Computer-Aided Manufacturing Planning (CAMP) of Mass Customization for Non-rotational Part Production

By

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ABSTRACT

This research is aimed at studying the key technologies of Computer-Aided Manufacturing Planning (CAMP) of mass customization for non-rotational part production. The main goal of the CAMP is to rapidly generate manufacturing plans by using of the best-of-practice (BOP) provided by specific companies.

A systematic information modeling hierarchy is proposed to facilitate changes in manufacturing plans according to changes in part design. The Object-oriented Systems Analysis (OSA) approach is used to represent information relationships and associativities in the CAMP. A feature-based part information model, a process model, a setup planning model, and manufacturing resource capability models are established.

A three-level decision-making mechanism is proposed for the CAMP. At the feature-level, combined features are defined based on part families, and a process model is proposed to describe the information associativities between features and their manufacturing strategies, which include customized cutters and toolpaths. At the part level, graph-based setup planning is carried out by tolerance analysis and manufacturing resource capability analysis. At the machine level, multi-part fixtures are utilized to pursue high productivity. Cycle time is used to evaluate manufacturing plans.

Computer software for the CAMP has been developed and integrated with CAD package Unigraphs. The BOP of part families is stored in XML format, which has good extendibility and can be read and edited by standard browsers.

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Chapter 1: Introduction

This chapter gives an introduction of the research – the problem statement, objectives and goal of the research, and the technologies used in the research and overall tasks of computer-Aided Manufacturing Planning (CAMP) for mass customization. The organization of the dissertation is also listed at the end of this chapter.

1.1 Problem statement

In today's advanced manufacturing, investments in automated production machinery and systems have increased steadily. These machines and systems place high demands on manufacturing planning that serves as the bridge between product design and fabrication in order to convert design specifications to manufacturing instructions. Although productivity improves due to increased hardware automation, and quality improves due to increased accuracy and repeatability, the anticipated increase in flexibility and adaptability has not materialized due to the increased preparatory work, most of which is carried out in manufacturing planning activities that must be done before the actual production takes place. The main tasks of manufacturing planning include identifying design information, determining a sequence of manufacturing operations, preparing corresponding manufacturing resources such as machine tools, cutters and fixtures, and generating manufacturing documents and NC codes. These tasks are traditionally done using the experience of the planners and are performed manually. Figure 1.1 shows the roles and issues of manufacturing planning in the production cycle, which is composed of three stages: design, manufacturing planning and production.

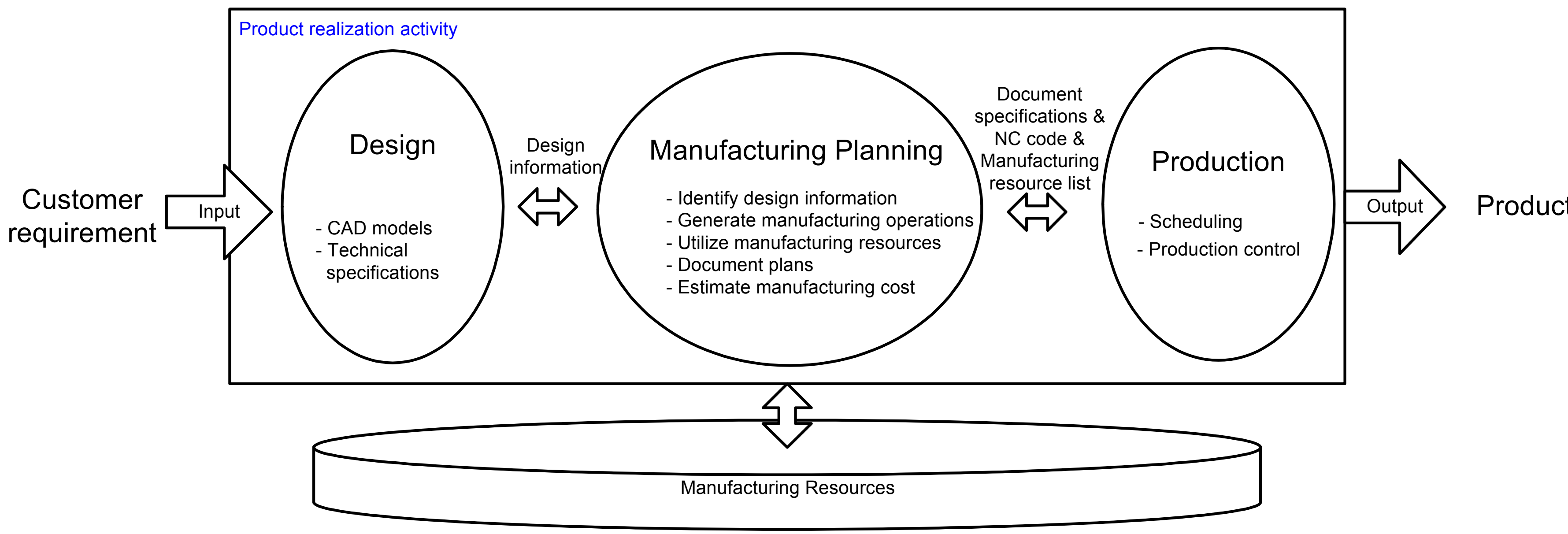


Figure 1. 1 The role and issues of manufacturing planning in the production cycle

Computer technology has greatly impacted the life cycle of products. Currently, Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems have become standard engineering tools that are used in industry. One the other hand, although a tremendous effort has been made in developing CAMP systems in the last three decades, the effectiveness of these systems is not fully satisfactory. CAMP has not kept pace with the development of CAD and CAM. CAMP is also called CAPP (Computer-Aided Process Planning) in other's research work. In this research, the scope of CAMP may be slightly different from other researchers' definitions.

The automation of manufacturing planning activities presents many challenges, since it involves a multitude of conflicting criteria and competing objectives and also requires a great deal of expertise and knowledge, both of which are not easy to model and codify. For example, minimizing product costs and keeping on a tight delivery time schedule is always a dilemma, and it is hard to fulfill these two objectives simultaneously. Hence, some research in CAMP focuses on isolated portions of planning activities, especially on the improvement of manufacturing process performance such as selection of cutters and optimal machining parameters and the generation of optimal cutting toolpaths, etc. Moreover, many advanced techniques and approaches such as feature-based modeling, object-oriented (O-O) programming, graphical user interfaces, expert systems, and databases have been adopted in the research and led to some success. However, several questions in CAMP remain unanswered and many issues must still be resolved.

Hoda stated that the primary reason for the unsuccessful application of CAMP is the lack of correct information models of parts, planning methodologies, manufacturing processes, and resources (1993). There are two aspects to these information models, the conceptual models and the implemented or the computer models. It should be pointed out that finding conceptual models for manufacturing planning is very difficult not only because of the complex interaction between manufacturing planning and other activities in a manufacturing enterprise, but also because of the distinctive challenges of planning within different types of industries.

Another difficulty is the fact that the scope of manufacturing planning is constantly changing, due to the new demands in product development practice. In recent years, a new production mode, mass customization, has been introduced and widely applied in industries (Jiao, 2001). It allows customized products to be made to suit special customer needs while maintaining near mass production efficiency. Compared to conventional mass production, mass customization allows for more product variety in which products are grouped into families. In the design stage, product structures are decomposed into modules by the use of modularity principles. The reuse of certain modules may simplify new product design. In the production stage, the low cost is achieved primarily through the full utilization of manufacturing process capability, in which multi-axis machining centers and multi-part fixtures are widely used. Hence, the difficulty of manufacturing planning in mass customization is greatly increased due to the complexity of manufacturing process capability analysis and utilization. In order to pursue smaller turn-around time and increase the response speed to customer's needs, the modularity analysis in the design stage can be applied to the manufacturing planning stage to finish the total tasks by interrelated modules. Some of the modules, including the planning methodologies and information modeling, are to be realized by the research of the CAMP. The others are designed for specific companies that have accumulated a variety of best-of-practice (BOP). The reuse of planning methodologies and BOP will greatly reduce engineers' workload and increase their planning efficiency. As a result, the study on CAMP of mass customization requires a clear structure of planning tasks, a redefinition of planning methodologies, and the establishment of correct information models, as well as the description and utilization of BOP.

1.2 Objectives and goal

The objectives of the research are to define the tasks of the CAMP of mass customization, to find proper planning strategies and to establish conceptual information models in the CAMP with the consideration of generality and extendibility. The goal of the research is to help develop software that can quickly and accurately generate feasible manufacturing plans in mass customization based on existing BOP. Cycle time is the main factor in mass customization used to evaluate manufacturing plans.

1.3 Task clarification of the CAMP

The research of the CAMP is the extension of CAPP. In addition to the successful technologies used in CAPP such as feature techniques, generative decision-making methodologies, and O-O information modeling methods, the steps of the CAMP are adapted from CAPP; its total tasks are broken down into five sub-tasks, which is shown in Figure 1.2.

1. Feature-based part information modeling

The analysis of part design information is always the starting point of manufacturing planning activities. Feature technology has been proven as a powerful tool to represent part information. A feature is defined to represent the engineering meaning or significance of the geometry of a part (Shah, 1995). For example, a flat surface, a hole, and a chamfer can be treated as features that are represented by geometry information, such as the features' shape, dimension, and also by non-geometry information, such as form tolerances and surface finish. Part information is composed of feature information and the relationships between features, which are described by dimension, position, and orientation tolerances. A Feature Tolerance relationship Graph (FTG) has been used to describe these tolerances.

In the CAMP, the definition of feature is extended to include combined feature, which is defined as a collection of related geometry that as a whole corresponds to a sequence of particular manufacturing processes for creating the geometry. In order to reduce the machining time of a feature, combination cutters and their toolpaths that imply the axis movement of machine tools, are used to machine the surfaces of the feature sequentially. All this information is stored in pre-defined process templates. Hence, process templates are the link between features and the manufacturing resources used to machine the features. The changes in feature may influence the utilization of corresponding manufacturing resources. And adding or dropping a manufacturing resource may change the process capabilities to produce features. The choice of process templates for a feature is called a feature-level decision-making procedure, which depends on the manufacturing resource capabilities of specific companies. In this research, process templates are derived from company-specific BOP and will be represented by the integrated information models in the CAMP.

2. Setup planning

In machining, the combination of different processes to be executed on one machine tool is called a "setup" (Halevi, 1995). Due to the limitation of manufacturing resources, a part may need several setups to finish all machining processes. This decision-making procedure is called part-level setup planning, which is the most critical and the most difficult issue in manufacturing planning. The tasks of setup planning are to determine the number of set-ups, the part orientation on fixtures, and the features and process sequence in each setup. Setup planning and fixture design are two closely related tasks in the CAMP. To setup a part is to locate the part in a desired position on the machine table. A fixture is then used to provide a clamping mechanism to maintain the workpiece in the position and to resist the effects of gravity and operational forces. While setup planning is constrained by the fixtures to be applied, it also provides guidelines for fixture design. The output of setup planning is also used to generate detailed manufacturing plans.

Setup planning is carried out based on tolerance analysis and manufacturing resource capability analysis. It is divided into two steps: feature grouping and setup generation

(Yao, 2003). In general, features that have tolerance requirements are suggested to machine in the same setup to eliminate machining error stack-up. A successful mathematical method of the tolerance analysis of FTG has been applied (Zhang, Y., 2001) to group manufacturing features, and a Datum Machining feature relationship Graph (DMG) has been generated to represent setup planning information. However, the solutions to setup generation are still not satisfactory because only limited manufacturing resource capabilities are considered in the former research, such as 3-axis milling machine tools and standard fixtures. In the CAMP, flexible manufacturing resources are widely used so that more processes can be carried out in one setup to increase productivity; for example, machine motions are controlled in as many as 4-axis with high accuracy, and multi-part fixtures are designed to mount as many parts as possible. Hence, manufacturing resource capabilities become one of the critical factors to influence setup planning strategies. Furthermore, BOP of part families is another factor that affects the setup planning strategies. The expertise and knowledge in BOP include optimal solutions, which have been verified in specific companies, and should be identified and incorporated in the research.

3. Manufacturing resource capability modeling

Manufacturing resources include machine tools, cutters and fixtures, which are provided by many vendors in the marketplace. Manufacturing resource capabilities have been divided into shape capability, dimension and precision capability, and position and orientation capability, which is achieved by the interaction among manufacturing resources used in the production (Zhang, Y., 1999). A mechanism and corresponding information models are needed to describe the manufacturing resource capabilities thoroughly, so that engineers choose manufacturing resources quickly and achieve optimal manufacturing cost.

In the CAMP, the information about the manufacturing resource capabilities is embedded in the part family's BOP, in which manufacturing resources are provided by particular suppliers. Therefore, the relationships between manufacturing resource capabilities, part design, and manufacturing processes should be described explicitly, and corresponding information models should be established. Hence, when a new part design comes, the manufacturing resources designated in the BOP may be quickly adjusted to accommodate the production of new part. Otherwise, alternative manufacturing resources that have the same capabilities as required in BOP can be applied in new part production.

