane relationship has a significant advantage in filtering the important VIP and sequencing them to define MPP.

Table 4-2 The best configuration of each MPP.

MPP	Machining sequence (MS)							MT (sec)	TCT (sec)	DCT (sec)	ST (sec)	PT (sec)	
	1	2	3	4	*	5	6						7
1	-x	+x	+x	+x		-x	-x	+x	11857	30	10	600	12497
	2	3	3	2		3	3	3	<< Tool ID assignment				
2	-x	+x	+x	+x		-x	-x	+x	11857	30	10	600	12497
	2	3	3	2		3	3	3	<< Tool ID assignment				
3	+x	-x	+x	+x		-x	-x	+x	11857	40	15	600	12512
	3	2	3	2		3	3	3	<< Tool ID assignment				

* Setup Changes

Table 4-3 The details of MPP and the corresponding MS.

Setup (S)	Machining Sequence	Alternative of MPP		
		MPP1	MPP2	MPP3
S_1	① ↓ ② ↓ ③			
	↓ ④			
S_2	↓ ⑤ ↓ ⑥ ↓ ⑦			

2. The improved machinable space formation involving the tool cone and actual machine tool specification can estimate the alignment of the workpiece. Although the estimation was limited to a rough estimation of the colliding position between the tool cone and the table, it shows the possibility of defining machinable positions in earlier stages of machining operations. Furthermore, the requirement for successful fixtures can be planned more conveniently.
3. The rough formation of both the removal volume and setups gathered machining information for the corresponding process plans. The workpiece machining time and setup can be established by checking the corresponding VIP (*VC* requirement) thoroughly. Therefore, each MPP can be evaluated and compared with each other to find the best alternative.

In order to make the proposed system more practical, actual machining is needed. The real tool paths and machining parameters need to be considered to analyze the machining time more accurately. This consideration can lead to a better estimation of machining cost. Alternative process plans can be used to make a fair adjustment and analysis before performing the related machining operation. The flexibility of the MPP was gathered and analyzed automatically from the 3D model to support the actual machining. Consequently, the efforts of the planner can be reduced, and the seamless interaction between the CAD-CAM can be defined more clearly.

Chapter 5 Translation of MPP into MOP and Consideration of Design Requirements of MPP

5.1 Introduction

This chapter elaborates the translation of MPP configuration into MOP. A corresponding set of VIP is enhanced to handle two distinct features which a complete representation to accommodate MOP generation. The handling of shapes during machining stage still becomes the challenging task when it comes to the problem of automating the MOP generation. Two products can be highlighted to be the example of the shape's variety, component, and mold. The recent practice shows that these products are increased in the term of design and evolved into many varieties of required MF. By considering these varieties of MF, the CAPP is needed to be more flexible and robust in order to be more useful in practical works.

The existing common practice for constructing the MOP is by using a pre-defined MF [33]. The pre-defined features might be associated with a particular machining information. Recently, a database-oriented planning was also proposed to be used for constructing the MOP [23]. Accordingly, the extraction of MOP based on the database will still depend on the production (IF-THEN) rule basis [25]. The long cause expressions might affect the time to find the suitable operation. In TRV cases, the definition of operations is still needed to represent the know-how aspect in succeeding the corresponding MOP.

In Chapter 3, VIP as the new iteration form of TRV has been discussed. The VIP has been able to simply and uniquely define the MPP configuration. However, it is still unclear how to extend the MPP into further corresponding MOP. This chapter discusses another possible enhancement of TRV to support the linkage between CAD and CAM. Moreover, another objective consideration in configuring the MPP generation is proposed by incorporating the product's tolerance into the decomposition process of VIP. This product's tolerance represents the design requirement.

5.2 TRV shapes enrichment

By recalling again several facts from the first section, the TRV might also be dissolved into a sequence by considering the order of the reference plane. In this case, the VIP (the dissolved volumes of TRV) will have its natural and dynamic shape. At this point, the pre-defined feature might be lacking information to recognize the feature. This paper proposes a new way of treating the dynamic of features so it may trigger the features to evolve more generatively.

The common way of constructing the MPP is to be mainly based on the design of a product, i.e. the target shape [25]. This practice is primarily comprehended because of the process plan is decided more on the upstream of the production line. Since the realization of the product most likely will be determined by the downstream situation, i.e. the shop floor, the MPP will need to be prepared with MOP

to perform the actual machining operation to achieve the target shape eventually. Previous work by Wang et al. [85] showed the example of consideration based on the VIP enrichment to sequence the MPP. In this research, the enriched machining features (EMF) to accommodate the occurrence of the intermediate machining volumes (IMV) during the machining stages. These IMVs will be the analog to the VIP and play a significant role in the EMF-based reasoning. However, a sufficient basic machining information was still not associated to determine the corresponding MOP. Moreover, the treatment for a free-form surface feature was not available.

In this paper, VIP is enriched by introducing two kinds of forms, actual removal volume (ARV) and primitive removal volume (PRV) as illustrated in Figure 5-1. ARV is used for holding the real shape information while PRV is used for holding the estimated geometry information. Both forms are going to be used for providing TRV description to find the corresponding MOP and can be expressed as in Equation (5-1) and (5-2).

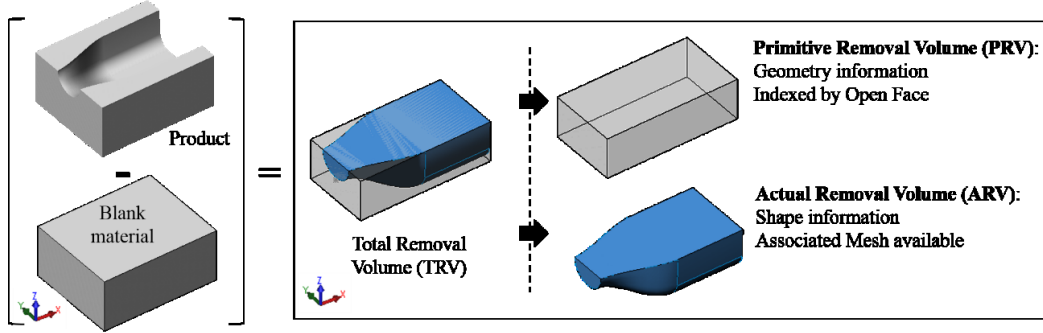


Figure 5-1 TRV enrichment.

$$PRV \equiv \left\{ \bigcup_{i=1}^j p_i, \bigcup_{i=1}^k OF_i \right\} \quad (5-1)$$

$$ARV \equiv \{b, mp\} \quad (5-2)$$

$$VIP \equiv \{PRV, ARV\} \quad (5-3)$$

ARV can simply support the feature description that might have a difficulty in definition based on geometry reasoning only, by relying on the definition of its actual solid body, b and corresponding machining reference, mp . PRV can simply support the definition of removal shapes by defining its collection of the plane, p , and topology of open faces, OF . The relation between VIP, PRV and ARV can be expressed as in Equation (5-3). In VIP collections, each VIP will consist of PRV and ARV. One PRV might have several ARV forms.

5.3 MOP generation

In this section, the strategy to generate a TRV-based MOP will be explained. A new machining information (MI): a particular cutting condition, tool path pattern, and other required parameters are reconfigured based on past machining case data that is associated with MFs. The main idea is to perform a CBR for constructing the new machining information as also previously introduced by Champati et al. [47]. In this research, the indexer for retrieving the similar case will be based on the PRV and ARV.

Two stages of machining operation planning are proposed as depicted in Figure 5-2. The first stage is to collect the suitable PRV. The second stage is to find the similarity between the new ARV shape and the ARV within the past machining shape data. The following sub-section describes each stage function.

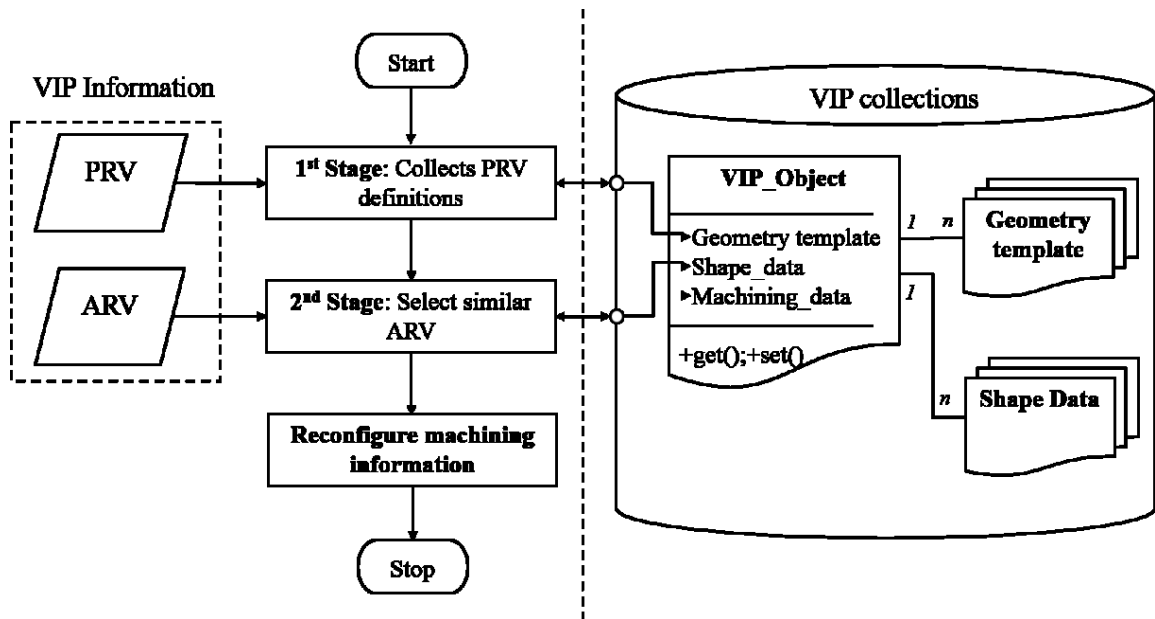


Figure 5-2 The framework of MOP generation.

5.3.1 First stage: Collection of PRV definitions

In the first stage, all similar PRV will be gathered to recognize further the corresponding ARV. The topology of open faces, *OF*, on PRV is needed. The *OF* is defined as a surface of PRV, which is in contact with the air. Afterward, the topology is used for elaborating the criterion of *OF*. This stage gathers all possible PRV based on the criterion depicted in Figure 5-3. Since the PRV shape will be similar to primitive MF, the recognition of PRV topology is developed based on MF recognition which is proposed by Shinoki et al. [86]. Eight PRV templates in Figure 5-4 are used in this proposed methodology. This stage filters unrelated recent machining data based on the PRV.

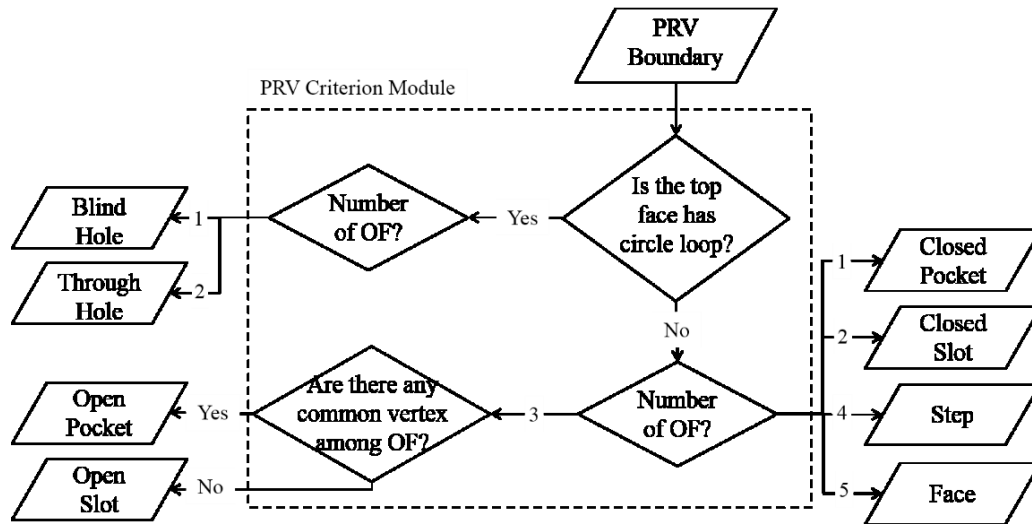


Figure 5-3 The criterion of open faces (OF) for collecting PRV definitions.