4. Fixture design

In the CAMP, multi-part fixtures are widely used to enhance productivity. Fixture design is divided in two steps: conceptual fixture design and detail fixture design. Conceptual fixture design is a special step in the CAMP, in which only the part layout, the position and orientation of parts on the fixtures, are considered. This is called a machine-level decision-making procedure. The machine tool capabilities are the major constraints that affect conceptual fixture design strategies. The detailed fixture design servers to determine the fixture structure, including the locating and clamping position and selection of fixture components. It is not available in the manufacturing planning stage. Therefore, former fixture designs in the BOP become precious and are used in the conceptual design, based on pre-defined reasoning strategies. As a result, an information model will be established to represent conceptual fixture designs in the BOP and machine-level reasoning strategies. Corresponding algorithms are developed to generate feasible conceptual fixture design solutions.

5. Manufacturing plan generation

The last step of the CAMP is manufacturing plan generation, which determines the selection of machine tools, the process sequence of all parts on the fixtures, and the process parameters. Corresponding global toolpaths and NC code will be generated in this step, with interference checking. Cycle time is the most important factor which influences manufacturing costs in mass customization. The adjustment of process sequence, process parameters, and the global toolpaths may decrease cycle time and increase productivity. Hence, algorithms are developed to generate feasible manufacturing plans, and the company-specific adjustment strategies are incorporated.

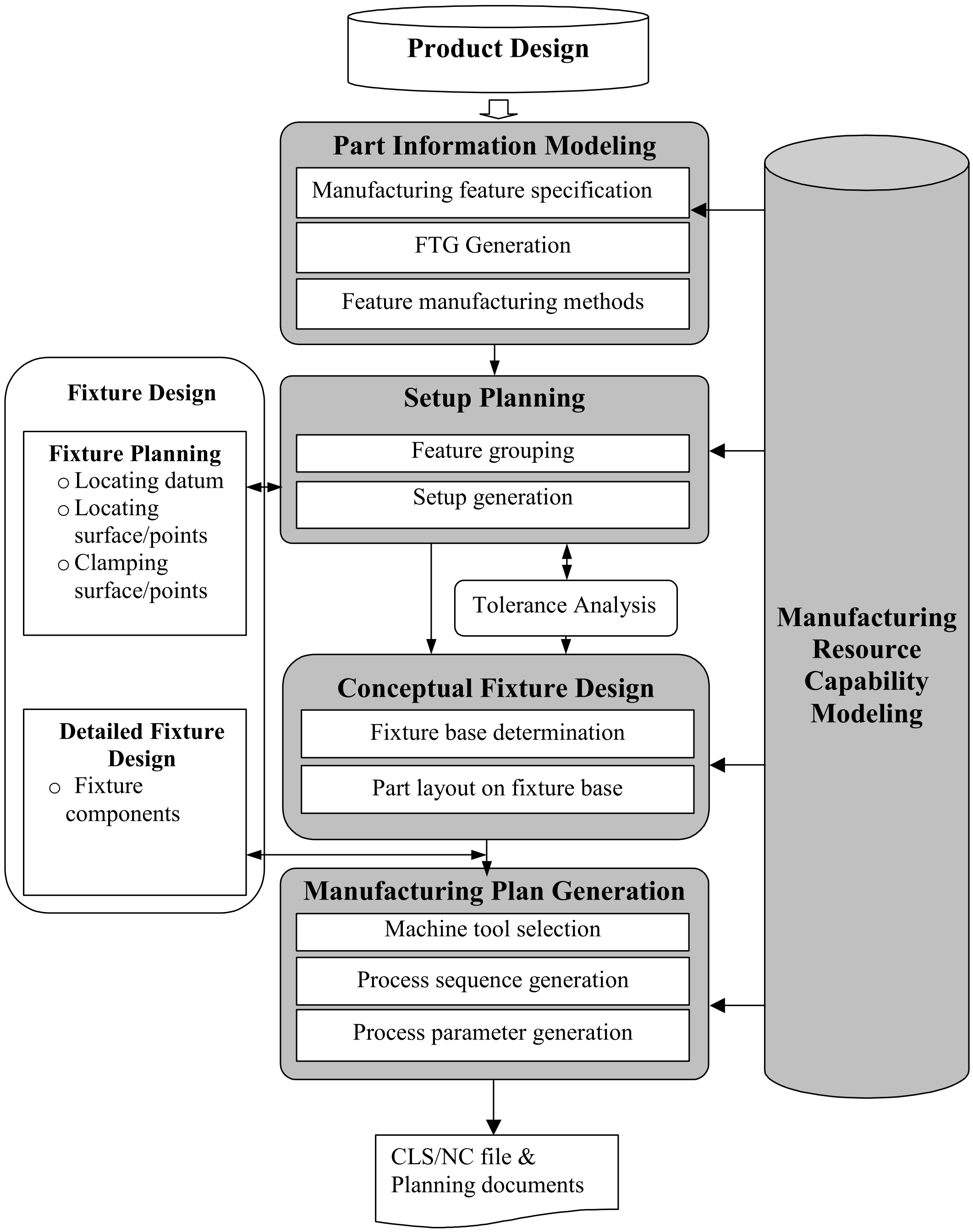


Figure 1. 2 Tasks of the CAMP of mass customization

In summary, the studies on the CAMP include three-level decision-making strategies: feature, part, and machine-level decision-making, and the establishment of information models in each level: feature based part models, manufacturing resource capability models, setup planning models, and conceptual fixture design models. The information relationships among the information models are also discussed so that changes in part design may quickly facilitate the change of corresponding manufacturing plans.

1.4 Technologies and approaches

The quality of the CAMP depends on the efficiency of generating feasible manufacturing planning solutions. Instead of studying all possible areas, this study focuses on two: the establishment of information models that can facilitate the generation of manufacturing plans based on BOP, and the decision-making strategies specifically used in the mass customization.

A systematic information modeling technology is proposed to describe the information relationships and associativities, in which Object-oriented Systems Analysis (OSA) approach is employed to establish the information models in the CAMP. The concept of an object is derived from software engineering and is considered as the computerized representation of entities in the real world. The OSA uses three kinds of models: an Object-Relationship Model (ORM) describes the static characteristics such as information composition of objects; An Object-Behavior Model (OBM) defines the dynamic characteristics of objects; An Object-Interaction Model (OIM) pictures information associativities and interactions between objects.

A three-level decision-making mechanism is proposed for the CAMP. At the feature level, case-based reasoning is applied to get the appropriate manufacturing methods for features, based on the BOP, in which pre-defined cutters and toolpaths are associated with features. At the part-level, setup planning is carried out, based on tolerance analysis and manufacturing resource capability analysis. At the machine-level, the selection of multi-part fixtures, process parameters, and toolpath optimization are completely dependent on BOP. Therefore, BOP is core information in the CAMP, which is also represented in three levels: feature, setup planning, and machine-level. If the BOP does not exist, an analysis and rule-based reasoning mechanism will be applied to generate feasible manufacturing plans.

1.5 Scope

This study focuses on building an overall framework of the CAMP and providing a study of four subtasks: feature-based part information modeling, graph-based setup planning, manufacturing resource capability analysis and modeling, and manufacturing plan generation. Other tasks of CAMP such as tolerance analysis, fixture planning, and fixture configuration design have been identified but have not been studied in this research.

Instead of studying all possible production modes, the realization of mass customization is the main objective of the CAMP. In other word, the special requirement of job, batch, and mass production have not been considered in the research.

In the dissertation, all the research work is focused on non-rotational parts. The production of rotational parts in mass customization has not been included.

1.6 Dissertation organization

This dissertation is organized into five parts, as shown in Figure 1.3:

Part Ⅰ: (Chapters 1-2) Introduction and literature review

- Chapter 1 introduces the background and objectives of the research, the tasks of the CAMP, and key technologies applied in the research, as well the scope of the research.
- Chapter 2 gives a review of earlier studies on CAPP. The existing state-of-the-art has been compared and summarized according to their applied technologies.

Part Ⅱ: (Chapters 3- 7) Study of the key technologies for the CAMP

- Chapter 3 introduces the OSA approach and establishes systematic information modeling hierarchy for the CAMP, based on the analysis of manufacturing information content in the CAMP.
- Chapter 4 discusses feature-level decision-making strategies. Combined features and process models have been studies in depth.
- Chapter 5 models manufacturing resource capabilities. The relationships between manufacturing resources and manufacturing planning activities have been pointed out explicitly. O-O models for machine resources are presented.
- Chapter 6 studies part-level decision-making strategies. Graph-based setup planning has been discussed, based on tolerance analysis and manufacturing resource capability analysis.

- Chapter 7 studies machine-level decision-making strategies. Manufacturing resource capabilities have been extended to multi-part fixtures.

Part Ⅲ: (Chapter 8) System implementation

- Chapter 8 lists the detailed implementation algorithms, software design and case studies,

Part Ⅳ: (Chapter 9) Summary and future work

- Chapter 9 gives a summary of the research.

Part Ⅴ: Reference and Appendices

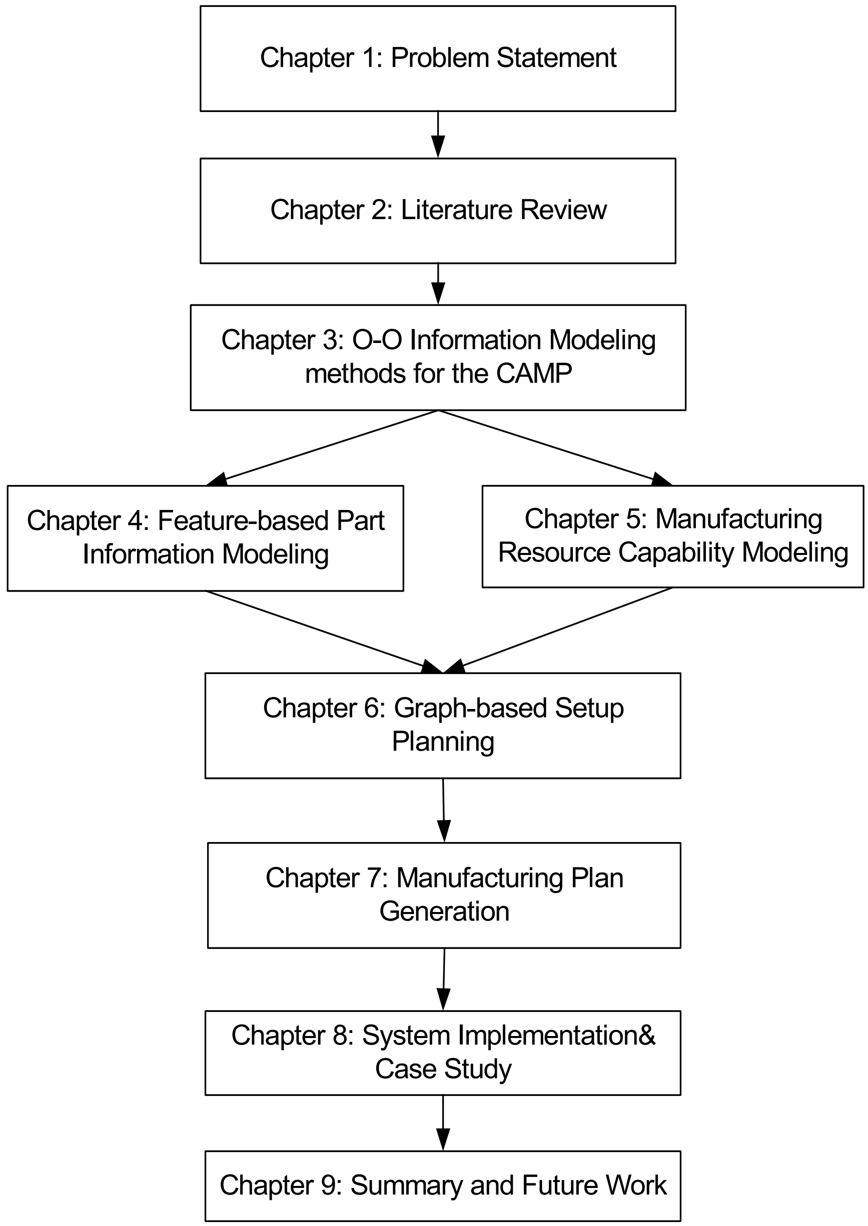


Figure 1. 3 Dissertation structure

Chapter 2: Literature Review

This chapter gives a review of the literature related to this research. Because the CAMP is an extension of CAPP, the research on CAPP is discussed first, including the basic methodologies of CAPP, different viewpoints in CAPP, and the key technologies applied in CAPP. Next, the literature of information technology applied in CAPP is discussed in depth. Last, a summary is presented about the current status of CAPP , including the main contributions in this research of the CAMP.

2.1 Overview of CAPP

Process planning is defined by SME as "the systematic determination of the methods by which a product is to be manufactured economically and completively" (Kamrani, 1995). The initial motivation to develop CAPP systems came from the lack of experienced process planners in 1970s. At that time, it was expected that CAPP could take the place of process planners to automatically generate correct solutions. During the last three decades, CAPP has been applied to a wide variety of manufacturing processes including metal removal, casting, forming, heat treatment, fabrication, welding, surface treatment, inspection and assembly (Honda, 1993). Until recently, research and development efforts have focused on metal removal, particularly in NC machining. The basic tasks of CAPP for metal removal include the following steps (Kamrani, 1995):

- Design analysis and interpretation
- Process selection
- Tolerance analysis

- Operation sequencing
- Cutting tools, fixtures, and machine tool specification
- Cutting parameters determination

The variant and generative approaches are two fundamental methodologies used to develop CAPP systems. The variant approach, which marks the beginning of CAPP systems, is basically a computerized database-retrieval approach. It is based on group technology, classifying and coding parts for the purpose of segregating these parts into family groups (Chang, T., 1998). Standard process plans are stored for each part family. The plans for new parts are derived from the modification of the standard process plans of part families. The major deficiencies of the variant approach are as follows:

- The quality of plans still relies on human planners' experience.
- Adequate classification models, which can provide consistency in classifying and coding parts, are missing.
- It is hard to update existing plans if manufacturing resources are changed.

The generative approach is used to automatically generate plans based on the analysis of part geometry, material, and other factors that may influence the manufacturing decisions (Chang, T., 1998). The need for a part description suitable for automated process planning led to the use of CAD models, mostly with a user's interaction for selecting the features of interest and providing data for planning. The use of knowledge-based systems and artificial intelligence techniques were the next major development in the direction of generative process planning. Examples of knowledge-based CAPP systems, such as

EXCAP, SIPP, Turbo-CAPP, COMPLAN and TVCAPP have been documented by (Alting, 1989) and (Marri, 1998). The generative approach has the advantage of representing and manipulating knowledge and experience effectively in a specific domain to generate feasible solutions. However, it is invariably faced with the problem of exploding search space, when the number of combinations and permutations of choices grows to the point where it takes a prohibitively long time to reach a feasible solution (if any), let alone an optimal solution. A good combination of algorithmic procedures and heuristics are essential for obtaining a good process plan.

2.1.1 Mass customization

Through the use of variant and generative approaches, a large number of CAPP systems have been developed (Cay, 1997). But the effectiveness of these systems is not fully satisfactory. This situation has led to some doubt about the current state of the research and the implementation of process planning. As stated by Prof. Honda, the primary reason for this dilemma is the lack of correct models for parts, planning methodologies, processes, and equipment (1993). Furthermore, the scope of process planning is constantly changing due to new demands in product development practice. Hence, it is hard to design a clear structure of process planning tasks and establish the corresponding models.

Shah's summary of the perspectives of the overall development of CAPP systems (1995) is shown in Figure 2.1. Each coordinate axis has a strong influence on the architecture of CAPP. The meanings of the four coordinate axes are as follows:

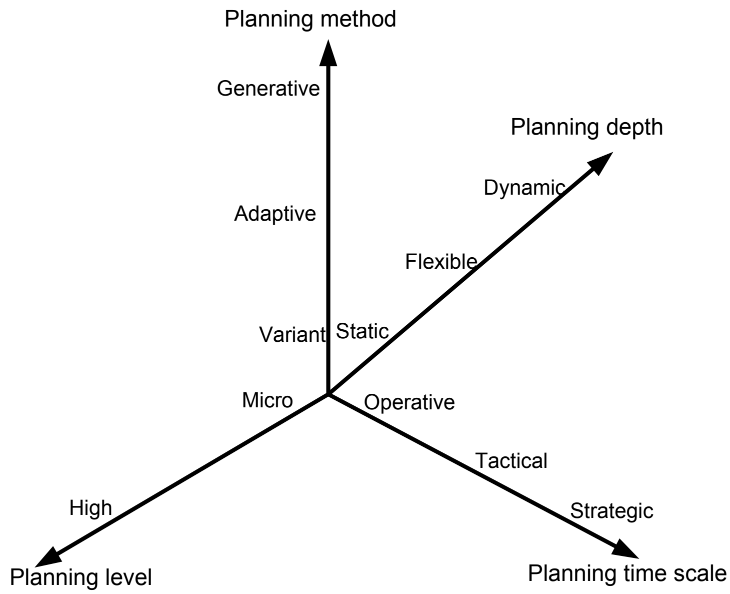


Figure 2. 1 Four-dimensional frameworks for CAPP

- *Planning level*: Planning may be performed either on a high level, which focuses on the overall selection of rough production strategies, or on a low level that increasingly concentrate on particular processes, such as the determination of cutting parameters, process sequences, cutters, machine tools, and other manufacturing resources.

- *Planning time scale:* The planning time scale can range from short-term planning of a certain production to long-term development of the entire production facilities. Short-term planning is more concerned with manufacturing operations at the shop-floor level, for example, processes, process sequences, and manufacturing resource utilization. Medium-scale planning is based on cost, quality, and process capability, while long-scale planning is carried out at the company level to control the total production activities of a manufacturing company. The material planning, production technology, machine cell layout, and production system capability are considered in this scale.

- *Planning methods:* Variant and generative approaches are two basic approaches of the decision-making strategies. Some systems use hybrid decision-making strategies, which utilize both variant and generative approaches (Cay, 1997).

- *Planning depth:* The generated plans can be treated as fixed or variable according the shop-floor scheduling systems. If a system uses a static planning, the plans cannot be modified after being generated. For flexible planning, rough plans without actual manufacturing resources, are created off-line. It is the shop-floor schedulers who carry out the final detailed on-line planning and the choice of manufacturing resources. Dynamic planning can change results during the manufacture of parts according to the dynamic state of manufacturing systems.

In addition to the above perspectives of CAPP, it is found that the production mode is another important factor that affects the study of CAPP (Yao, 2003). Besides the three conventional production modes, mass production, job production, and batch production, a new production mode, mass customization, has been introduced into industries to allow customized products to be made to suit special customer needs while maintaining near mass production efficiency. Currently, most of the research focuses on job and batch production, whose objectives are to produce customized parts while trying to maintain minimum manufacturing cost by using of standard cutters, fixtures and machine tools. Little effort has been focused on the planning methodologies of mass production because the manufacturing operations, transfer line machines, and dedicated fixtures used in the operations are designed for particular parts and have little flexibility to accommodate

Table 2. 1 Characteristics of manufacturing planning in different production modes

(For medium size and small size part production)

	Job production	Batch production	Mass production	Mass customization
Volume	<100/year	100- 5000/year	>5000/year	100- 8000/year
Product variety	Large	Medium (Parts are grouped into families)	Small	Large (Parts are grouped into families to reduce the variety)
Machine tool	General machines	General or special machines	Special machines	CNC machines
Machine layout	Function based layout	Manufacturing cells	Transfer lines	CNC machines or Manufacturing cells
Fixture	General fixtures or modular fixtures	Dedicated fixtures	Dedicated fixtures	Dedicated fixtures for part families
Cutter	General cutters	General or special cutters	Special cutters	Special cutter designed to machine multiple surfaces
Product repeat rate	Little	By batch	Continuous production	By batch
Productivity	Low	Medium	High	High
Cost per part	High	Medium	Low	Low (approaches to mass production cost)
Cycle time	Long	Medium	Short	Short
Turnaround time	Short	Medium	Long	Short

Note: Turn around time means the time that is needed to adjust manufacturing systems from a specific part production to another part production. Cycle time is the total time to machine a part.

changes in product designs. In fact, it is hard to conduct a study on mass production. Mass customization is considered a synthesis of mass production and individually customized production; it is expected to accommodate more design variation within a family of products. Table 2.1 shows the major characteristics of the above production modes.

The notion of “mass customization ” was first proposed by Kotler from a marketing management perspective (1989). Pine brought mass customization into the production areas (1993). Some research has been carried out on product design, but few pay attention to manufacturing planning for mass customization. Six types of modularity for mass customization have been defined to simplify product design by reusing certain design modules (Magrab, 1997). Tseng proposed a unifying product platform to describe product family architecture, by which previous product design is stored in the hierarchies and represented in an O-O fashion (1997). Jiao pointed out that the fundamental concern regarding the product design and manufacturing platforms for mass customization is that the company must optimize external variety versus internal complexity that results from product differentiation (2003). External variety comes from customer preferences and is reflected in product design, while internal complexity is associated with a company’s process capabilities, especially on the utilization of manufacturing resources. An important step toward establishing manufacturing planning platforms for mass customization is the development of planning methodologies that provide easy access to information in the previous manufacturing plans. Due to the similarity/commonality among production systems or among specific customized products, reuse suggests itself as a natural technique to facilitate increasingly efficient and cost effective product development. That is, a new manufacturing plan that reuses a previous plan at some level or to some extent should be less expensive to develop than a plan that is designed from scratch. By reusing prior plans, an engineer can save design time and cost by leveraging off previously worked-out solutions.

2.2 State-of-the-art in CAPP

Currently, most of the research on CAPP focuses on feature technology and feature manufacturing strategies, setup planning, manufacturing resource modeling and fixture design. Therefore, the research in these four areas is discussed in depth.

2.2.1 Feature technology and feature manufacturing strategies

Part information includes geometry information and design specification information (tolerance, surface finish, etc.), which either come directly from part CAD models or neutral files (STEP, IGES, etc) generated by CAD packages. In variant CAPP, part information is represented by GT codes. There are some commercial coding systems in the marketplace (Chang, T., 1998). In generative CAPP, a comprehensive description of part CAD models and design information is needed. Feature technology is well known as a successful tool to represent part information (Shah, 1995). There have been two main methods of representing features: the superficial approach, in which features are defined as sets of surfaces having topological relationships, and the volume approach, in which volumes are used to define features (Park, 2003). By the use of graph theory, part information can be represented by a FTG, in which parts are composed of features, and design specifications are described by the relationships between features (Zhang, Y., 2001).

A feature's manufacturing strategies are defined as the candidate routines of processes to manufacture the feature. The major factors that affect process selection are (Yu, 1993): (1) material factors; (2) part geometry factors, such as part shape, tolerances and surface finish; (3) and production factors, including time to market, production quantity, and production rate. Feature manufacturing strategies are represented in two ways. One is associating a list of candidate processes to a feature type. The other is associating features with a process type that can machine these features (Naish, 1996). Both methods define a strong relationship between features and processes, in which cutters and machine tools are described in details (Gaines, 1999). Hence, if a new feature type or process type is added, related feature manufacturing strategies should be redefined. Moreover, if cutters or machine tools in a company are changed, all the processes that use these cutters or machine tools have to be updated. The maintenance work is huge and time-consuming.

Some efforts have been made to capture the fundamental characteristics of machining processes and establish an abstract machining process model to link features and their processes (Tanaka, 2000). Only the cutter type and the machine tool's feed motion are considered in the study, and limited feature types are included.

2.2.2 Setup planning

The objective of setup planning is to determine the number of setups needed, the orientation of parts and the machining process sequence in each setup. In the research of setup planning, the analysis on part information is always the starting point. Currently, graph-based representation has been recognized as an effective tool to describe the many-to-many relationships in part information and setup planning. A hybrid graph that contains both directed and undirected graphs was introduced to represent feature relationships. A tolerance factor was developed to compare different tolerances (Zhang, H., 1999). Britton presented a generic graph representation scheme for setup planning, in which relationships between cut, datum surfaces, and machining operations are represented by a graph consisting of connected boxes. Each box represents a machine setup, and machining operations are depicted as arrows inside the box (2002). Zhang, Y. used extended directed graph, including a FTG and a DMG, to represent part design tolerance specifications and operational tolerance relationships based on true positioning datum reference frames (2001). Through the use of graphs, it is easy to track the tolerance generation routines among manufacturing processes.

In addition to tolerance analysis, feature orientation, precedence constraints, kinematic analysis and force analysis have been considered in setup planning (Huang, 2002). Several methodologies and algorithms have been proposed for setup planning, including a graph-matrix approach for rotational parts, based on tolerance analysis (Huang, 1997); a hybrid-graph theory, accompanied by a matrix theory to aid setup plan generation that was carried on a 3-axis vertical milling center (Zhang, H., 1999); an approach for setup planning of prismatic parts with Hopfield neural networks, where the algorithm converts the feature sequencing problem to a constraint-based traveling salesman problem (TSP) (Chen, 1998); and a graph-based analysis and seven setup planning principles defined to minimize machining error stack-up under a true positioning GD&T scheme (Zhang, Y., 2001). In all these strategies, limited manufacturing resource capabilities have been considered. It is hard to generate feasible setup plans when multi-axis CNC machines and multi-part fixtures are used, especially in mass customization. Furthermore, setup planning and fixture design are two closely related tasks. Fixtures are used to provide some kinds of clamping mechanism to maintain a part in a specified position and to resist the effects of gravity and operational forces. Hence, setup planning is constrained by the fixtures to be applied. But most researchers circumvent this problem by focusing on either setup planning or fixture design (Huang, 2002).