5.3.2 Second Stage: Selection of similar ARV shape

In the second stage, the similarity of ARV is evaluated based on three aspects: shape, size and material. Each aspect evaluation is explained further in the following subsections. Each stage Both of ARV forms are matched by finding the similarity based on the shape, size, and material aspects. The most similar ARV in the past machining shape data is selected, and the associated machining information is reconfigured for the new machining information of the corresponding ARV. In this research, the ARV collections are assumed to be available and will consist of previous ARV machining data.

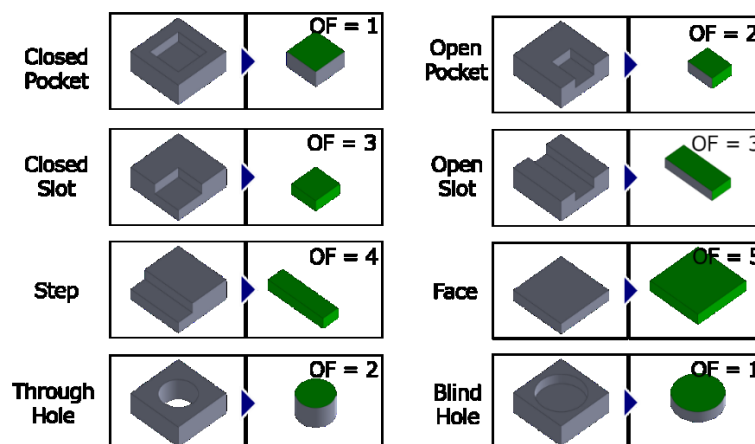


Figure 5-4 Template of PRV's open faces.

5.3.2.1 Shape and size evaluation of ARV

In practical machining, the size of removal volume will affect the criterion for selecting a cutting tool and machine tool. By considering the tool approach, the cutting tool axis is aligned with the Z-axis in the case of a milling process. Then, the normal reference point for Z-axis alignment on each machining surface can be evaluated. Based on the requirements of size estimation and tool alignment in Z-axis, a methodology is proposed for evaluating the similarity of ARV regarding shape, size and the reference of Z-axis. The previous research by Ohbuchi et al. [87] has developed the concept of absolute angle and distance (AAD) for characterizing a solid model. The unnormalized version of AAD is used for evaluating the shape and size of ARV. In this stage, two AAD for the new ARV shape and the ARV in the past machining shape data are compared to evaluate the similarity of both ARVs. The steps of AAD construction are summarized in the following points:

1. Generate triangle meshes on the model surfaces and calculate the number of triangle meshes, Num as illustrated in Figure 5-5(A).

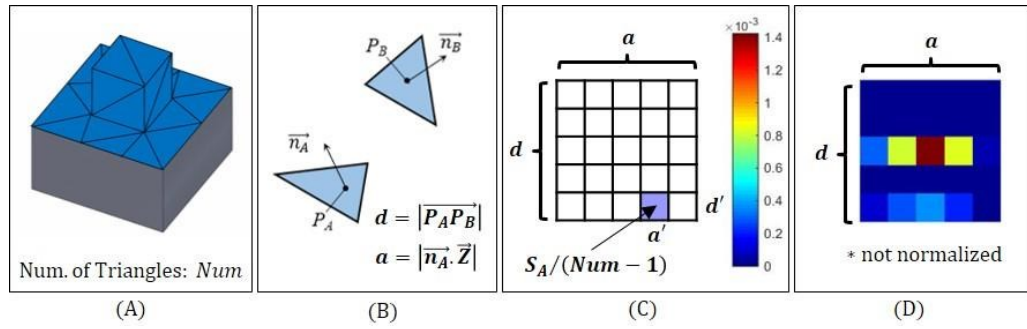


Figure 5-5 Steps of AAD diagram generation for ARV.

2. Select two random triangle meshes, A and B. Calculate and define their center of gravity as P_A and P_B . Also, define the normal $\vec{n_A}$ and $\vec{n_B}$ from each triangle A and B, consecutively, as illustrated in Figure 5-5(B).
3. Calculate the distance, d , between the two centers of gravity P_A and P_B .
4. Calculate the absolute value, a , of the inner product between the normal vector $\vec{n_A}$ and the +Z vector.
5. Set the combination with the proportion of triangle surface area as $(S_A / Num - 1)$, where S_A is defined as the triangle mesh area.
6. Repeat step (2) to (5) until all possible combination of triangle meshes are evaluated
7. Prepare a matrix of N by M size. The matrix size will affect the characterization. The bigger value of N and M can make a better characterization of the model shape.

8. Round (a, d) value in each combination to the nearest value (a', d') thus sorts the combination based on the lowest to the highest value of (a', d') . The (a', d') will correspond to a cell location in the matrix.
9. Fill the proportion area from each combination of triangle meshes into the matrix according to (a', d') location as illustrated in Figure 5-5(C). The definite matrix can be made for representing the characteristic of the shape. The range of color may be used for illustrating the characteristic as shown in Figure 5-5(D).

The AAD diagram corresponds to each ARV shape and will be used for evaluating the shape and size aspect. Consequently, the ARV can be re-expressed as in Equation (5-4). The example of ARV can be seen in Figure 5-6. The similarity of shape, S_{Shape} , is evaluated by Equation (5-5) while the similarity of the TRV size is assessed by Equation (5-6). New ARV shape is defined as X while past ARV's machining shape is defined as Y .

$$ARV \equiv \{b, mp, AAD\} \quad (5-4)$$

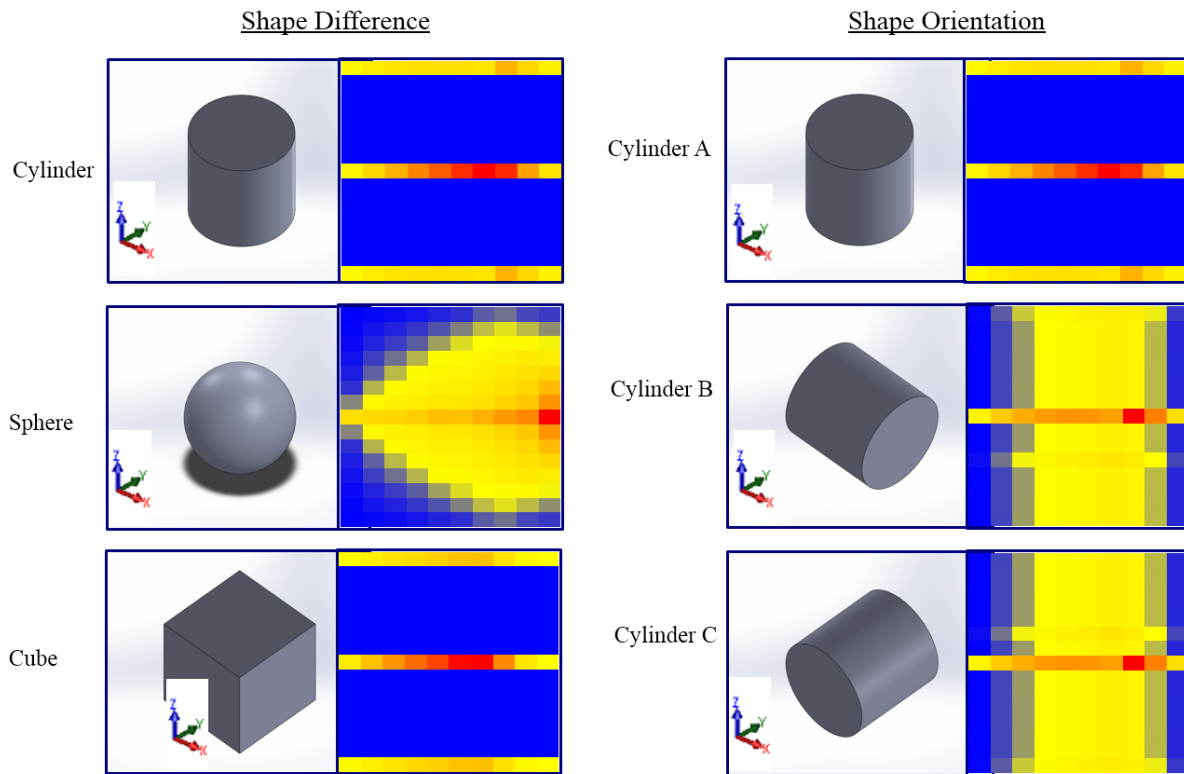


Figure 5-6 Example of ARV representation by using AAD diagram.

$$S_{Shape} = 1.0 - \frac{1}{2} \sum_{i=1}^N \sum_{j=1}^M \left| \frac{X_{i,j}}{\sum_{i=1}^N \sum_{j=1}^M X_{i,j}} - \frac{Y_{i,j}}{\sum_{i=1}^N \sum_{j=1}^M Y_{i,j}} \right| \quad (5-5)$$

$$S_{Scale} = 1.0 - \frac{\left| \sum_{i=1}^N \sum_{j=1}^M X_{i,j} - \sum_{i=1}^N \sum_{j=1}^M Y_{i,j} \right|}{\sum_{i=1}^N \sum_{j=1}^M X_{i,j} + \sum_{i=1}^N \sum_{j=1}^M Y_{i,j}} \quad (5-6)$$

5.3.2.2 Material evaluation of ARV

In actual machining, the cutting condition is varied and based on the workpiece material. Therefore, the similarity of material between new ARV shape and past ARV's machining shape also need to be evaluated. In the proposed methodology, the tensile strength is used for representing the physical characteristic between two ARV shapes. Thus, the similarity of material, $S_{Material}$ can be evaluated by using Equation (5-7).

$$S_{Material} = 1.0 - \frac{|x - y|}{x + y} \quad (5-7)$$

5.3.2.3 Total evaluation of ARV

Finally, by using all considerations in shape, size and material of ARV, the total similarity value, S_{Total} , can be evaluated by Equation (5-8). S_{Shape} , S_{Size} , $S_{Material}$, and S_{Total} will have values between 0 and 1.

$$S_{Total} = S_{Shape} * S_{Scale} * S_{Material} \quad (5-8)$$

5.3.3 Reconfiguration of machining information

Lastly, past machining information that is associated with the most similar past ARV's machining shape will be selected as the new machining information for the new ARV shape. The machining information consists of three parts as depicted in Table 5-1. The first part related to cutting condition of ARV. Currently, all of this parameter is derived from the past machining information. The second part is related to tool path. The tool motion pattern will follow the past machining information, but the process order will be adjusted to the new machining information. The third part is related to cutting region. All of the parameters within the third part will be adjusted to the new ARV's shape. Thus, a new tool path can be generated by using all machining information in all parts to each new ARV shape.

In the proposed system, the NC part program data is generated by using a commercial ESPRIT CAM software and post processor for DMG Mori Seiki 1500-DCG.

Table 5-1 Parameters of Machining Information [22].

Category	Parameter in Esprit	Meaning
Cutting Condition	Operation Name	Operation Name
	Tool Name	Cutting Tool
	Spindle Speed	Spindle Speed
	XY Feed Rate	Feed Speed in Radial Direction
	Z Feed Rate	Feed Speed in Axial Direction
	Step Over	Radial Depth of Cut
	Incremental Depth	Axial Depth of Cut
	Cutting Strategy	Cutting Direction
Tool Path	Tool Motion Pattern	Tool Path Pattern
	Process Order	Process Order
Cutting Region	Start Depth	Depth at Cutting Start
	Total Cutting Depth	Total Cutting Depth
	Path Num	Tool Path Number

5.3.4 Case study

This section explains the example of a case study that is used for analyzing the performance of the proposed MOP generation system. The main logic is made and worked as an add-in software within ESPRIT. A new model and two reference model of bottle' molds are established and shown in Figure 5-7. The corresponding MPP for the new model is derived from MPP generator which has been explained previously in Chapter 3 and 4. The generation of process plan will not be explained in this paper. ARV and PRV are also constructed from each VIP. Moreover, tool database is also provided and consist of five types of square end mill and five types of ball end mill.