2.2.3 Manufacturing resource modeling

Manufacturing resources include machine tools, cutting tools, and fixtures. Currently, supplier-based manufacturing is widely adopted so that planners have considerable choices of manufacturing resources to finish manufacturing plans. How to evaluate a candidate manufacturing resource's capabilities has become one of the critical factors in reducing manufacturing costs in mass customization. Most of the research has paid attention to the management of manufacturing resources and realized it through relational database management systems (RDBMS) (Chang, T., 1998), which is very weak in describing manufacturing resource capabilities. Several O-O manufacturing resource models were established to express the relationships between manufacturing resource capabilities and feature attributes (Zhang, Y., 1999). However, an applicable methodology is still not available that can give a proper evaluation to the enormous manufacturing resources in the marketplace.

2.2.4 Fixture design

Within the research of manufacturing resources, a lot of effort has focused on fixture design. The objective of fixture design is to generate fixture configurations to hold workpieces firmly and accurately during manufacturing processes. Previous work has been focused on automatic modular fixture design, which utilizes standard fixture components to construct fixture configuration (Rong, 1999), dedicated fixture design with pre-defined fixture component types (An, 1999), variation fixture design for part families (Rong, 2002), and fixture design verifications (Kang, 2002). All the fixture designs in the above research are intended to hold one workpiece on one fixture. However, multi-part fixtures are widely used to achieve optimal cycle time in mass customization. Thus, more research work is needed on fixture design for mass customization, including fixture base selection/design, optimal part layout on fixture base, and multi-part fixture configuration. Accordingly, the tasks of manufacturing planning need to be added to determine optimal process sequence to machine the manufacturing features of all the parts on a fixture and to determine an optimal toolpath to machine all the features, according to the process sequence. Currently, no research is available in this field.

Through the review of the state-of-the-art in CAPP, we can find that it is so important to establish appropriate information models, including the models for part information, processes, manufacturing resources, and decision-making methodologies. It is necessary to review the existing information technologies with the consideration of the specific requirement of manufacturing enterprises.

2.3 Information technologies used in CAPP

Two information technologies have been applied in the CAPP: information modeling technology and decision-making technology.

2.3.1 Information modeling technologies

Information models are data structures that represent information contents. A large amount of information in manufacturing planning needs to be computerized so that CAPP systems can manipulate them. All this information is identified and represented by information models. There are basically four categories of information in the CAPP:

- Design information

  Design information is the input of CAPP. Generally, part information, including part geometry information, tolerance information, functional information, and production information (production volume, material), are analyzed and represented in CAPP systems (Shah, 1995).

- Manufacturing resource information

Manufacturing resources may include cutting tools, machine tools, fixtures, and inspection tools. Some of them are standard tools and readily available. Others are designed specifically for particular processes used in manufacturing plans.

- Manufacturing knowledge

Manufacturing knowledge is the constraint to help engineers make the right decisions. It is composed of general manufacturing rules and best practice knowledge that is summarized by manufacturing industries.

- Information generated by CAPP systems

The result generated by CAPP systems also needs to be described by information models. This consists process information, including the utilization of manufacturing resources and process parameters, setup information, and manufacturing planning information.

Several information models have been provided for representing and storing the above information. Group technology and coding systems were applied to represent part design information by fixed-length codes or flexible-length codes (Teicholz, 1987). These codes were used to group parts into part families that link with standard process plans; Graphs were utilized to describe part and setup planning information (Shah, 1995) (Zhang, Y., 2001); Decision tables and decision trees were used to computerize the decision-making procedures that incorporate manufacturing knowledge (Chang, T., 1998); Relational databases were employed to store part design and manufacturing resource information. The O-O modeling technology has received much more attention since 1990. It was good at representing logic relationships for real-world entities and had excellent flexibility, incremental system development and reusability. O-O technology has been applied in all aspects of CAPP, which include O-O product models (Usher, 1996), O-O databases for machining operations (Chep, 1998), O-O case-based process planning (Marefat, 1997), and O-O manufacturing resource modeling (Zhang, Y., 1999). All these research focused on the representation of static relationships in CAPP such as information composition, but little study is available of describing the dynamic relationships such as information interaction or associativity in CAPP, for example, how the change in part design influences the manufacturing planning strategies and the utilization of manufacturing resources is not discussed.

2.3.2 Decision-making technologies

The knowledge used in CAPP is represented either by cases (cased-based reasoning) or by sets of manufacturing rules (rule-based reasoning). Cased-based CAPP (Marefat, 1997) can retrieve previous experiences stored in CAPP systems, modify the old solution for new parts, and abstract and store the newly generated solutions in CAPP systems. Therefore, the process plan generated is based on existing experience. While rule-based CAPP generates process plans from scratch by the use of manufacturing rules that come from manufacturing companies. There are several advantages for case-based systems over rule-based systems, including the following:

- Case-based systems have the ability to become more efficient by abstracting and storing previous solutions and reusing these solutions to solve similar problems in the future. A rule-based system will always generate solutions from scratch, duplicating previous solution efforts.

- Case-based systems have the ability to learn from their mistakes, once a solution is corrected and stored as a case. A rule-based system will repeat mistakes until its rule base is updated with new rules.

However, rule-based systems do have an advantage over case-based systems: easy maintainability. When manufacturing resources change in a company, or the CAPP systems are applied in another company, it is really hard to update corresponding cases in a case-based system. If the system is a rule-based system, only corresponding rules are needed to be updated.

2.4 Summary of current research

As a result, the current state-of-the-art technologies suffer some major limitations that can be discussed at three levels:

At the feature level, features and their manufacturing strategies are restricted to pre-defined format. The difficulty in the application of current feature-based part information modeling is two-fold: (1) Due to the use of combination cutters in mass customization for a part family, a more complicated feature shape can be achieved in one process. Therefore, the definition of the feature must be adjusted to accommodate such a case; (2) the lack of a facility that allows new features, new cutters and machine tools to be added without additional programming effort.

At the part-level, setup planning lacks a mechanism that takes in consideration both tolerance relationships and flexible manufacturing resource capabilities. Without such a mechanism, realistic setup plans cannot be generated for mass customization.

At the machine-level, simple or limited machining environments are designed for handling planning tasks within rather simple manufacturing resources. No research can deal with multi-part fixtures and the corresponding global process generation.

This dissertation offers a comprehensive study on the CAMP for mass customization. (1) Through analysis of the information relationships among the part design, the processes, and the manufacturing resource capabilities, it enables that new features, processes, and manufacturing resources can be added and utilized in the CAMP without extra programming work. (2) More flexible machine tools and fixtures are considered in the research, and part-level setup planning are carried out based on tolerance and manufacturing resource capability analysis for the real manufacturing environment of mass customization. (3) Also in this work, the BOP of part families is divided into three levels and incorporated in the CAMP so that manufacturing plans of new parts can be generated based on BOP of specific part families. Table 2.3 shows a summary of existing research work and the research work in this dissertation.

Table 2. 2 Overview of the dissertation research

Tasks	Previous work	Challenge in previous work	Dissertation research
Feature-based part information modeling	Feature definition is well done. Part information is described by FTG.		Combined feature definition is provided based on part families
Feature manufacturing strategies	The associativity between feature and its specific manufacturing methods has been established.	The associativity is represented as a many-to-many relationship between a feature and the cutters, machine tools used to machine the feature. It is hard to add a new feature or a new process.	A feature-process-manufacturing resource structure is established so that general feature machining methods can be generated, which are not directly related to the specific manufacturing resources.
Manufacturing resource capability modeling	Specification of manufacturing resource has been stored in relational database.	Research on manufacturing resource capability is just at the feature level and has not been extend to manufacturing planning level.	Manufacturing resource capabilities are modeled and incorporated at the feature level, setup planning, and manufacturing planning level.
Setup planning	Setup planning information is represented by DMG. Features are grouped based on tolerance analysis of FTG, and DMG1 is generated.	Limited manufacturing resource capabilities have been considered.	DMG2 is generated based on manufacturing resource capabilities, and fixture issues are considered.
Manufacturing plan generation	N/A		Machine tool capabilities and fixture capabilities serve as two constraints on the part layout on fixtures. Cycle time serves as the main objective to achieve optimal process sequences and global toolpaths.

Chapter 3: Systematic Information Modeling in the CAMP

In the CAMP, the main challenge is to analyze the information involved in the manufacturing planning activities and to construct integrated information models, which can facilitate the rapid generation of manufacturing plans according to changes of part design. Information models are data structures that represent information content in part design and manufacturing. The main task of information modeling is to capture, describe, and maintain the information structure and information relationships in the CAMP. In this chapter, an Object-oriented Systems Analysis (OSA) approach (Embley, 1992) is utilized to analyze and represent the information models in the CAMP.

3.1 Information content in the CAMP

The tasks of CAMP are carried out sequentially by four functional modules. The part information modeling module abstracts features from part CAD models and represents part information by FTGs, which are composed of features and the relationships between features. In the meantime, the features' manufacturing strategies are associated with features based on the BOP of part families, which is called feature-level decision-making. Setup planning is carried out based on either the BOP or tolerance and manufacturing resource capability analysis, in which manufacturing knowledge for mass customization is incorporated. Setup planning is also called part-level decision-making. Conceptual fixture design and manufacturing plan generation are mainly derived from the BOP of part families. Both of them incorporate the machine-level decision-making strategies.

Corresponding to the above functional modules of the CAMP for mass customization, the information involved in the CAMP is organized into three categories, which are shown in Figure 3.1:

- Manufacturing data and knowledge bases store the manufacturing data and knowledge applied in mass customization;
- BOP represents the company-specific best-of-practice of part families;
- The blackboards store the information generated by the functional modules of the CAMP.

In the CAMP, information in each category is divided into three levels: the feature-level, the part setup planning level and the machine-level. Information in the same level serves for the same function module.

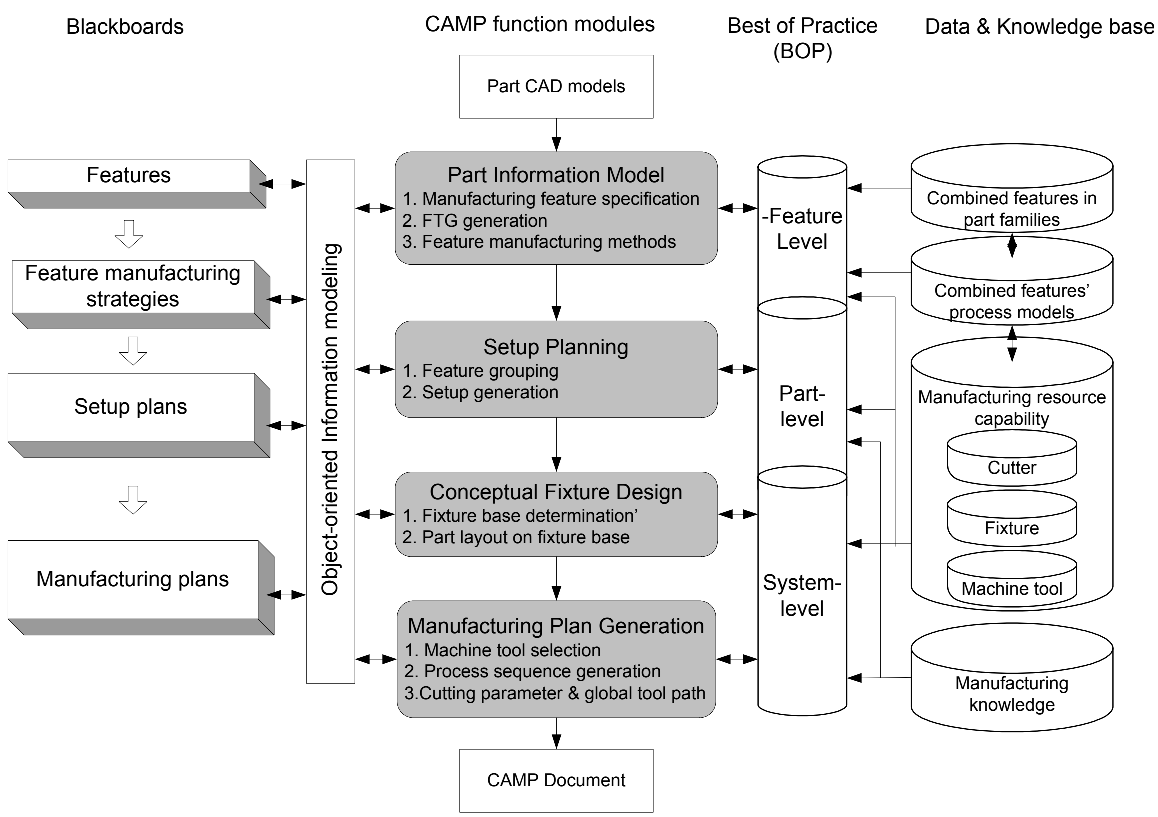


Figure 3. 1 Information content in the CAMP

1. Manufacturing data and knowledge bases

In the CAMP, the following information is considered and stored in the manufacturing data and knowledge bases:

(1) Combined features

Combined features are defined based on particular part families. The parts in the same part family may have the same type of combined features and feature relationships so that the part family's BOP can be used as the reference to generate new plans.