In this section, only the removal volume from the 6th of the selected machining process is used for showing the robustness of the similarity evaluation. Figure 5-8 shows six of past ARV machining data that have similar PRV. All of these ARVs are categorized as a closed slot feature according to the *OF* of the corresponding PRV. Next, the similarity values between new ARV's model and ARV's reference are calculated, and the results are shown in Table 5-2 The result of similarity evaluation. The result shows that the fifth ARV of the second reference model is selected as the most similar ARV by 0.773 points. Thus, by validating the real appearance of the actual model's ARV and the most similar ARV in Figure 5-8, the proposed system clearly able to suggest the most similar characteristic of ARV. Additionally, the new machining information can be selected, and a succeeding NC part program can be generated. Validation of the generated NC program is performed successfully within ESPRIT to achieve the final shape as shown in Figure 5-8.

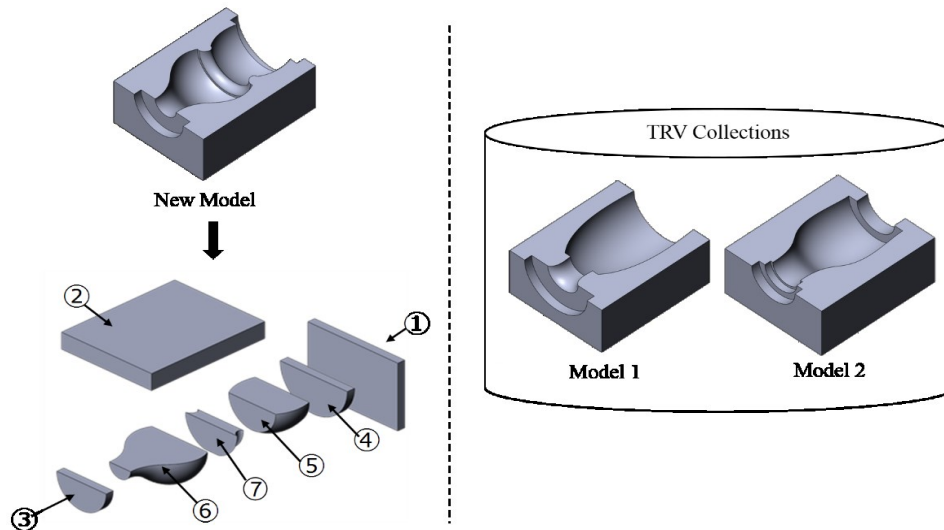


Figure 5-7 The new model of bottle's mold and the order of its TRV removal.

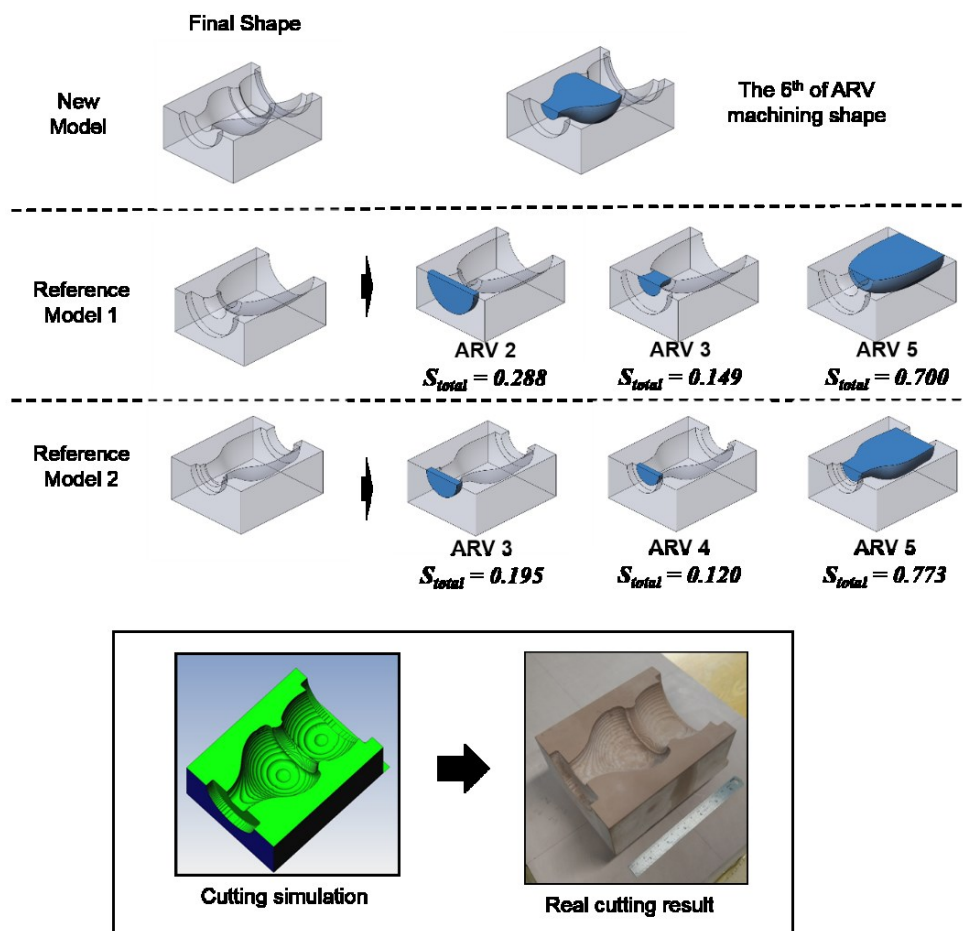


Figure 5-8 The example of the 6th of ARV machining shape and their reference ARV.

Table 5-2 The result of similarity evaluation

	S_{Total}	S_{Shape}	S_{Size}	$S_{Material}$
Model 2 – TRV 5	0.773	0.857	0.902	1.000
Model 1 – TRV 5	0.700	0.818	0.855	1.000
Model 1 – TRV 2	0.288	0.527	0.547	1.000
Model 2 – TRV 3	0.195	0.615	0.318	1.000
Model 1 – TRV 3	0.149	0.687	0.217	1.000
Model 2 – TRV 4	0.120	0.626	0.191	1.000

5.4 Involvement of Design Requirements inside the TRV

In this section, a preliminary study of another objective consideration in configuring the best MPP is elaborated. The previous mentioned VIP can be efficiently used for representing the MPP configuration based on its reference plane. However, the decision of the importance of each reference plane only depends on their relationship. In order to accommodate further analysis on MPP generation, a corresponding methodology is constructed by incorporating the design requirement of a product into the decomposition of VIP. The geometric dimensioning and tolerance (GDT) is used for representing this design requirements.

From the well-known concept of Axiomatic Design, the design parameter is acquired by interpreting the functional domain as illustrated in Figure 5-9. The functional domain represents the functional requirement of a product [88]. In design, this practice can be found by noticing the existence of particular tolerance on several shapes of product. Particularly in the assembly process, the tolerance will influence the mating process between components. Table 5-3 shows the example of utilization of this axiomatic design in the manufacturing cycle. In previous chapters, the VIP is described as the dynamic representation based on its machining reference by analyzing the properties of its reference plane, i.e. machining reference. This machining reference may directly correlate with the requirement of GDT on the workpiece surface. Therefore, the evaluation of plane properties is believed will be richer and efficiently show the actual requirements of the machining sequence which may influence the products functional quality, e.g. surface roughness, surface alignment, etc.

5.4.1 Geometric and Dimension Tolerances (GDT)

The GDT is used mainly for inspecting the product's quality and assembling the component of a product. Accordingly, further analysis on product's GDT can lead to another significant aspect of the machining process. The accumulated variations on a geometric attribute of interest, e.g., dimension, location, and orientation can be further confirmed and shows the stack path [89]. The stack, which represent a tolerance chain, the flow of datum chain, is a continuous and shortest series of specified dimension from one feature of interest to another (start and end of stack).

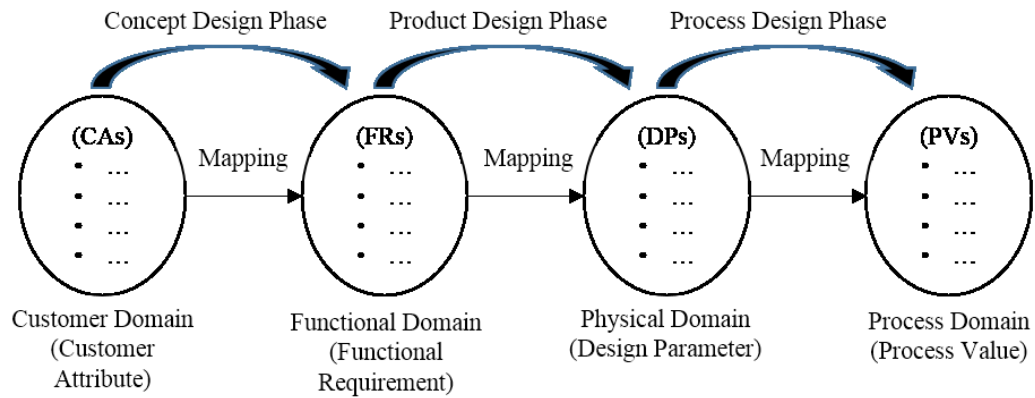


Figure 5-9 The concept of four domain design (Axiomatic Design) [88].

Table 5-3 Characteristics of the four domains in manufacturing [88].

Domain	Manufacturing
Customer Domain	Attributes which consumers desire
Functional Domain	Functional requirements specified for the product
Physical Domain	Physical variables which can satisfy the functional requirements
Process Domain	Process variables that can control design parameters

There are two standards for specifying GDT on product's information, ISO 1101 and ANSI/ASME Y14.5M. The standards have classified dimensional variations (size) and geometric variations (form, orientation, profile, position, and run-out) into classes as shown in Figure 5-10. Furthermore, only several GDTs are eligible to be applied for constructing the MPP, i.e. flatness to control the form factor, all orientation aspect (parallelism, angularity, perpendicularity), and position to control specific feature. The other GDTs are used more for inspection purposes.

As it mentioned in the previous, the tolerance chain between features can be shown clearly by using the product's GDT. Therefore, the MPP generation process is necessary to refer to the corresponding tolerance chain so that it might produce a conformed product shapes. The previous study by Rong [90] has showed the use of GDT in constructing MPP. A feature tolerance graph (FTG) and datum manufacturing graph (DMG) can be constructed to show the relationship of tolerances between features. The related studies by Wang et al. [85] also implemented the FTG and DMG further for automating the workpiece's setup.

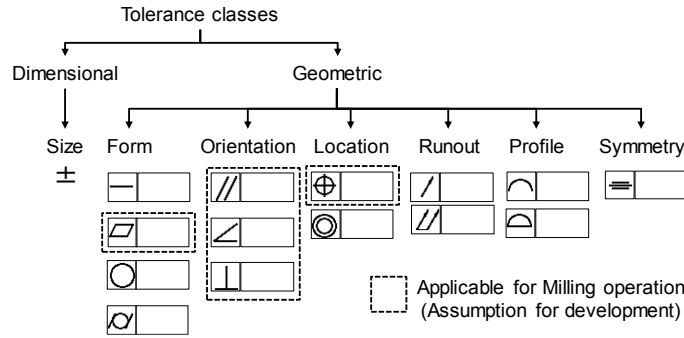


Figure 5-10 GDT's classification (modified from [89]).

5.4.2 The proposed concept of GDT implementation

The algorithm is constructed by adopting the main concept of FTG and DMG. The main difference is a plane will be used for the evaluation unit instead of a feature. From Chapter 3, the VIP constitutes a removal volume and is constructed by using a plane. The corresponding plane can also be maintained as the corresponding machining reference (cutting tool alignment) for each VIP. Therefore, the evaluation of all corresponding planes will be well-assured by incorporating the product's GDT and should be eligible to be used for sequencing the removal process of VIP. The algorithm consists of five steps: (1) collect all reference guides; (2) map all reference guides' properties and relationship; (3) define the datum; (4) group the reference guide into tiers; (5) order the removal process in each tier by using their plane relationship and distance. The elaboration of each algorithm step is based on the product's shape in Figure 5-11. Figure 5-12 shows the example of product's information which is prepared by GDT requirements.

The first stage: collect all reference guides. All reference guides are identified and gathered from all product's faces. It consists of plane and profile. Any inner loops on each face are identified as a profile. Each face will correspond to one plane. The collection of reference guides based on the corresponding product's information can be seen in Figure 5-13.

The second stage: define the datum. All datums need to be defined beforehand. Two types of datum are established in this study, a regular datum (*DT*) and an intermediate datum (*IDT*). The *DT* is a datum that is acquired from the product's information while the *IDT* is a datum that is defined because of the existence of a profile. The *IDT* will be established for reference plane that has a profile without any datum's requirement.

The third stage: map all reference guides' properties and relationship. Each reference guide's properties, e.g. datum definition (*DT* or *IDT*), datum reference (*DTR*), flatness requirement, and remarks will be documented. The *DTR* shows the precedence relationship between reference guides and its datum. The flatness requirement shows the information of a face quality that will be used for evaluating in the

fifth stage. Remarks indicate the existence of profile on and the state of a reference guide. The mapping result is shown in Table 5-4. The reference plane is symbolized by RP_n , while the reference profile is symbolized by RPR_n , with n represents the counter. In Table 5-4, RP_{10} is the candidate for an *IDT*. Several free state reference also can be observed. A free state is the condition of a reference plane that has no requirement of GDT. RP_6 , RP_7 , RP_8 , and RP_9 are the example of the free state reference.

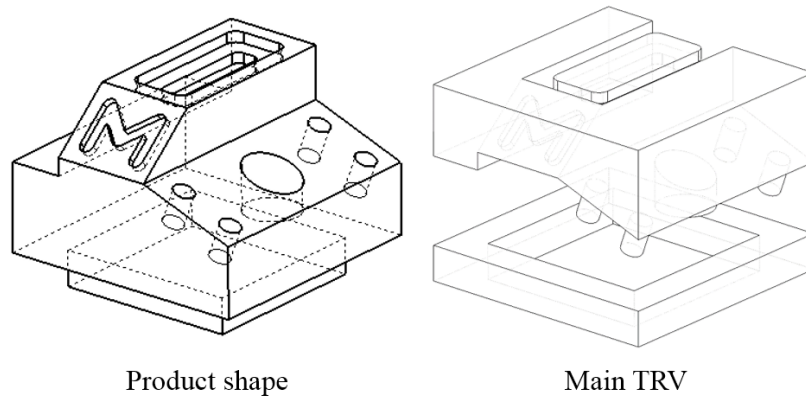


Figure 5-11 Example of the workpiece.

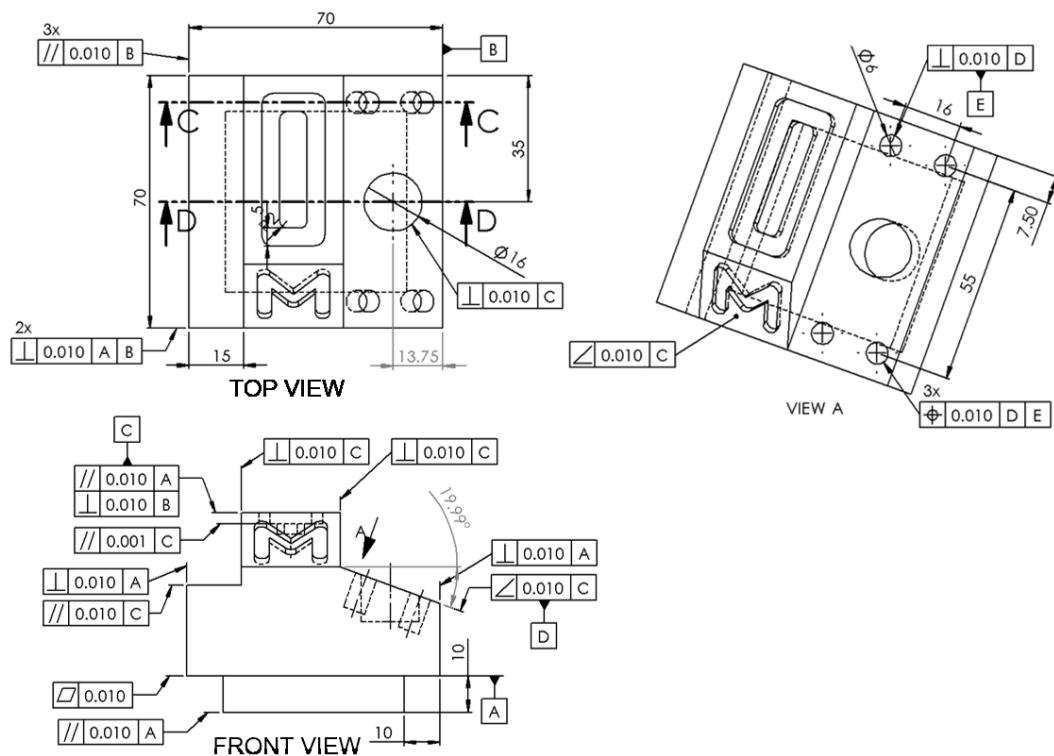


Figure 5-12 GDT on the front, top and auxiliary view.

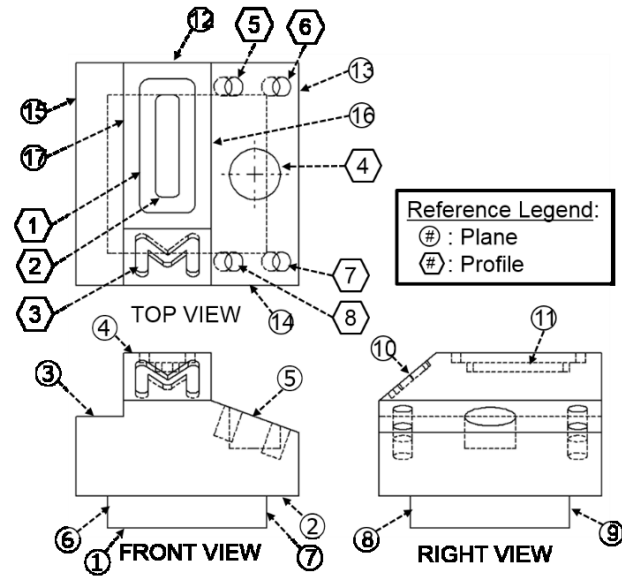


Figure 5-13 The reference (plane and profile) guides for product's shape.

Table 5-4 Collections of reference guides.

Type (RP: Plane, RPR: Profile)	Reference No	Datum (DT)	Intermediate Datum (IDT)	Datum Reference (DTR)	Flatness Requirement 	Remarks
RP	1	-	-	A	-	-
RP	2	A	-	-	Yes	-
RP	3	-	-	C	-	-
RP	4	C	-	A, B	-	Profile exists
RP	5	D	-	C	-	Profile exists
RP	6	-	-		-	Free State
RP	7	-	-		-	Free State
RP	8	-	-		-	Free State
RP	9	-	-		-	Free State
RP	10	-	F	C	-	Profile exists
RP	11	-	-	C	-	Profile exists
RP	12	-	-	A, B	-	-
RP	13	B	-	A	-	-
RP	14	-	-	A, B	-	-
RP	15	-	-	A, B	-	-
RP	16	-	-	B, C	-	-
RP	17	-	-	B, C	-	-
RPR	1	-	-	C	-	Outer Pocket
RPR	2	-	-	C	-	Inner Pocket
RPR	3	-	-	F	-	Letter M
RPR	4	-	-	C	-	Big Hole
RPR	5	E	-	D	-	Small Hole
RPR	6	-	-	D, E	-	Small Hole
RPR	7	-	-	D, E	-	Small Hole
RPR	8	-	-	D, E	-	Small Hole

The fourth stage: group the reference guides into tiers. From the previous stages, reference planes and profiles can be grouped by its *DT* and *IDT* by following the corresponding *DTR* as shown in Table 5-4. The grouping result which is shown in Figure 5-14, can be divided into several tiers and each tier can be observed as a machining stage. These tiers may also display the hierarchy of all datums and its colony of reference planes and profiles. The order of tier shows the priority of its references. For instance, the reference in Tier 1 will need to be processed earlier than the reference in Tier 2, and so on until the last tier. These tiers may also represent the raw form of MPP sequences. The references within the same tier show the candidacy of MPP's route. These references will be evaluated further in the fifth stage.

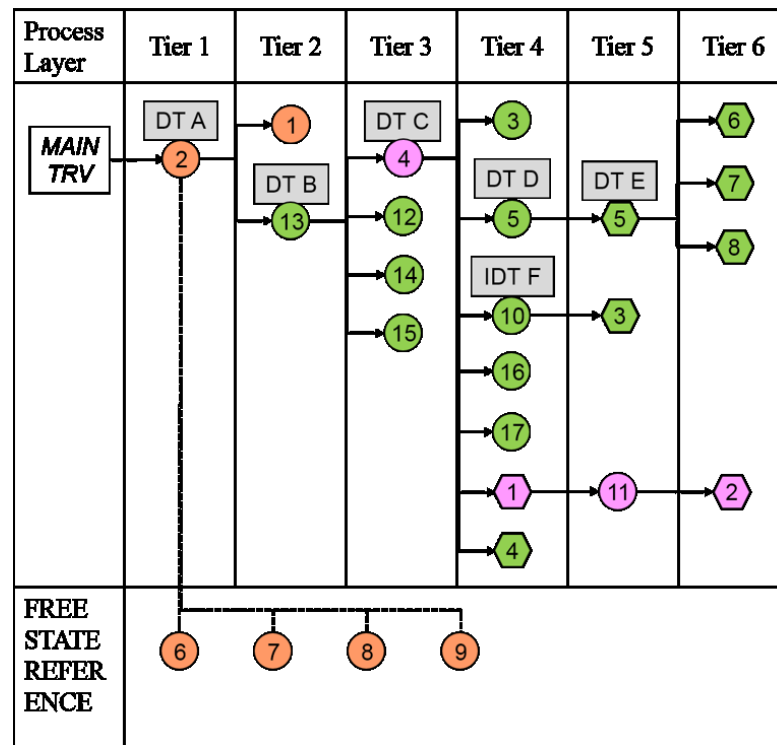


Figure 5-14 The tree of MPP's tiers.

The fifth stage: order the removal process in each tier by using reference plane relationship and distance. In order to reduce the number of routes, only the references which are referred to the same datum or reference, and located within the same tier need to be evaluated. The result of the evaluation can be seen further in Appendix B. The evaluation will consider in five aspects:

1. The reference is suggested to be localized. Therefore, the reference guide which exist within the same VIP body is preferred to be processed earlier to reduce the setup. Figure 5-15 shows the distribution of references to TRV bodies. For example in Tier 2, RP_1 will be treated first because it is located in the same VIP body as shown in Figure 5-15.

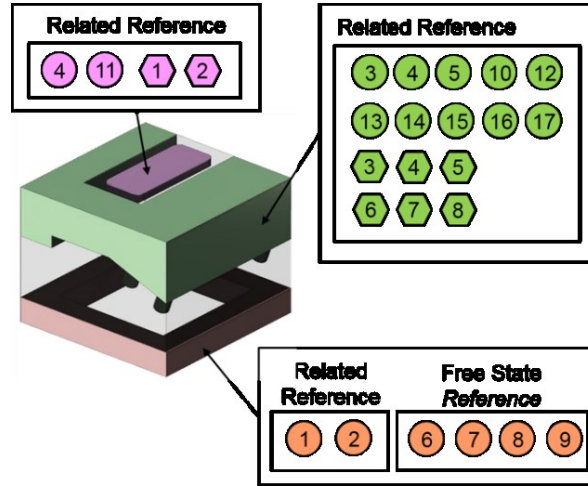


Figure 5-15 The distribution of references on TRV bodies.

2. The reference profile is prioritized. A profile is designed to a particular shape. Therefore, to maintain the accuracy, it is suggested to perform the profile machining right after the required GDT has been completed. For instance in Tier 4, RPR_1 or RPR_4 will need to be processed earlier than other references to maintain the accuracy to RP_4 in Tier 3.
3. The reference with less number of subsequent references is preferred. For instance from the second aspect, RPR_4 will be processed first instead of RPR_1 because it has no successive reference.
4. If two or more reference planes are located on the same VIP, the evaluation is based on the Length-Width-Depth (LWD) evaluation of VIP. The plane which can give lower Depth and larger Length-Width is preferred. The implementation of this aspect is briefly explained in the next subsection.
5. The importance and distance of a reference plane are necessary to consider the accessibility of the cutting tool. Chapter 3 has showed the capability to order the reference planes by using the plane's importance and distance values. Reference planes importance can be defined by calculating the number of intersection with other reference planes. The distance is measured from a centroid point of the corresponding VIP body. The purpose of the fifth aspect is to maintain the selection of process after each aspect can no longer be used for determining the route. For instance in Tier 3, RP_{12} , RP_{14} , and RP_{15} can be configured as three MPP's routes, which can be started by either one of them. In this matter, the fifth aspect is applicable for determining the best configuration of these references.