(2) Combined features manufacturing strategies

Combined features are associated with pre-defined manufacturing strategies, in which customized combination cutters, toolpaths, and machine tool motion requirements are specified for particular part families. The designs of cutters and toolpaths are based on former experience and are stored in templates. Therefore, when the same combined feature is encountered, the existing experience can be reused.

(3) Manufacturing resource capabilities

Manufacturing resources include cutters, machine tools, and fixtures. Some of them are standard tools and can be brought from the market. The others are designed specifically for particular processes used in manufacturing plans. The capabilities of available manufacturing resources should be described and stored in a format that the CAMP can interpret and manipulate.

(4) Manufacturing knowledge

Manufacturing rules and knowledge are extracted from BOP and can be applied in the automated reasoning mechanism such as automated determination of feature manufacturing strategy, automated setup planning, and automated manufacturing plan generation. In the research, three levels of manufacturing knowledge are identified:

- Universal. General knowledge without regard to a particular shop
- Shop level. Additional process details based on the particular manufacturing systems in a shop
- Part-level. Full information based on particular part family's production in a specific machine shop

All this information is embedded in the BOP. It needs to be identified and stored in the CAMP so that when BOP is missing, CAMP can use the above knowledge to generate feasible manufacturing plans.

2. Best-of-practice (BOP)

BOP for part families is the most important reference enabling engineers to design a new manufacturing plan. The specific decision-making strategies of part families are embedded in the BOP, which include strategies about how to deal with the information associativity between part design, part manufacturing, and the utilization of manufacturing resource capabilities. Therefore, the decision-making strategies in the BOP must be identified first, and then the BOP should be described in a format that is accurate, complete, and unambiguous, so that it can be used by the CAMP system. In this research, information in BOP is divided into three levels: feature level, part setup planning level, and machine-level. The detailed format of BOP will be discussed in Chapter 7.

3. Blackboards

Blackboards are used to store the shared information generated by the modules of the CAMP. It is in the blackboards that computers are dealing with the manufacturing information that is represented by information models. There are four blackboards in CAMP that store features, features' manufacturing strategies, part setup planning and manufacturing plan information. The design of information models considers the following issues:

(1) Information relationship. The design of information models should pay attention to information associativity and try to avoid information redundancy in models.

(2) Information integration. The design of information models should consider the overall information requirements of the CAMP system. Different functional modules may have different requirements for the same information model. For example, only geometry information can be abstracted from CAD models. On the manufacturing planning side, part production volume and materials must be used to make decisions. Hence a part information model should include geometry information, as well as material and production volume information.

(3) Information extendibility. With the consideration of the new demands in product development practice, the scope of the CAMP may change accordingly. Therefore, the information models should be extendable to accommodate more

information content without damaging origin information content and information relationships.

An OSA approach is used in this research to analyze and represent the information in the blackboards, focusing primarily on the information associativities of part design, part manufacturing, and manufacturing resource capabilities used in part production. The objective of the utilization of the OSA approach is to facilitate the use of part families' BOP to help engineers rapidly design new manufacturing plans.

3.2 The Object-oriented Systems Analysis (OSA) approach

O-O modeling is recognized as a powerful tool to model real-world systems. An object is an encapsulation of data and procedures (or methods) that operate on the data. An object may be defined as an existing entity in the real world such as a part, a manufacturing plan, and a machine tool. The real world can be considered as a group of interacting objects. The interaction is described according to the way that human beings think. Therefore, O-O modeling can create information models that exhibit close resemblance to real world systems, and the main task of O-O modeling for a system is to identify objects and analyze their interaction within the system.

Here are some basic concepts used in O-O modeling:

- *Object.* An object is a bundle of variables and related methods. A variable is an item of data named by an identifier. An object implements its behavior with methods. A method is a function associated with an object. For example, a part is an object. Its name, type and weight are variables of the parts. And the algorithm about how to calculate the weight is a method of the part object. We can also use objects to model abstract concepts, like a piece of manufacturing knowledge and a decision-making strategy.

- *Class.* A class is a set of objects that have shared properties. A class is represented by a rectangle in the research.

- *Encapsulation.* Packaging an object's variables within the protective custody of its methods is called encapsulation. This is one of the important characteristics of O-O modeling. It allows the information represented by the object variables to behave only as the object methods permit.

- *Relationship.* A relationship establishes a logical connection among objects. The identification of relationships among objects is one of the most important tasks of O-O modeling.

- *Inheritance.* Inheritance is a kind of relationship between objects. O-O modeling allows classes to be defined in terms of other classes. For example, a rotational part is a kind of a part. Therefore, the part is a superclass and the rotational part is a subclass. The subclass inherits all the variables and methods in the superclass. Inheritance can avoid information redundancy.

In the research, the OSA approach is used to analyze the information in the CAMP: The object-relationship model (ORM) is used to represent the static relationships between objects; The object-behavior model (OBM) describes the behavior of individual objects and how objects respond to dynamically occurring events and conditions; The object-interaction model (OIM) expresses the information associativities between objects.

3.2.1 Object-relationship model (ORM)

An ORM is created to represent the static relationships between objects. ORMs are usually described by ORM diagrams. Users can define their own relationships with the specific relationship name attached to ORM diagrams. There are two basic relationships used frequently, and specific symbols are assigned to represent them in ORM diagrams (Embley, 1992).

1. Generalization – Specification relationship

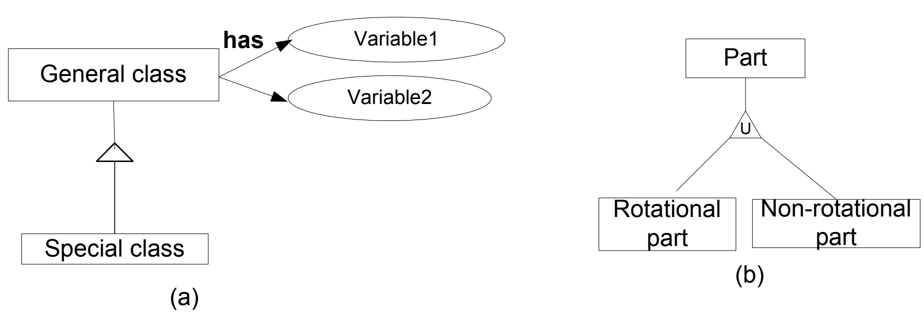


Figure 3. 2 Generalization-Specification relationship

In an ORM diagram, a rectangle represents an object, an ellipse represents a variable of an object, and a transparent triangle represents the Generalization-Specification relationship. The relationship in Figure 3.2(a) is read: “special class is a kind of general class.” The special class inherits the variables and methods of the general class, which are implied by the Generalization-Specification relationship.

Constraints are created to limit the relationships. Figure 3.2(b) shows an example of a union constraint. The union symbol (U) inside the triangle represents the union constraint and ensures that a part is either a rotational part or non-rational part. The use of this constraint can identify the scope of the general class.

2. Whole-Part relationship

Another type of relationship that appears often is the Whole-Part relationship. The relationship declares that an object, called a superobject, is composed of other objects called subobjects. Figure 3.3 shows an example of a Whole-Part relationship. Figure 3.3 b is read as “The block is composed of a flat surface, a hole feature and a slot feature.” A solid-filled triangle is used to represent the whole-part relationship.

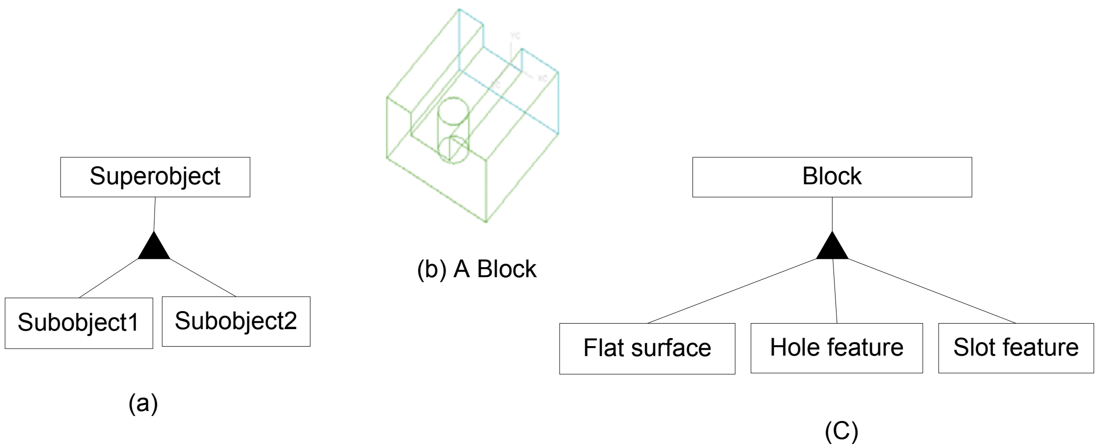


Figure 3. 3 Whole-Part relationship

A Whole-Part relationship does not require that all subobjects be represented. Thus, a reader of an ORM should not assume that the collection of subobjects constitutes the whole superobject.

3. User-defined relationship

In the CAMP, the user-defined relationships reflect the pre-defined information relationships, which may come from the BOP or general manufacturing knowledge. For example, a hole feature has 5 alternative manufacturing processes. The feature is defined as an object, and a process is defined as another object, as shown in Figure 3.4.

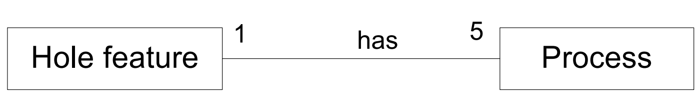


Figure 3. 4 A user-defined relationship

By using of Generalization–Specification, Whole-Part, and user-defined relationship, the system's ORM can be setup as shown in Figure 3.5, so that information can be classified into objects. For example, in order to describe the part shown in Figure 3.3, a part object is created to represent the design information of the part, which is composed of a flat surface object, a hole object and a slot object. Each feature is associated with specific processes. At the same time, this part is a non-rotational part. Thus a non-rotational part object is associated with the part object so that the part object can have all the characteristics of non-rotational part.

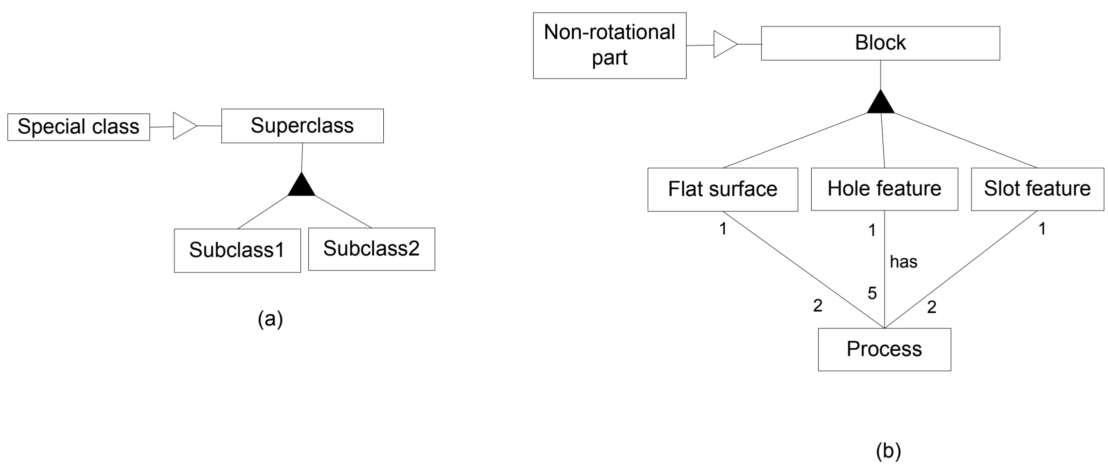
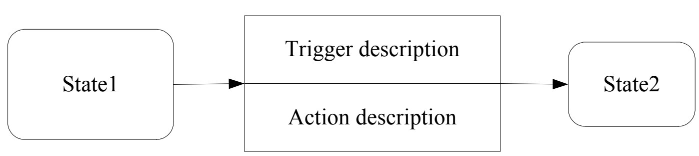


Figure 3. 5 An ORM diagram for the block and its features

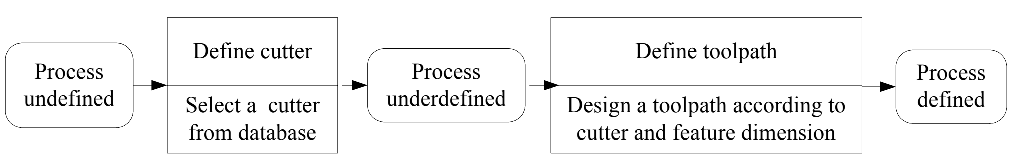
3.2.2 Object-behavior model (OBM)

The objective of a behavior model is to describe the way that each object in a system interacts, functions, responds, or performs. A behavior model for an object is similar to a job description for an object. In the research, state nets are used to represent OBMs.