5.4.3 The advantages of GDT implementation on proposed algorithm

Assurance of tool alignment. From the section view C-C in Figure 5-16, the processing of step feature conflicts if there is no GDT involved. By knowing RP_3 and RP_{17} have an orientation to the same $DT C$, the assurance of having further evaluation by shape's LWD can be trusted. In practical use, the T2 alignment which has a removal volume with a large area of LW and low D is believed to be more

preferable, because a large portion of removal volume can be processed with bigger tool diameter and tool length's limits can be avoided. Moreover, by analyzing the GDT's requirements, associated reference plane can be well-confirmed for each hole's profile. From Figure 5-17, two types of holes are available in the case study. For instance, detail view H show the different of datum for each hole's profile. Therefore, RPR_4 is preferred to be processed right after RP_4 has been completed.

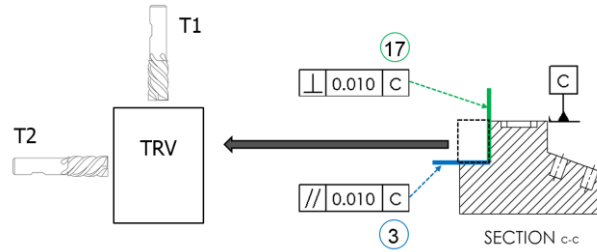


Figure 5-16 The evaluation of LWD based on RP_3 and RP_{17} .

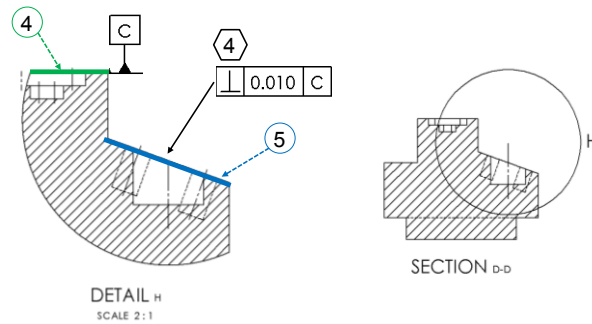


Figure 5-17 The GDT's requirement of RPR_4 .

Better arrangement of removal volume. From the detail view G in Figure 5-18, interacting features are involved. Several configurations can be found for removal volumes. By knowing the reference relationship and GDT's requirement, the interacting features might be well-extracted by considering two profiles RPR_1 and RPR_2 .

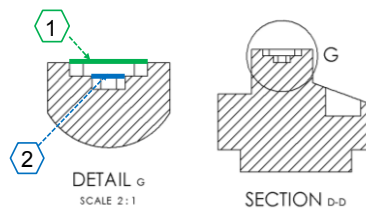


Figure 5-18 The interaction of two profile RPR_1 and RPR_2 .

5.5 Conclusion

In this chapter, the construction of MOP generation based on VIP is discussed. A new evaluation methodology to express the CBR technology is elaborated. The evaluation is performed by considering shape, size, and material aspects are proposed as one of the solutions to evaluate the past machining case data rapidly.

Two form of removal volumes ARV and PRV are also proposed as a new way to maintain an efficient pre-defined feature evaluation. By treating two different kinds of VIP gives the process planner to analyze the VIP more comprehensive to consider another aspect, such as the setup of the product. Moreover, several difficult definition for features can be determined easily without neglecting the necessity control of the corresponding shapes, for example, free-form surface. By this treatment, the pre-defined features in Figure 2-6 might be simplified further which each type will have several ARVs that shares the similar PRV topology characteristics. For instance, OF also implicitly means as the six access directions of XYZ axes to a primitive feature. If based on OF, then square boss, edge boss, corner boss, and square base can be seen as one similar PRV because all of these features have 5 OFs. By these simplifications, we can observe more ARV shapes in the latter stages (manufacturing stage) to elaborate the machining condition properly. However, more study is required. The distinction is mainly to acknowledge that the sequence of VIP is needed to maintain the proper machining condition. In order to realize the smooth information transfer from the design stage to the machining stage, more elaboration on PRV and ARV can be performed differently and to have a useful result of the machining process. Although it might infer that two kinds of the database which consist of PRV and ARV is needed respectively, this might enable the flexibility of data while keep maintains the unique aspect of its topology.

Consequently, the result of the case study shows the robustness of the proposed strategy in constructing the MOP for TRV-based MPP system. Additionally, the NC part program can be generated successfully by using a commercial ESPRIT CAM system in the case study. Further work is still needed to modify the machining information for the cutting condition based on the actual machine tool's performance.

Moreover, from the elaboration of the enhanced algorithm, the GDT requirement on the product's information shows the beneficial use for constructing the removal volumes. The manipulation of reference planes instead of features by utilizing the GDT requirements can simplify the number of reference planes that will be used for finding the removal volumes. The profiles of features can also support the generation of removal volumes. Thus, the proposed concept can show the great benefit to incorporate GDT in maintaining the removal volumes generatively. Practical aspects, the tool alignment, and the removal volumes formation can be well-maintained by integrating the GDT inside the construction of machining process plane based on TRV. Future works are still available for confirming further machining information for the corresponding TRV in each MPP route.

Chapter 6 Conclusion and Future Works

The agile environment of competition between manufacturers has been a great influence on the adjustment of practices on the shop floor. The evolution of CNC machine tools showed the capability to perform a machining operation completely with less human intervention in preparing the NC program. This situation also needs to be highlighted as the next milestone to achieve the intelligent machine tool to provide a comfortable environment which may work autonomously from the design stage to the machining stage. This research proposes a CAPP system to generate MPP, which considers the dynamic of feature development during machining stages. The MPP is developed to be the feeder for supporting the MOP generation which considers a flexibility of shapes in an intelligent framework of machining tool within the shop floor. The automated MPP system is developed for handling the design process translation until preparing the machining conditions.

Chapter 2 contributes to show the prominence and map the requirement of future development on CAPP technologies towards the flexible environment. The early development of each CAPP task, particularly, for metal removal processes, are shown. The broader view of related aspects, e.g. features, logics and example of developed the CAPP system are also shown. The CAPP system has been developing into various kinds of the system to support machining operation. Since the first code system named with MICLASS has existed, the elaboration of CAPP has been diversified into individual elements of macro planning and micro planning to analyze and determine a proper process plan. Several tools are constructed from heuristic to analytical approaches to solve these elements of CAPP. Many heuristic approaches are available, e.g., CBR, OSTs, TRV, but each is limited to solving a particular problem for a machine tool or a type of product. The ICA approach is believed to be the most promising analytical approach to finding the optimum solution compared to GA, SA, and others. However, further studies are still needed to apply it in a practical situation.

Recent CAPP technologies are found to be capable of solving combinatorial problems that involve knowledge of machining resources. However, generated machining process plans are still limited to particular conditions and are not native to machining operations. Structurally, machining process plans can be divided into two main processes: generating process sequences and generating operation conditions. To comply with the requirements of these two processes, the full scale of CAPP systems has evolved into several kinds of information architectural designs. Thus, the knowledge management, and the flexibility of process plan will be the primary issues that need to be covered by future CAPP systems in supporting the machining operations.

Chapter 3 contributes to establish a new of volume in-process (VIP) feature-based unit to escalate the flexibility of a CAPP system in generating an MPP. The VIP feature is intended to become the alternative support for the traditional machining feature to support a flexible environment that may

consist of various or irregular shapes. In this chapter, further study of TRV is performed as the effort to construct the VIP feature which can support the flexible MPP generation. The VIP feature is used for straightforwardly decomposing the initial TRV thoroughly. By using the VIP, the evaluation of TRV cells can be avoided. The flexibility of MPP is shown by the natural and dynamic configuration of VIP which represent the set of available machining reference for the corresponding TRV. The VIP configuration can also be considered as an alternative method to represent a solid model by considering both of the CSG method to represent the solid and the B-Rep method to evaluate of geometric entities. The simple expression of VIP might be promising to be implemented in an autonomous CAPP system design.

Moreover, the succeeding of MPP has been able to be generated from the proposed system. The result showed that by iterating the TRV using its VIP can reduce the number of total configuration of MPP. However, the result still lacks evaluation regarding its requirement to be considered as MPP, which can support a machining operation. Other attempts of evaluation in the succeeding chapter are discussed to apply another objective consideration. The application of several objective considerations is considered to be more reliable in selecting the best MPP.

Chapter 4 contributes to show further evaluation for the candidates of MPP based on the generated set of VIP. The evaluation is based on the total process time which is required for each MPP. Further concept regarding the evaluation of corresponding setup are shown. In order to evaluate its effectiveness, a prototype made to work within a commercial CAD-CAM environment was developed. The current development of the proposed system in this chapter has several advantages:

1. A direct decomposition process by using the machining plane candidates to form VIP was more efficient in estimating the removal volume than traditional decomposition. The use of machining plane relationship has a significant advantage in filtering the important VIP and sequencing them to define machining process plans.
2. The setup evaluation of MPP can be established by checking the generated VIP set thoroughly. Although the estimation was limited only to estimate the colliding position between the tool cone and the table, it shows the possibility of defining machinable positions in earlier stages before it goes into machining operations. Furthermore, the requirement for a successful fixturing process can be planned more conveniently.
3. Each machining process plan can be evaluated and compared with each other to find the best alternative. Alternative process plans can be used to make a fair adjustment and analysis before performing the related machining operation. The flexibility of the machining process plan was gathered and analyzed automatically from the 3D model to support the actual machining. Consequently, the efforts of the planner can be reduced, and the seamless interaction between the CAD-CAM can be defined more clearly.

Chapter 5 contributes to show another possible enhancement of TRV to support the linkage between CAD and CAM to support MOP generation. Two form of removal volumes ARV and PRV are proposed as a new way to maintain an efficient pre-defined feature evaluation. ARV is used for holding the real shape information and useful within CAM operations while PRV is used for holding the estimated geometry information and useful within CAD operations. Both forms are going to be used for providing TRV description to find the corresponding MOP.

By these simplifications, we can observe more ARV shapes in the latter stages (CAM) to elaborate the machining condition properly while keep the necessary information as PRV for data manipulation in earlier stage (CAD). Several difficult definition for features can be determined easily without neglecting the necessity control of the corresponding shapes, for example, free-form surface. Although it might infer that two kinds of the database which consist of PRV and ARV is needed respectively, this might enable the flexibility of data and manage the evolution of shapes while keep maintains the unique aspect of its topology. Consequently, the result of the case study shows the robustness of the proposed strategy in constructing the MOP for TRV-based MPP system. Additionally, the NC part program can be generated successfully by using a commercial ESPRIT CAM system in the case study. Further work is still needed to modify the machining information for the cutting condition based on the actual machine tool's performance.

The last contribution is to investigate further the objective consideration in incorporating the design requirement the decomposition process of VIP. This is to show that the generated MPP can accommodate both roughing and finishing process from at the earlier stages. The GDT is used for representing the design requirements. The manipulation of reference planes by utilizing the GDT requirements can simplify the number of reference planes that will be used for finding the VIP. The proposed concept shows the great benefit to incorporate GDT in maintaining the removal volumes generatively. Practical aspects, the tool alignment, and the removal volumes formation can be well-maintained by integrating the GDT inside the construction of machining process plane based on TRV. Future works are still available for confirming further machining information for the corresponding VIP in each MPP configuration.

Moreover, the different ways of thinking between designers and machining operators can never be changed and will always be a hot issue in implementing CAPP. The natural behavior of humans cannot be altered easily to smooth out the process from designing to machining. This also needs to be highlighted as the next milestone to achieve the intelligent machine tool to provide a comfortable environment from the design stage to the machining stage in one package.

Additionally, the 5th through 8th sequences depicted in Figure 6-1 are still needed to be accomplished to simulate the actual machining and to present the proposed system to work autonomously. The 5th sequence represents the selection process of MPP, so it can be further analyzed in the 6th and 7th sequence to generate the corresponding MOP. The 8th sequence is intended for

managing the distribution of related knowledge of PRV and ARV shapes for further use. Finally, the 9th sequence might dispatch the final configuration of MPP and MOP to further machining module within the intelligent machining tool framework.