A basic concept of behavior modeling is the set of states that an object exhibits in a system. In OSA, a state represents an object's status, phase, situation, or activity. Figure 3.6 shows some states of process objects. The procedure of changing the state of an object is called transition. The events and conditions that activate state transitions are called triggers. The activity that an object performs is called action. A state net is a configuration of symbols representing states and state transitions for an object. In state net, rounded rectangles represent states. Rectangles that are divided into two sections represent transitions. The top section contains a trigger description. The bottom section contains the actions. For example, Figure 3.6(a) shows the components that construct a state net. Figure 3.6(b) shows an example of the activities to define a process object. There are three states of a process object: process undefined, process underdefined and process defined. The first step of a process object is to select a cutter that is used in this process. The process is incomplete when it only has cutter information, and the state is under defined. The second step is the definition of toolpath. After this step, the definition of a process is finished.



(a)



(b)

Figure 3. 6 A state net for a process object

3.2.3 Object-interaction model (OIM)

The ORMs describe the static relationships among objects. The OBMs describe the behavior of an object, but in isolation from other objects. An OIM model is used to describe the interaction such as information associativities among objects.

One object interacts with another in many different ways. For example, an object may send information to another object; an object may request information from another object; an object may alter another object; and an object may cause another object to do some actions. To understand object interaction, we must understand: (1) What objects are involved in the interaction; (2) How the objects act or react in the interaction; (3) The nature of the interaction (Embley, 1992).

Since objects are identified in ORMs, ORM components are used in OIMs to show which objects are involved in interactions. To understand how objects may act or react in a given interaction, we must understand the behavior of each object involved. Since we are able to define the behavior of objects with state nets, we use state nets in OIMs to describe how objects act and react in interactions. To understand the nature of an interaction, we must describe the activity that constitutes the interaction, and we must describe the information transmitted or exchanged in the interaction. A zigzag arrow is used to describe the interaction, and an appropriate combination of ORMs and start nets is used to create OIMs.

Figure 3.7 shows an example of the interaction between a part object and its process object, which were defined in Figure 3.5 and Figure 3.6. The part object is composed of a flat surface, a hole feature and a slot feature. Each feature has its own parameters. When choosing the process to machine the flat surface, the cutter and the toolpath in the process are determined by the feature's parameters. The two zigzag arrows in Figure 3.7 show the parameter-driven interaction between the flat surface and the process. When the dimensions of the flat surface are changed, the process to machine the flat surface may change accordingly. The zigzag arrow indicates that programming work is needed to implement this interaction activity.

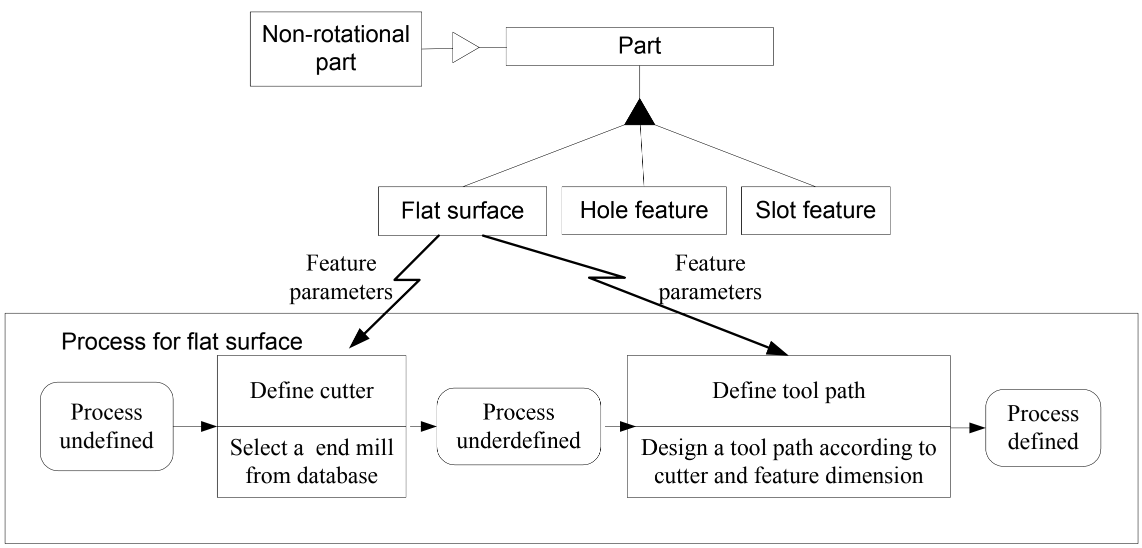


Figure 3. 7 OIM between a part object and one of the process objects

3.2.4 Systematic information modeling hierarchy

When using OSA approach to model a complex system such as the CAMP in the research, high-level abstraction of objects is applied to reduce complexity and make the information models easy to create, maintain, and display. A high-level object groups relative objects and the relationship among the objects into a single object. The top-down approach is used to expand a high-level object into low-level objects and relationships.

Figure 3.8 shows the hierarchic structure of system information models. The building of the information models is split into three levels:

- The definition of a system model, which contains domains that are subdivided into subsystems. The system model may be deduced from analysis of the system's high-level object interaction models.
- The definition of an information model, which contains objects that are subdivided into states.
- The definition of the state model, which describes the behavior of objects.

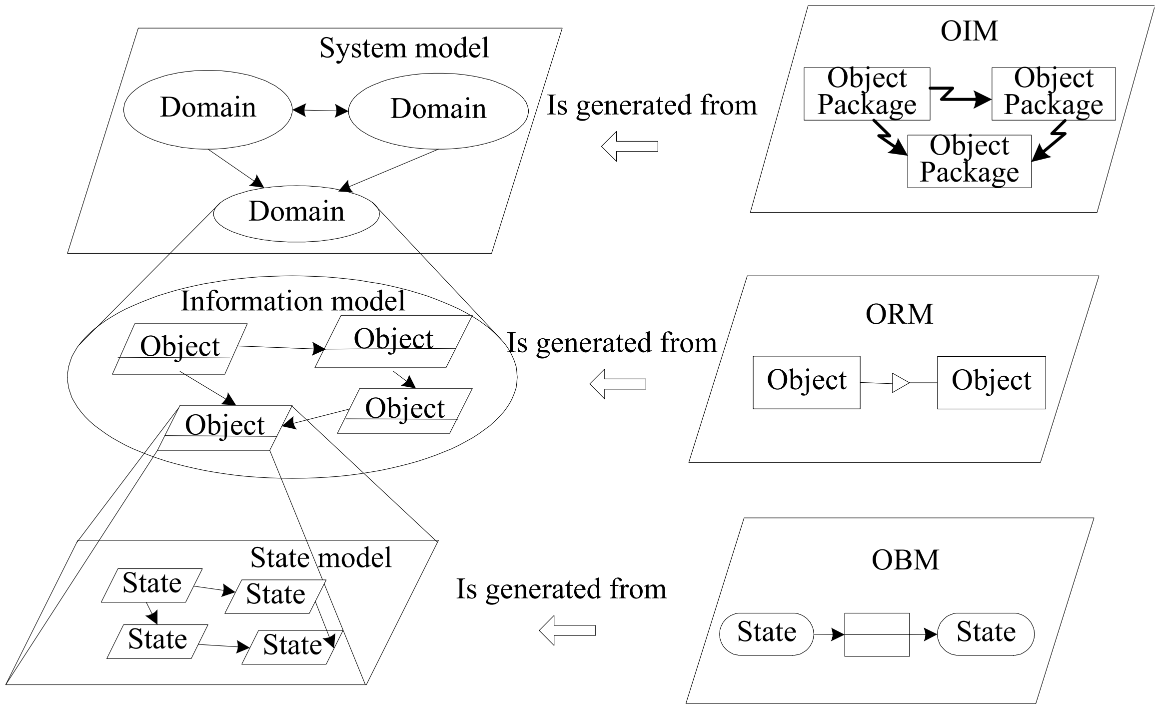


Figure 3. 8 Systematic information modeling hierarchy

3.3 Information modeling in the CAMP

By using the OSA approach, a system model is proposed for the high-level view of the CAMP, as shown is Figure 3.9. It is divided into four object packages: part design, manufacturing knowledge, manufacturing resource capability, and manufacturing planning packages. The arrows in Figure 3.9 indicate the relationship and interaction between these object packages. The part information is the input, which is composed of features and the relationships between features, and feature's manufacturing strategies are linked with features. Manufacturing planning package includes both part-level and machine-level decision-making strategies. The manufacturing knowledge package provides the knowledge constraint to control the manufacturing planning behaviors. The manufacturing resource capability package provides the description of the manufacturing resources, such as machine tools, cutters and fixtures in specific manufacturing companies.

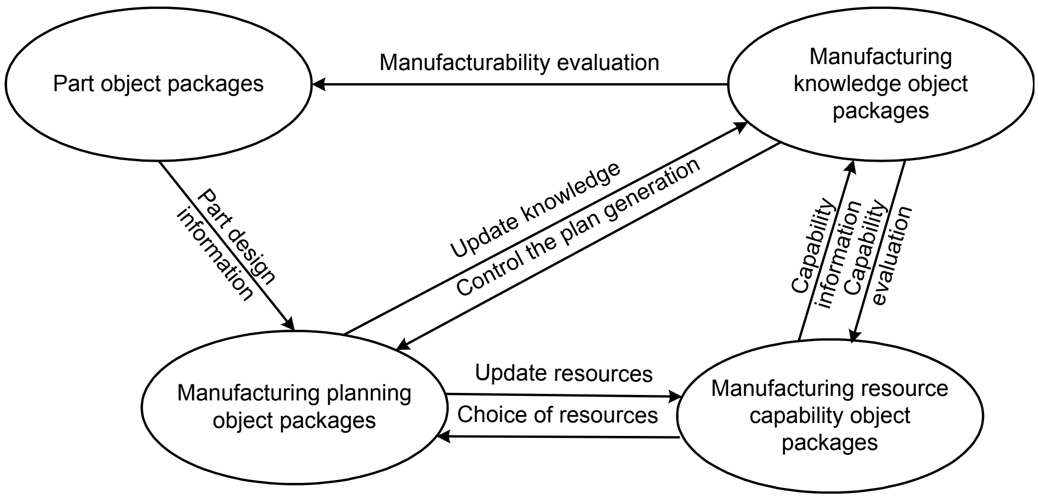


Figure 3. 9 Information modeling in the CAMP

Each object packages in the system model will be broken down into low-level objects. The relationships and associativities among the low-level objects will be the focus of this research. In Chapter 4, the part object package and the interaction between part package and manufacturing planning package will be discussed in depth. In Chapter 5, manufacturing resource capability packages will be addressed. In Chapter 6, part-level setup planning will be studies based on the incorporation of the tolerance analysis and manufacturing resource capability analysis. In Chapter 7, machine-level planning is to be carried out that is specifically applied in mass customization.

Chapter 4: Combined Feature Information Modeling for Part Families

Part design information is represented by features and manufacturing planning in the CAMP is done on a feature-by-feature basis. Generally, a feature is defined in simple geometry, and machining processes are linked with the feature in which one cutter machines only one or two surfaces. In the CAMP, manufacturing processes are usually designed to machine as many surfaces as possible to reduce machining time. This makes it difficult to use the conventional feature technology to generate a feature's manufacturing processes. Therefore, the concept of combined feature is proposed in this research to represent part information, and a process model is established for the linkage between features and the manufacturing resources used to machine the feature. By the use of combined features and their process models, the change in part design will be reflected on the processes and the utilization of manufacturing resources.

4.1 Combined manufacturing feature modeling

In the CAMP, the concept of part family is applied. The parts in the same part family have similar structures and can provide similar functions. The manufacturing plans of these parts should be similar. In order to represent these similarities, the definition of manufacturing feature of part families is extended to combined features. A combined feature is composed of simple features and could provide a particular function in a part family.

Figure 4.1 shows a simplified part named a caliper housing. Caliper housing is a part used in an automobile's brake systems. Its function is to hold two braking pads that can move along the caliper's piston axes to press the rotors, which are mounted on the car's tires, so that a car can reduce its speed and stop.