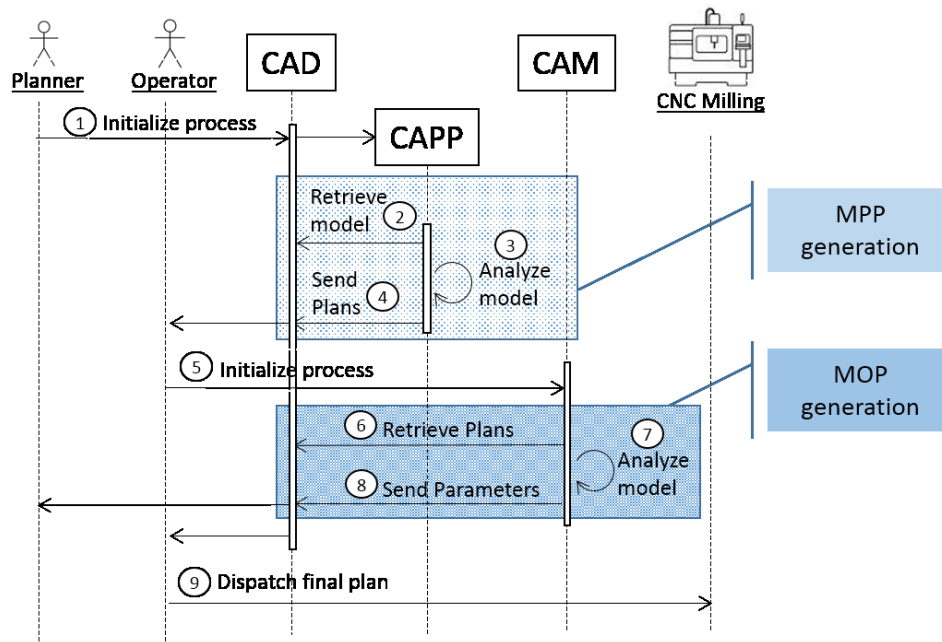


Figure 6-1 CAD-CAM process sequence interactions.

References

- [1] S. K. Chandrasegaran, K. Ramani, R. D. Sriram, I. Horvath, A. Bernard, R. F. Harik, and W. Gao, "The evolution, challenges, and future of knowledge representation in product design systems," *Comput.-Aided Des.*, vol. 45, no. 2, pp. 204–228, 2013.
- [2] B. Babic, N. Nesic, and Z. Miljkovic, "A review of automated feature recognition with rule-based pattern recognition," *Comput. Ind.*, vol. 59, no. 4, pp. 321–337, 2008.
- [3] M. G. Marchetta and R. Q. Forradellas, "An artificial intelligence approach to manufacturing feature recognition," *Comput.-Aided Des.*, vol. 42, no. 3, pp. 248–256, 2010.
- [4] I. Ham and S. C. Y. Lu, "Computer-Aided Process Planning: The Present and The Future," *CIRP Ann. – Manuf. Technol.*, vol. 37, no. 2, pp. 591–601, 1988.
- [5] X. Xu, L. Wang, and S. T. Newman, "Computer-aided process planning – A critical review of recent developments and future trends," *Int. J. Comput. Integr. Manuf.*, vol. 24, no. 1, pp. 1–31, 2011.
- [6] H. J. Steudel, "Computer-Aided Process Planning: past, present and future," *Int. J. Prod. Res.*, vol. 22, no. 2, pp. 253–266, 1984.
- [7] T. Gupta and B. K. Ghosh, "A survey of expert systems in manufacturing and process planning," *Comput. Ind.*, vol. 11, no. 2, pp. 195–204, 1988.
- [8] L. Alting and H. Zhang, "Computer Aided Process Planning: the state-of-the-art survey," *Int. J. Prod. Res.*, vol. 27, no. 4, pp. 553–585, 1989.
- [9] J. Shah, P. Sreevalsan, and A. Mathew, "Survey of CAD/feature-based process planning and NC programming techniques," *Comput.-Aided Eng. J.*, vol. 8, no. 1, pp. 25–33, 1991.
- [10] W. Eversheim and J. Scheewind, "Computer-aided process planning—State of the art and future development," *Robot. Comput.-Integr. Manuf.*, vol. 10, no. 1–2, pp. 65–70, 1993.
- [11] H. A. ElMaraghy, "Evolution and Future Perspective of CAPP," *CIRP Ann. – Manuf. Technol.*, vol. 42, no. 2, pp. 739–751, 1993.
- [12] D. Kiritsis, "A review of knowledge-based expert systems for process planning: methods and problems," *Int. J. Adv. Manuf. Technol.*, vol. 10, no. 4, pp. 240–262, 1995.
- [13] H. C. Leung, "Annotated bibliography on Computer-Aided Process Planning," *Int. J. Adv. Manuf. Technol.*, vol. 12, no. 5, pp. 309–329, 1996.
- [14] F. Cay and C. Chassapis, "An IT view on perspectives of Computer-Aided Process Planning research," *Comput. Ind.*, vol. 34, no. 3, pp. 307–337, 1997.
- [15] H. B. Marri, A. Gunasekaran, and R. J. Grieve, "Computer-Aided Process Planning: A State of Art," *Int. J. Adv. Manuf. Technol.*, vol. 14, no. 4, pp. 261–268, 1998.
- [16] B. Denkena, M. Shpitalni, K. G. Molcho, and Y. Zipori, "Knowledge management in process planning," *Ann. CIRP*, vol. 56, no. 1, pp. 175–180, 2007.
- [17] K. Shirase and S. Fuji, "Handbook of Automation," S. Y. Nof, Ed. Springer, 2009, pp. 837–857.

- [18] T. Moriwaki, "Multi-functional machine tool," *CIRP Ann. – Manuf. Technol.*, vol. 57, no. 2, pp. 736–749, 2008.
- [19] K. Shirase, K. Nakamoto, E. Arai, and T. Moriwaki, "Digital copy milling – autonomous milling process control without an NC program," *Robot. Comput.-Integr. Manuf.*, vol. 21, no. 4–5, pp. 312–317, 2005.
- [20] T. Shimada, K. Nakamoto, and K. Shirase, "Machining Strategy to Adapt Cutting Conditions under Digital Copy Milling Concept," *J. Adv. Mech. Des. Syst. Manuf.*, vol. 4, no. 5, pp. 924–935, 2010.
- [21] T. Hirooka, T. Kobayashi, A. Hakotani, R. Sato, and K. Shirase, "Surface roughness control based on digital copy milling concept to achieve autonomous milling operation," in *Procedia CIRP of 3rd CIRP Conference on Process Machine Interactions*, 2012, vol. 4, pp. 35–40.
- [22] Y. Shinoki, M. M. Isnaini, R. Sato, and K. Shirase, "Machining operation planning system which utilize past machining operation data to generate new NC program," *Trans. Jpn. Soc. Mech. Eng. JSME*, vol. 81, no. 832, pp. 15–00280, 2015.
- [23] S. Igari, F. Tanaka, and M. Onosato, "Computer-aided operation planning for an actual machine tool based on updatable machining database and database-oriented planning algorithm," *Int. J. Autom. Technol.*, vol. 6, no. 6, pp. 717–723, 2012.
- [24] T. Moriwaki and K. Shirase, "Intelligent Machine Tools - Current Status and Future Direction -," in *Proceedings of the 14th International Conference of the Flexible Automation and Intelligent Manufacturing*, 2004, pp. 10–17.
- [25] E. A. Nasr and A. K. Kamrani, *Computer-Based Design and Manufacturing: an Information Based Approach*. Springer Science, 2007.
- [26] M. P. Groover, *Principle of Modern Manufacturing*, 4th ed. John Wiley & Sons, 2011.
- [27] G. Boothroyd and W. A. Knight, *Fundamentals of Machining and Machine Tools*, 2nd ed. Marcel Dekker, 1989.
- [28] J. J. Shah and M. Mäntylä, *Parametric and Feature-Based CAD/CAM: Concepts – Techniques – Applications*. New York: John Wiley & Sons, Inc, 1995.
- [29] R. Jones, S. Mitchell, and S. Newman, "Feature-Based Systems for the Design and Manufacture of Sculptured Products," *Int. J. Prod. Res.*, vol. 31, no. 6, pp. 863–885, 1993.
- [30] X. Xu, *Integrating Advanced Computer-Aided Design, Manufacturing, and Numerical Control: Principles and Implementations*. Information Science Reference, 2009.
- [31] M. Chitroda and S. Sivaloganathan, "Adequacy of machining features for describing machining jobs," *Int. J. Ind. Syst. Eng.*, vol. 2, no. 2, pp. 211–229, 2007.
- [32] S. Somashekar and W. Michael, "An Overview of Automatic Feature Recognition Techniques for Computer-Aided Process Planning," *Comput. Ind.*, vol. 26, no. 1, pp. 1–21, 1995.
- [33] J. J. Shah, "Assessment of Features Technology," *Comput.-Aided Des.*, vol. 23, no. 5, pp. 331–343, 1991.
- [34] H. Opitz, *A Classification System to Design Products*. UK: Pergamon Press, 1970.

- [35] TNO, *An Introduction to MICLASS*. MA, USA: Organization for Industrial Research, Inc, 1975.
- [36] C. C. Gallagher and W. A. Knight, *Group Technology Production Methods in Manufacture*. Ellis Horwood, 1985.
- [37] T.-C. Chang and R. A. Wysk, *An Introduction to Automated Process Planning Systems*. New Jerseys: Prentice-Hall Inc, 1985.
- [38] H.-P. Wang and R. A. Wysk, "Applications of microcomputers in automated process planning," *J. Manuf. Syst.*, vol. 5, no. 2, pp. 103–111, 1986.
- [39] J. Jung and R. A. Ahluwalia, "FORCOD: a coding and classification system for formed parts," *J. Manuf. Syst.*, vol. 10, no. 3, pp. 223–232, 1992.
- [40] C. Emerson and I. Ham, "An automated coding and process planning system using a DEC PDP-10," *Comput. Ind. Eng.*, vol. 6, no. 2, pp. 159–168, 1982.
- [41] S. Subrahmanyam and M. Wozny, "An overview of automatic feature recognition techniques for computer-aided process planning," *Comput. Ind.*, vol. 26, no. 1, pp. 1–21, 1995.
- [42] K. Nakamoto, K. Shirase, H. Wakamatsu, A. Tsumaya, and E. Arai, "Automatic production planning system to achieve flexible direct machining," *JSME Int. J.*, vol. 47, no. 1, pp. 136–143, 2004.
- [43] X. Yan, K. Yamazaki, and J. Liu, "Recognition of machining features and feature topologies from NC programs," *Comput. Aided Des.*, vol. 32, no. 10, pp. 605–616, 2000.
- [44] M. Safaieh, A. Nassehi, and S. T. Newman, "A novel methodology for cross-technology interoperability in CNC machining," *Robot. Comput. Integr. Manuf.*, vol. 29, no. 3, pp. 79–87, 2012.
- [45] X. Zhang, A. Nassehi, M. Safaieh, and S. T. Newman, "Process comprehension for shopfloor manufacturing knowledge reuse," *Int. J. Prod. Res.*, vol. 51, no. 23–24, pp. 7405–7419, 2013.
- [46] B. J. Davies and I. L. Darbyshire, "The use of expert systems in process planning," *Ann. CIRP*, vol. 33, no. 1, pp. 303–306, 1984.
- [47] S. Champati, W. F. Lu, and A. C. Lin, "Automated operation sequencing in intelligent process planning: A case based reasoning approach," *Int. J. Adv. Manuf. Technol.*, vol. 12, no. 1, pp. 21–36, 1996.
- [48] Y. J. Tseng and H. W. Kung, "Evaluation of alternative tolerance allocations for multiple machining sequences with geometric tolerances," *Int. J. Prod. Res.*, vol. 37, no. 17, pp. 3883–3900, 1999.
- [49] J. Ciurana, M. L. Garcia-Romeu, and R. Castro, "Optimising process planning using groups of precedence between operations based on machined volumes," *Eng. Comput.*, vol. 20, no. 1, pp. 67–81, 2002.
- [50] Y.-C. Ho and C. L. Moodie, "Solving cell formation problems in a manufacturing environment with flexible and routing capabilities," *Int. J. Prod. Res.*, vol. 34, no. 10, pp. 2901–2923, 1996.
- [51] M. Shakeri, "Implementation of an automated operation planning and optimum operation sequencing and tool selection algorithms," *Comput. Ind.*, vol. 54, no. 3, pp. 223–236, 2004.