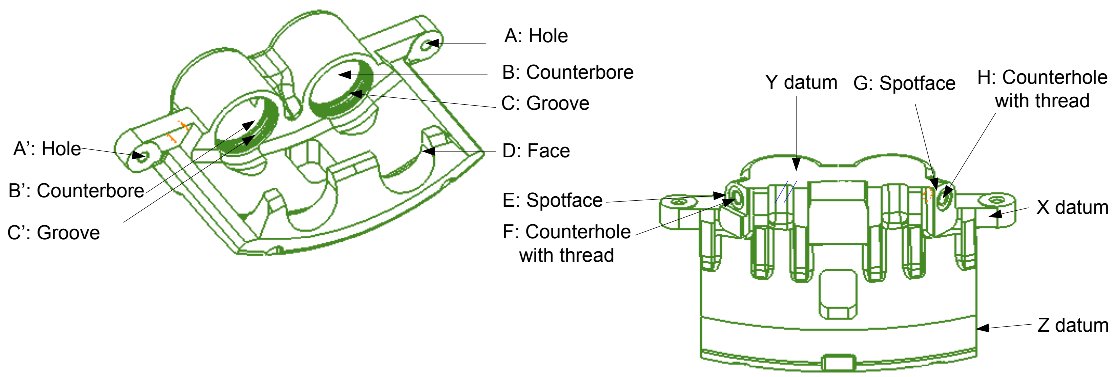
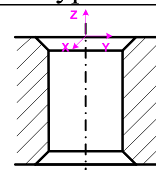
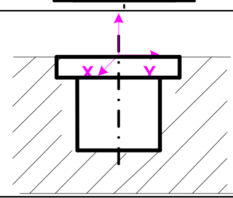
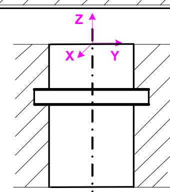
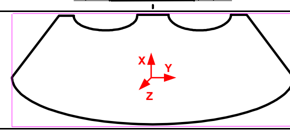
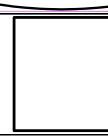
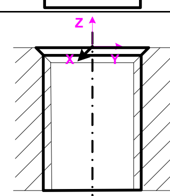


Figure 4. 1 An example of simplified caliper

The features of the above simplified caliper model are listed in Table 4.1. The feature types' parameters and their manufacturing methods are summarized in Appendix A. There are some other features that can provide more powerful functions to ensure the caliper's work. Because of confidentiality, they are not listed here.

Table 4. 1 Feature list in the caliper

ID	Feature name	Number	Feature type	Function
A	Mounting hole	2		Mounting caliper to bracket
B	Piston bore	2		Providing hydraulic pressure to brake pads
C	Seal groove	2		Sealing hydraulic fluid in piston bores
D	Outboard flange	1		Holding brake pads
E	Spotface	1		Providing surface to install hydraulic pipe
F	Connector hole	1		Connecting to the hydraulic pipe
G	Bleed hole spotface	1	Same as E	Same as E
H	Bleeder hole	1	Same as F	Same as F

The parts in the same caliper family have the same types of combined features to provide the same functions that are shown in Table 4.1. The difference is the dimensions and accuracy of these combined features. Also, their manufacturing strategies are expected to be the same, including the cutter types, fixture types, and machine tools, so that the work to design new manufacturing plans can be greatly reduced.

4.1.1 Definition of combined features

Actually, it is difficult to distinguish between simple features and combined features on an absolute basis. However, from the topological view, it is safe to say that simple features are the lowest level of feature, and combined feature can be broken down into two or more simple features. From the functional view, the function of simple features differs when used in different parts. The combined features have their pre-defined composition of simple features and provide fixed functions in a specific part family.

In this research, the surfaces are treated as simple features. The basic surfaces are flat surface, internal cylinder surface, and internal cone surface. The combined features are the combination of these simple surfaces.

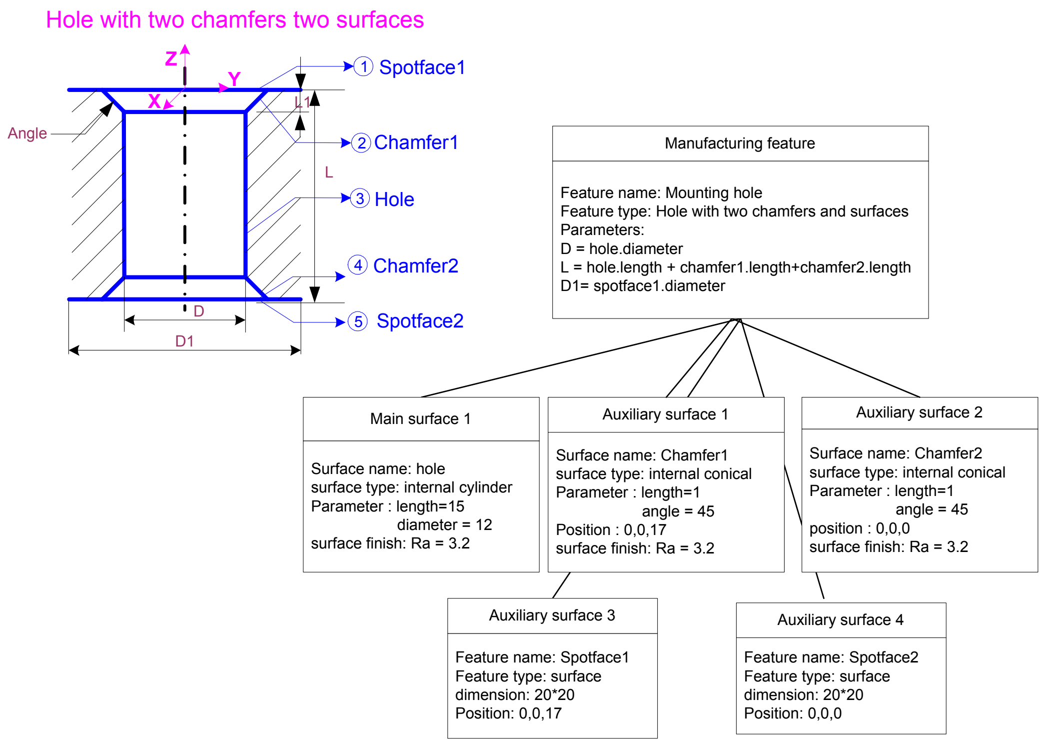
The definition of combined features follows the rules:

(1) The geometry of a combined feature must link together or have particular topological relationships.

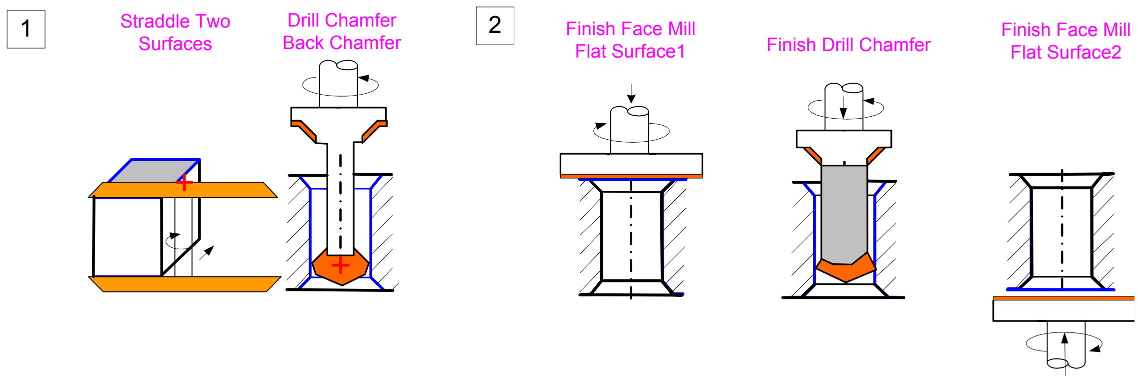
(2) A combined feature acts as a unit to provide a specified function in part families.

(3) A combined feature has one or a list of particular manufacturing processes in the manufacture of a part family.

Figure 4.2 shows an example of one of the combined features, the mounting hole in a caliper family. This feature is made of five surfaces and the internal cylinder surface is the main feature that determines the main dimension, position, and orientation of this combined feature. These five surfaces are topologically adjacent. There are two candidate manufacturing routines associated with this combined feature, which are shown in Figure 4.2 (b). The first routine includes milling the two spotfaces and drilling, chamfering and backchamfering the hole. The other routine is composed of drilling, chamfering, milling spotface1, backchamfering, and milling spotface 2. In the above processes, more than one surface is machined, and special cutting tools are designed to finish these processes.



(a) An example of a combined feature



(b) Manufacturing methods

Figure 4. 2 A combined feature and its manufacturing methods

4.1.2 Combined feature information structure

In order to represent the combined features, the detailed information of combined features should be studied first and organized into a hierarchical structure:

-An identifier, or an ID, which is needed to uniquely represent a feature.

- Feature type. Feature type is the most critical information that describes the greatest information content of a combined feature. A feature type includes:

  - Surface information. Surfaces are considered the atomic primary features and are mathematically represented by operational data sets. Then, the O-O modeling techniques can be applied for necessary reasoning. In each combined feature, there is a main surface (MS), which determines feature's parameters, position, and orientation. Auxiliary surfaces (AS) are those surfaces that are attached to main surfaces. The relationships between the main surface and auxiliary surfaces should be described as well.

- Manufacturing process information. The feature information can be further linked to the cutter and the local toolpath used to machine this feature. Their representation will be discussed in 4.2.3.

- Feature functions. The feature's functions indicate its particular functionality in a part family. Sometimes, the change of feature parameters may influence the whole part's function. For example, in the caliper family, the change of the diameters of piston bores will change the fluid pressure that the caliper can provide to the brake pads. Corresponding parameters of combined features in the caliper family may change accordingly, which causes the manufacturing plans of the whole parts to change greatly. Therefore, the critical feature's function should be identified and represented in feature model.

Figure 4.3 shows the combined feature information structure.

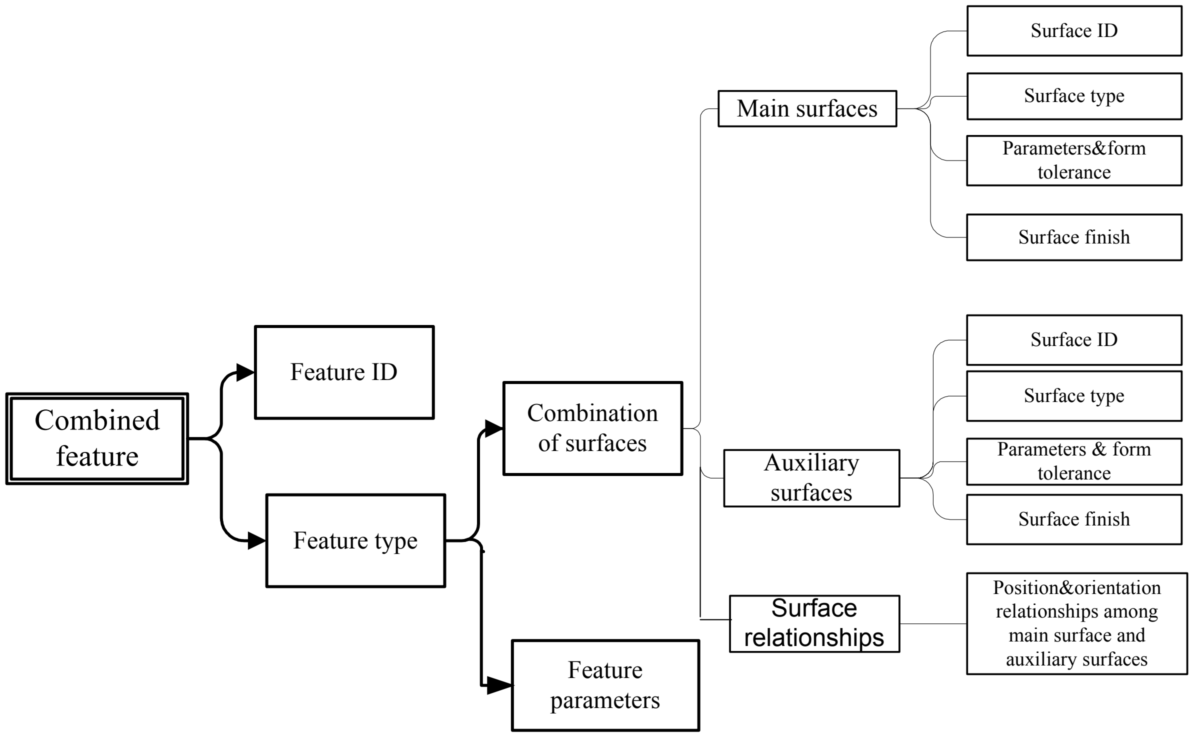
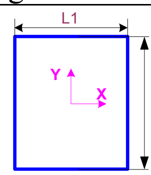
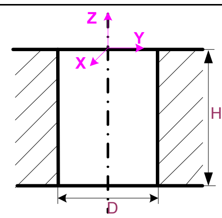
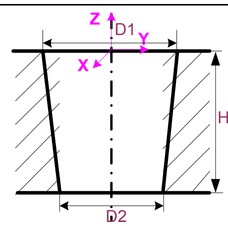


Figure 4. 3 Combined feature information structure

Three types of surfaces are currently used in the research to construct combined features. Their parameters are shown in Table 4.2. These surfaces can act as both main surfaces and auxiliary surfaces in combined features.