- [52] Y. Zhu, T. Sakaguchi, and K. Shirase, "Study on Automatic process planning support system for integrated milling-turning machine tool," in *Proceedings of International Symposium on Flexible Automation*, 2008.
- [53] E. Morinaga, M. Yamada, H. Wakamatsu, and E. Arai, "Flexible process planning method for milling," *Int. J. Autom. Technol.*, vol. 5, no. 5, pp. 700–707, 2011.
- [54] E. Horowitz and S. Sahni, *Fundamentals of Computer Algorithms*, 1st ed. Springer, 1983.
- [55] W. D. Li, S. K. Ong, and A. Y. C. Nee, "Hybrid genetic algorithm and simulated annealing approach for the optimization of process plans for prismatic parts," *Int. J. Prod. Res.*, vol. 40, no. 8, pp. 1899–1922, 2002.
- [56] X. Zhou, Y. Qiu, G. Hua, H. Wang, and X. Ruan, "A feasible approach to the integration of CAD and CAPP," *Comput.-Aided Des.*, vol. 39, no. 4, pp. 324–338, 2007.
- [57] K. Lian, C. Zhang, X. Shao, and Y. Zheng, "A multi-dimensional tabu search algorithm for the optimization of process planning," *Sci. China Technol. Sci.*, vol. 54, no. 12, pp. 3211–3219, 2011.
- [58] A. Prakash, F. T. S. Chan, and S. G. Deshmukh, "Application of knowledge-based artificial immune system (KBAIS) for computer aided process planning in CIM context," *Int. J. Prod. Res.*, vol. 50, no. 18, pp. 4937–4954, 2012.
- [59] K. Lian, C. Zhang, X. Shao, and L. Gao, "Optimization of process planning with various flexibilities using an imperialist competitive algorithm," *Int. J. Adv. Manuf. Technol.*, vol. 59, no. 5–8, pp. 815–828, 2012.
- [60] X. Wen, X. Li, L. Gao, and H. Y. Sang, "Honey bees mating optimization algorithm for process planning problem," *J. Intell. Manuf.*, vol. 25, no. 3, pp. 459–472, 2012.
- [61] C. R. Liu and R. Srinivasan, "Generative process planning using syntactic pattern recognition," *Comput. Mech. Eng. Vol2*, vol. 2, no. 5, pp. 63–66, 1984.
- [62] T. C. Chang, *Expert Process Planning for Manufacturing*. New York: Addison-Wesley, 1990.
- [63] C. C. P. Chu and R. Gadh, "Feature-based approach for set-up minimization of process design from product design," *Comput.-Aided Des.*, vol. 28, no. 5, pp. 321–332, 1996.
- [64] Y. H. Chen, Y. S. Lee, and S. C. Fang, "Optimal cutter selection and machining plane determination for process planning and NC machining of complex surfaces," *J. Manuf. Syst.*, vol. 17, no. 5, pp. 371–388, 1998.
- [65] R. P. Baker and P. G. Marupoulos, "An Architecture for the vertical integration of tooling considerations from design to process planning," *Robot. Comput. Integr. Manuf.*, vol. 16, no. 2–3, pp. 121–131, 2000.
- [66] R. M. Boogert, H. J. J. Kals, and F. J. A. M. van Houten, "Tool paths and cutting technology in Computer-Aided Process Planning," *Int. J. Adv. Manuf. Technol.*, vol. 11, no. 3, pp. 186–197, 1996.
- [67] D. P. Gupta, B. Gopalakrishnan, S. A. Chaudari, and S. Jalali, "Development of an integrated model for process planning and parameter selection for machining processes," *Int. J. Prod. Res.*, vol. 49, no. 21, pp. 6301–6319, 2011.

- [68] K. Kubota, T. Kotani, K. Nakamoto, T. Ishida, and Y. Takeuchi, "Development of CAM system for multi-tasking machine tools," *J. Adv. Mech. Des. Syst. Manuf.*, vol. 4, no. 5, pp. 816–826, 2010.
- [69] H. C. Lee, W. C. Jhee, and H. S. Park, "Generative CAPP through projective feature recognition," *Comput. Ind. Eng.*, vol. 53, no. 2, pp. 241–246, 2007.
- [70] T. C. Woo and B. F. V. Turkovich, "Visibility map and its application to numerical control," *Ann. CIRP*, vol. 39, no. 1, pp. 451–454, 1990.
- [71] J. K. Kang and S. H. Suh, "Machinability and set-up orientation for five-axis numerically controlled machining of free surfaces," *Int. J. Adv. Manuf. Technol.*, vol. 13, no. 5, pp. 311–325, 1997.
- [72] R. S. Lee, Y. H. Lin, M. Y. Tseng, and W. S. Wu, "Evaluation of workpiece orientation and configuration of multi-axis machine tool using visibility cone analysis," *Int. J. Comput. Integr. Manuf.*, vol. 23, no. 7, pp. 630–639, 2010.
- [73] W. Anotaiapaiboon, S. S. Makhanov, and E. L. J. Bohez, "Optimal setup for five-axis machining," *Int. J. Mach. Tools Manuf.*, vol. 46, no. 9, pp. 964–977, 2006.
- [74] T. Nishiyama, R. Sato, and K. Shirase, *Decision method of workpiece setting based on predicated machinable space of 5-axis machine tool*. 2012.
- [75] S. S. Madurai and L. Lin, "Rule-based Automatic Part Feature Extraction and Recognition from CAD Data," *Comput. Ind. Eng.*, vol. 22, no. 1, pp. 49–62, 1992.
- [76] X. Yan, K. Yamazaki, and J. Liu, "Reverse engineering of machining operation planning," *Int. J. Prod. Res.*, vol. 39, no. 9, pp. 1837–1849, 2001.
- [77] S. C. Feng, "A machining process planning activity model for system integration," *J. Intell. Manuf.*, vol. 14, no. 6, pp. 527–539, 2003.
- [78] F. Tanaka and T. Kishinami, "Geometrical characteristics of machined shape for computer-aided operation planning," *J. Mater. Process. Technol.*, vol. 76, no. 1–3, pp. 109–114, 1998.
- [79] F. J. A. M. Van_Houten, "PART: a computer-aided process planning system," Ph.D. thesis, University of Twente, Netherland, 1991.
- [80] S. Park, "Generating intermediate models for process planning," *Int. J. Prod. Res.*, vol. 44, no. 11, pp. 2169–2182, 2006.
- [81] J. H. Han, M. Pratt, and W. C. Regli, "Manufacturing feature recognition from solid model: a status report," *IEEE Trans. Robot. Autom.*, vol. 16, no. 6, pp. 782–796, 2000.
- [82] TC39/SC2N2003, "Numerical compensation of geometric errors of machine tools," ISO, 2003.
- [83] E. Morinaga, T. Hara, H. Joko, H. Wakamatsu, and E. Arai, "Improvement of computational efficiency in flexible Computer-Aided Process Planning," *Int. J. Autom. Technol.*, vol. 8, no. 3, pp. 396–405, 2014.
- [84] T. Nishiyama, R. Sato, and K. Shirase, "Machinable space derivation of 5-axis machine tool and multi-tasking machine tools for workpiece setting decision," *Trans. JSME*, vol. 79, no. 808, pp. 4543–4552, 2013.

- [85] L. Wang, N. Cai, H.-Y. Feng, and Z. Liu, "Enriched machining feature based-based reasoning for generic machining process sequencing," *Int. J. Prod. Res.*, vol. 44, no. 8, pp. 1479–1501, 2006.
- [86] Y. Shinoki, M. M. Isnaini, R. Sato, and K. Shirase, "Automation of machining operation planning by reconfiguring past case data on machining operations," in *Proceedings of 2014 International Symposium on Flexible Automation*, 2014, pp. 2014–63.
- [87] R. Ohbuchi, T. Minamitani, and T. Takei, "Shape-similarity search of 3D models using enhanced shape function," *Int. J. Comput. Appl. Technol.*, vol. 23, no. 2/3/4, pp. 70–85, 2005.
- [88] N. P. Suh, *Axiomatic Design: Advances and Applications*. New York: Oxford University Press, 2001.
- [89] J. J. Shah, G. Ameta, Z. Shen, and J. Davidson, "Navigating the tolerance analysis maze," *Comput.-Aided Des. Appl.*, vol. 4, no. 5, pp. 705–718, 2007.
- [90] Y. K. Rong, "Process Planning and Scheduling for Distributed Manufacturing," L. Wang and W. Shen, Eds. Springer, 2007, pp. 137–166.
- [91] K. Shirase and K. Nakamoto, "Simulation technologies for the development of an autonomous and intelligent machine tool," *Int. J. Autom. Technol.*, vol. 7, no. 1, pp. 6–15, 2013.

Appendix A

Example of provided cutting tools.

ID	Tool Type	Diameter (mm)	Number of cutting edge
1	End Mill	4	2
2	End Mill	8	2
3	End Mill	10	4

Example of cutting tool selection rule [91].

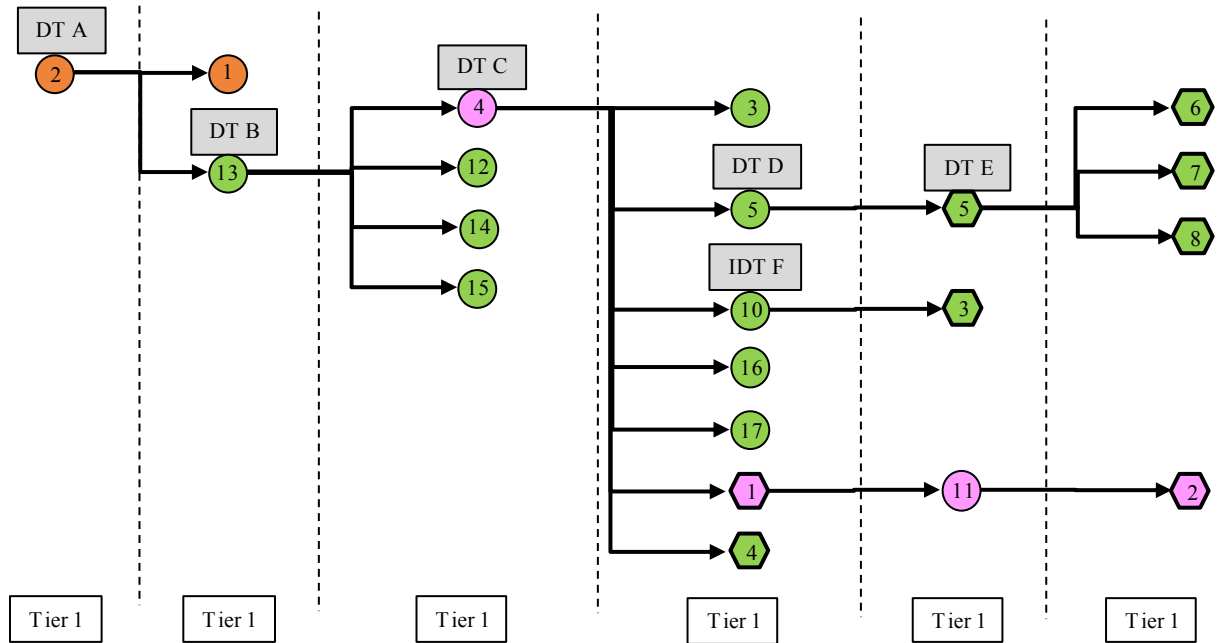
Number of TRV open face	Machining feature reference	Tool selection rule
1	Closed Pocket	End mill with the largest diameter and satisfying $5x \leq l \leq w^*$
2	Closed Slot	End mill with the largest diameter and satisfying $3x \leq w^*$
3	Open Pocket	End mill with the largest diameter
	Open Slot	End mill with the largest diameter and satisfying $3x \leq w^*$
4	Step	Face mill with the largest diameter
5	Face	Face mill with the largest diameter

* x = tool diameter, l = depth, w = width

Appendix B

The iteration process based on GDT's tier map

From Figure 5-14, each tier will consist of the following reference planes and profiles. Each tier can be evaluated further to define the order of reference (machining process) by using five aspects which have been mentioned in Section 5.4.2. The color distinguishes the location of the reference.

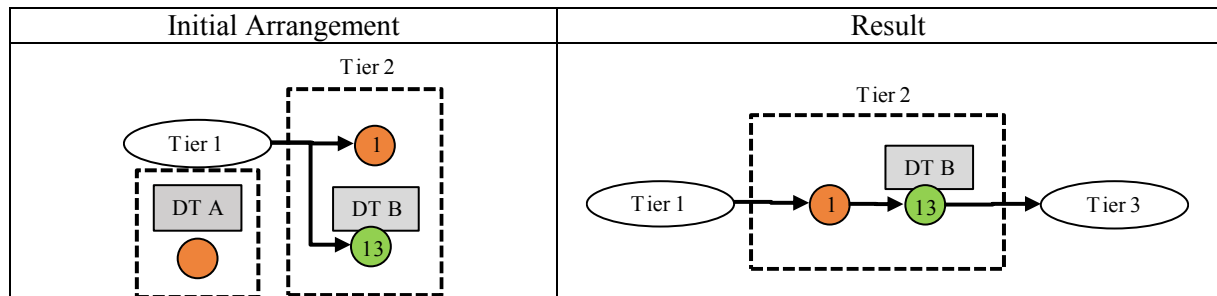


Iteration in Tier 1:

- Iteration was not needed because only one reference is available. Datum A (DT A) is selected among others because there is a flatness tolerance on RP_2 .

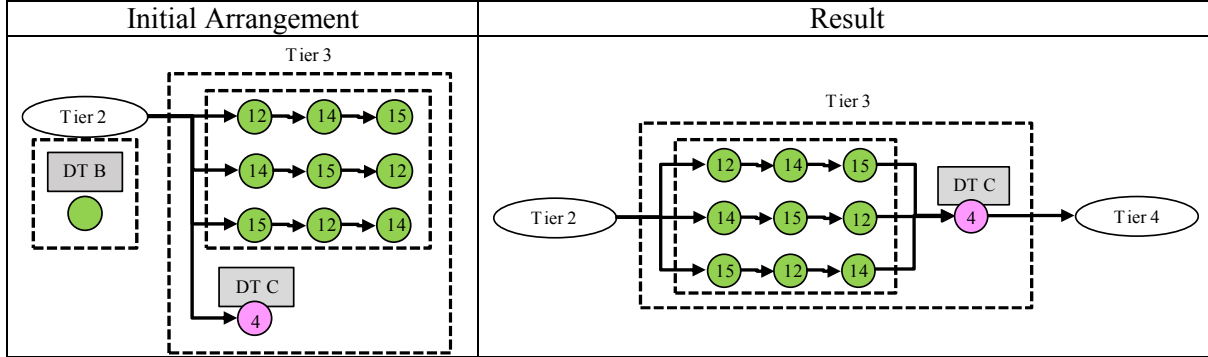
Iteration in Tier 2:

- RP_1 is selected to be the first according to the first aspect. RP_{13} is put at the last process as the remaining reference.



#Iteration in Tier 3:

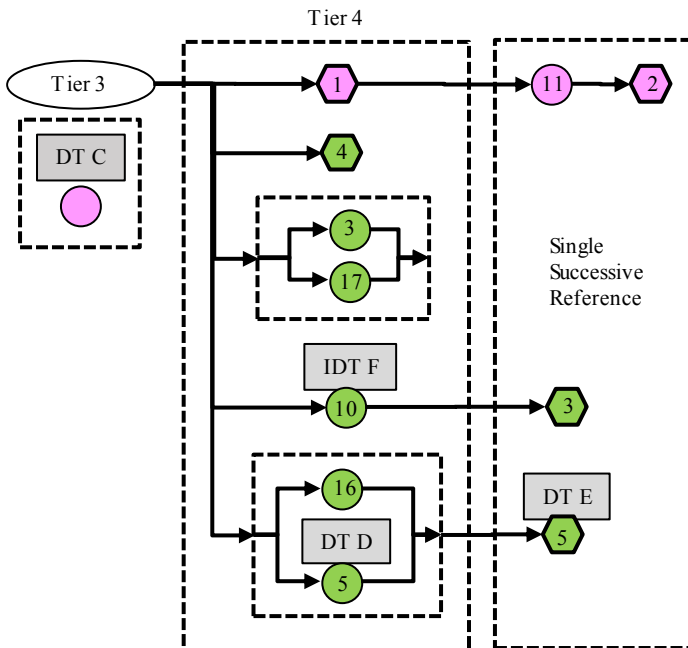
- RP_{12} , RP_{14} , or RP_{15} can be selected as the first process according to the third aspect. Therefore, three alternatives of route can be established: RP_{12} - RP_{14} - RP_{15} , RP_{14} - RP_{15} - RP_{12} , or RP_{15} - RP_{12} - RP_{14} . Further evaluation of these aspect should be made by implementing the fifth aspect. Thus, RP_4 is put at the last process as the remaining reference.



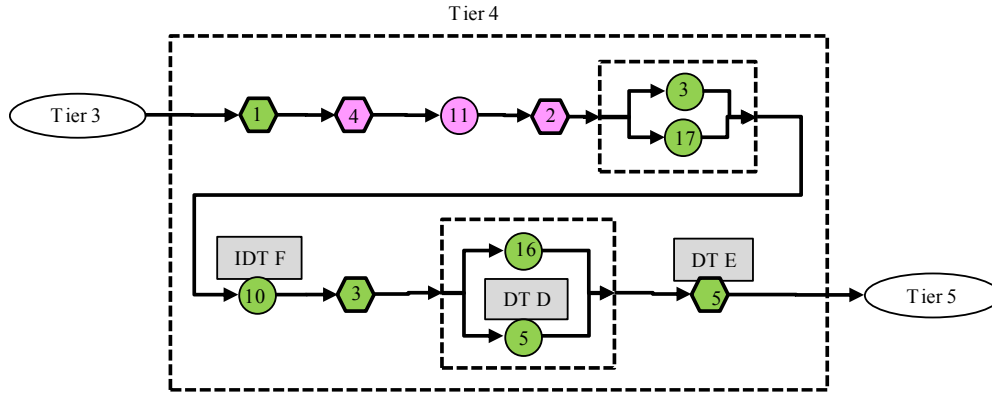
#Iteration in Tier 4:

- RPR_4 and RPR_1 are prioritized according to the second aspect. However, RPR_4 is selected as the first process according the third aspect because it has no other successive reference. RPR_1 is put accordingly as the as the second process. By considering the first aspect, any related single reference, e.g., RP_{11} and RPR_2 , is put accordingly as the next process after RPR_1 .
- RP_3 or RP_{17} can be selected as the next process according to the third aspect. Since RP_3 and RP_{17} are located on the same VIP, the fourth aspect will be needed to evaluate further based on LWD to select either RP_3 or RP_{17} .
- RP_{10} is selected as the following process by considering the third aspect, because no more reference can be found after RPR_3 .
- Lastly, the fourth aspect will be used to evaluate both RP_{16} and RP_5 . Then, RPR_5 is put as the next process by considering the first and second aspects.

Initial Arrangement



Result



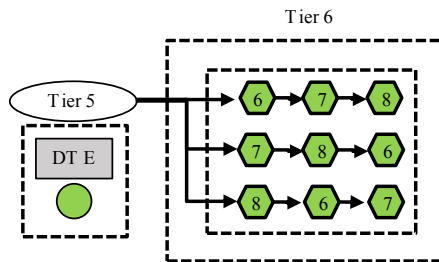
Iteration in Tier 5:

- Iteration was not needed because none of the references are referred to the same datum or reference in the previous tier. All references are independent and were already put into sequence from the iteration in Tier 4.

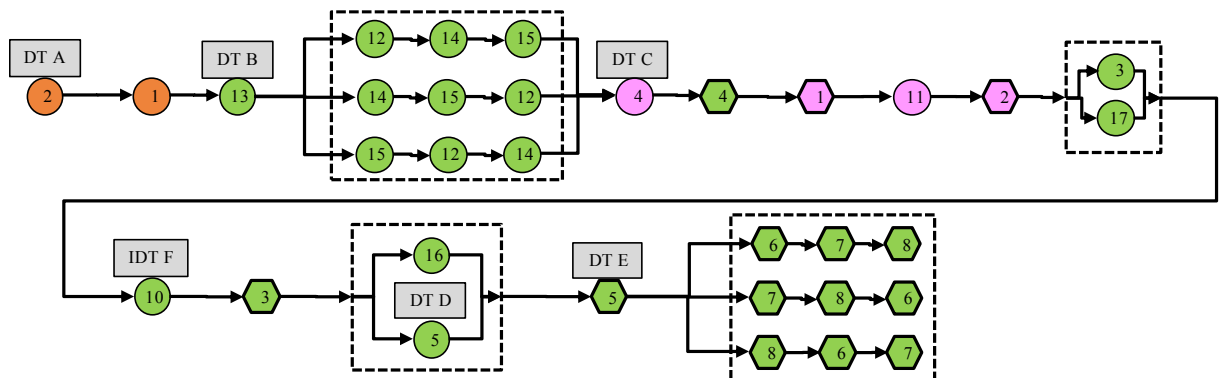
Iteration in Tier 6:

- RPR_2 does not need to be considered because it was already put into sequence from the iteration in Tier 4.
- Lastly, RPR_6 , RPR_7 , or RPR_8 can be selected as the next process according to the third aspect. Therefore, three alternatives of route can be established: $RPR_6-RPR_7-RPR_8$, $RPR_7-RPR_8-RPR_6$, or $RPR_8-RPR_6-RPR_7$. These sequence of profiles can be selected randomly because no other consideration can be found.

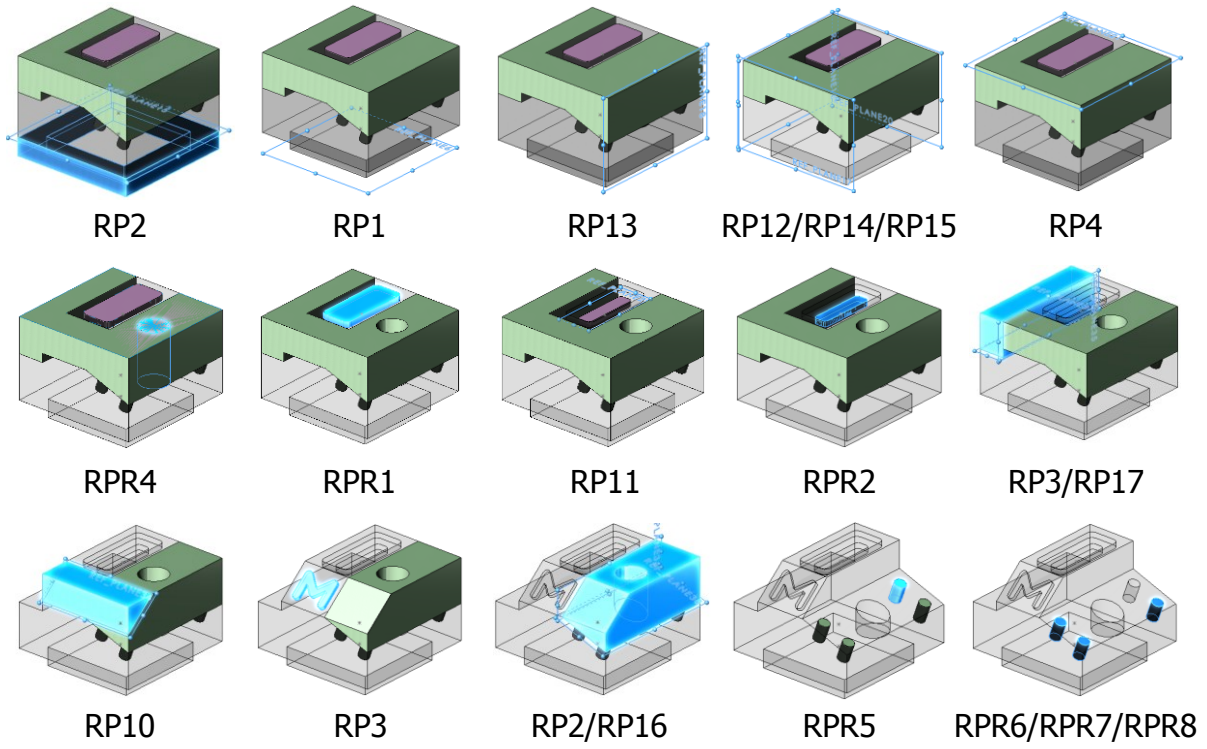
Result



#The final route can be possessed by combining the result from each Tier.



The example of MPP configuration.



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