Table 4. 2 Surface types and parameters

Surface type	Image	Parameters
Flat surface		L1: length L2: Width
Cylinder		H: Length of cylinder D: Diameter
Cone		D1: Max diameter D2: Min diameter H: length of cone

Based on the information structure, combined features could be represented mathematically.

$$F = \{id, featuretype\} \quad \text{(Equation 4.1)}$$

where:

id: an identifier to uniquely represent a feature in a part model

featuretype: an identifier to indicate a combined feature type

$$featuretype = \{MS, \sum AS, \sum R\} \quad \text{(Equation 4.2)}$$

MS: Main surface, there is only one main surface in each combined feature

AS: A set of auxiliary surfaces

$\sum R$: A set of topological and tolerance relationships among the surfaces

While:

$MS = \{S_0, S_1, S_2, S_3, S4\}$ (Equation 4.3)

S0: Surface ID, an identifier to uniquely represent the main surface in a manufacturing feature

S1: Main surface type. The surface types of main surfaces are listed in Table 4.2

S2: Set of surface parameters that are given in Table 4.2

S3: Form tolerance information of main surfaces. Form tolerance type are shown in Table 4.3

S4: Surface finish

Table 4. 3 Tolerance classifications

Tolerance	
Dimension	
Form	Straightness
	Flatness
	Circularity
	Cylindericity
Orientation	Parallelism
	Perpendicularity
	Angularity
Position	Location
	Concentricity
Runout	Circularity
	Total
Profile	Line
	Surface

$AS = \{S_0, S_1, S_2, S_3, S_4\}$ (Equation 4.4)

S0: Surface ID

S1: Auxiliary surface type

S2: Auxiliary surface parameters

S3: Form tolerance information of auxiliary surfaces

S4: Auxiliary surface finish

$$R = \{Suf1, Suf2, R1, R2, R3\} \qquad \text{(Equation 4.5)}$$

Suf1, Suf2: Surfaces that are the main surface or in the auxiliary surface set

R1: Topological adjacency information

R2: Geometric relationships, such as perpendicular or parallel

R3: Position or orientation tolerance relationships between $Suf1$ and $Suf2$

The tolerance used in feature model is defined in Table 4.3. Form tolerance is associated with surfaces. Orientation, position, and profile tolerances are described in surface relationship R3.

A face adjacency graph (FAG) is used to model the surface relationships in combined features. A FAG is represented by a directed graph, in which the surfaces are considered nodes of the graph and the surface-surface relationships form the arcs of the graph. The advantage of the graph is that the well-established techniques of graph algorithms can be readily adapted to feature modeling. Figure 4.4 shows the FAG for the combined feature – a hole with two chamfers and two surfaces, shown in Figure 4.2. This FAG will be used in the feature recognition algorithms, which will be discussed in Section 4.1.4.

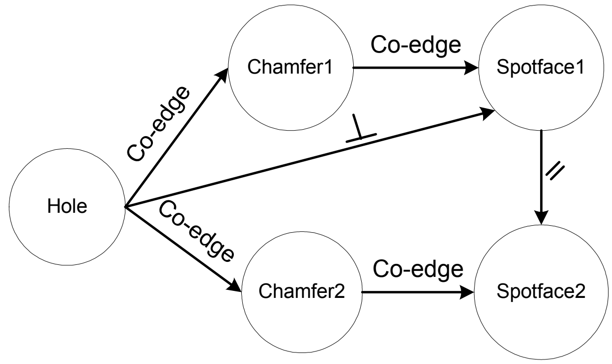


Figure 4. 4 FAG of a combined feature

By using feature information structure, new combined features can be added by the prescription of the main surface, the auxiliary surface, and their combination relationships.

4.1.3 ORM of combined features

Based on the combined feature's information structure discussed in 4.1.2, the ORM of combined features is established, as shown in Figure 4.5. There are 24 objects defined in the combined feature's ORM. A combined feature has its own manufacturing feature type that is composed of a main surface, auxiliary surfaces, and surface relationship objects. Three surface types are involved in this ORM. They are flat surface, cylinder surface and cone surface. The form tolerance, position and orientation tolerance, and runout tolerance are treated as object in this ORM.

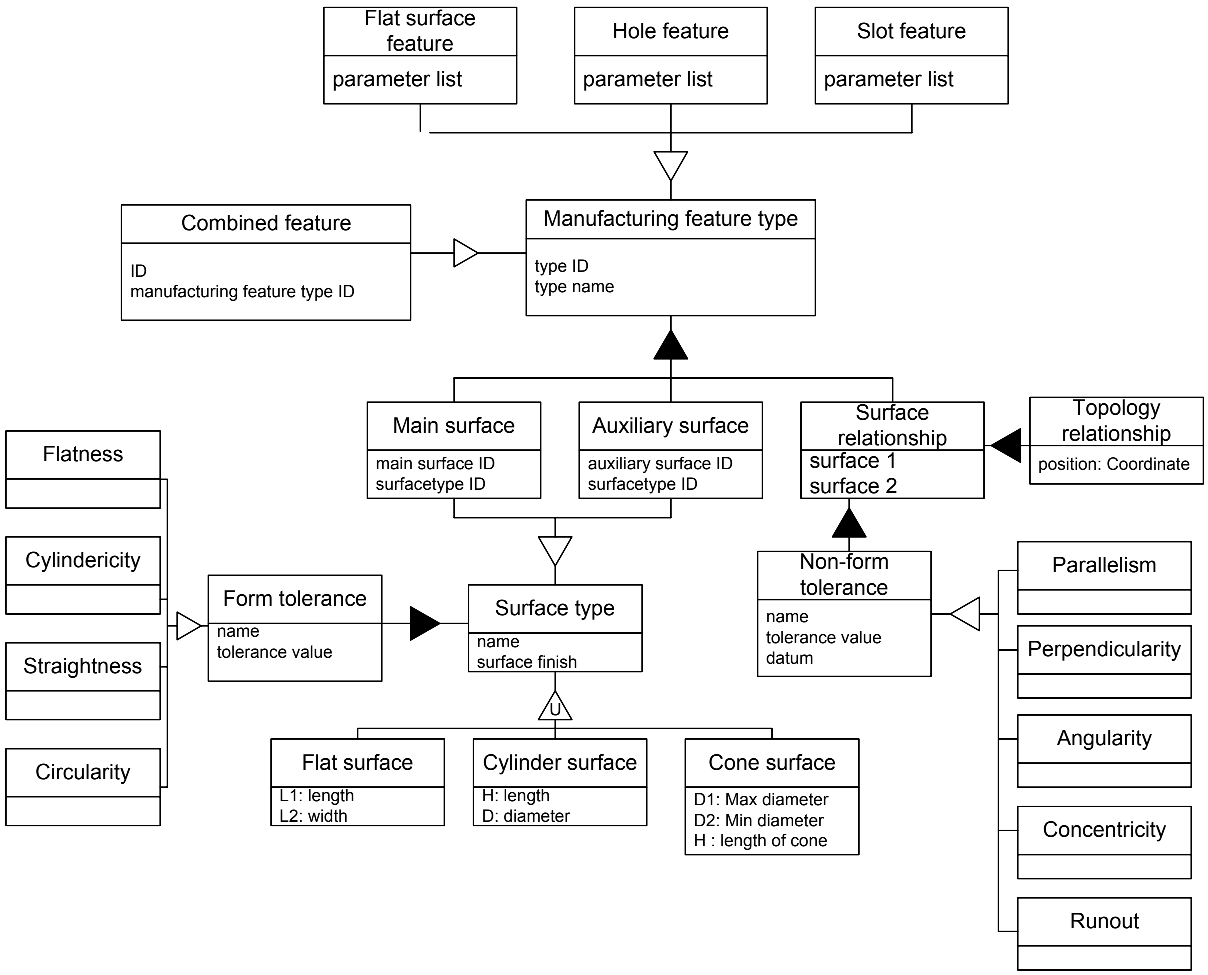
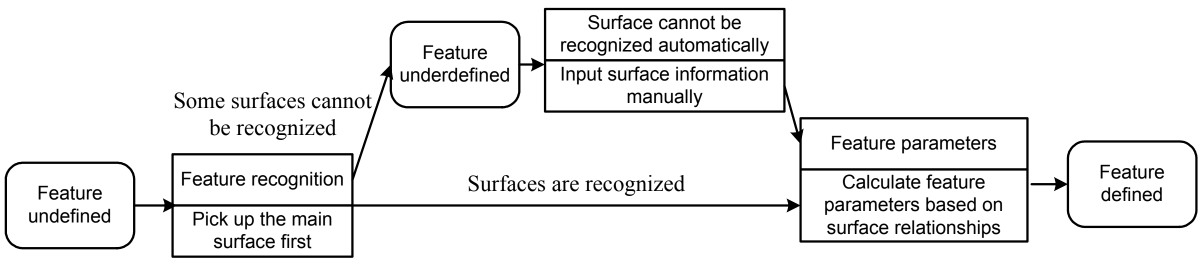


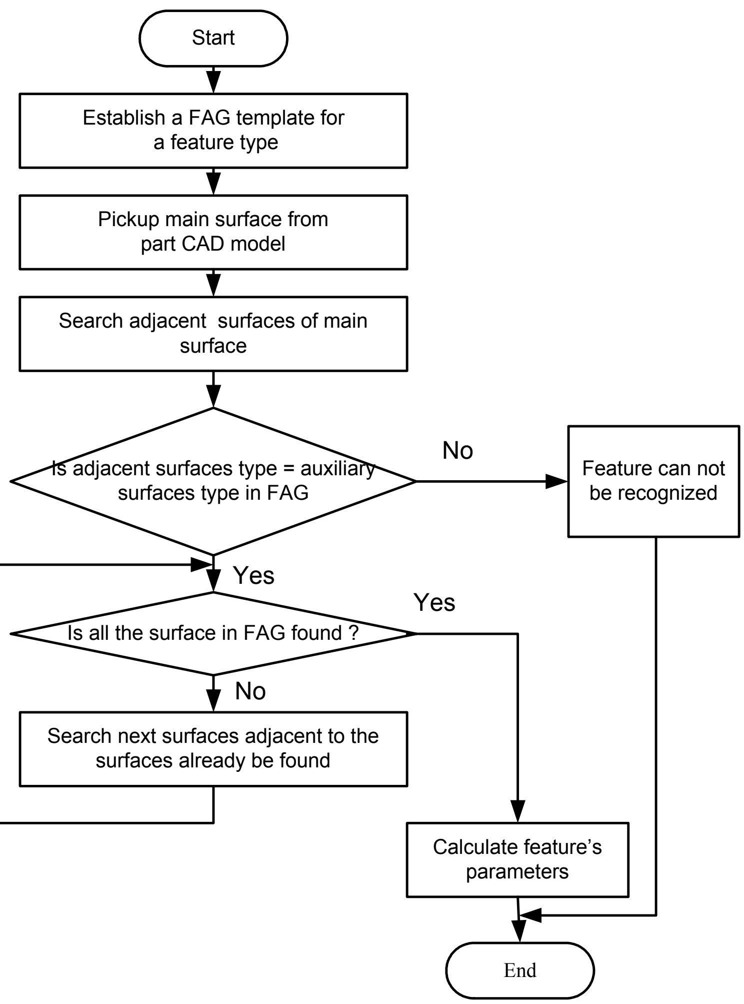
Figure 4. 5 ORM of combined features

4.1.4 Automated combined feature recognition

Automated combined feature recognition serves to automatically identify all the surfaces in a combined feature from a part CAD model and get a feature's parameters quickly. A part CAD model should be described in a boundary representation so that succeeding algorithms for feature recognition can take effect. For the non-rotational parts, only part of their surfaces need to be machined. Therefore, in order to recognize a combined feature from its part CAD model, its main surface needs to be identified first by manual selection. The feature's FAG is used as a template to guild the search algorithm. Figure 4.6 shows (a) the OBM of combined feature object and (b) the feature recognition algorithms.



(a) OBM of feature recognition



(b) Algorithm for feature recognition

Figure 4. 6 Automated feature recognition

4.2 Process modeling for manufacturing strategies of combined features

Manufacturing strategies of combined features are intended to design a sequence of processes to remove required machining volume of the features while maintaining manufacturing costs and process constraints. In general, the following manufacturing knowledge is used to determine a feature's manufacturing strategies (Chang, T., 1990):

1. A feature's shapes and sizes that a process can produce, or, inversely, the process that can create a given feature.
2. The dimensions and tolerances that can be obtained by a process
3. Geometric and technological process constraints that determine the conditions under which a process is applicable.
4. The economics of a process

In the research, a process model is established to capture the fundamental characteristics of combined feature's manufacturing strategies. These characteristics include customized cutters and toolpaths, which imply the requirement for a machine tool's motion. No specific machine tools are used in this stage. The dimensions of cutters and toolpaths are driven by combined features' parameters. Hence, when the design of combined features change, their manufacturing strategies can be changed automatically.

4.2.1 Process information structure

The process information structure is composed of cutters, cutting motions, and economic process accuracy, as shown in Figure 4.7. The economic process accuracy describes the process capability of surface finish and tolerance limitation. Each feature may have several alternative manufacturing processes.

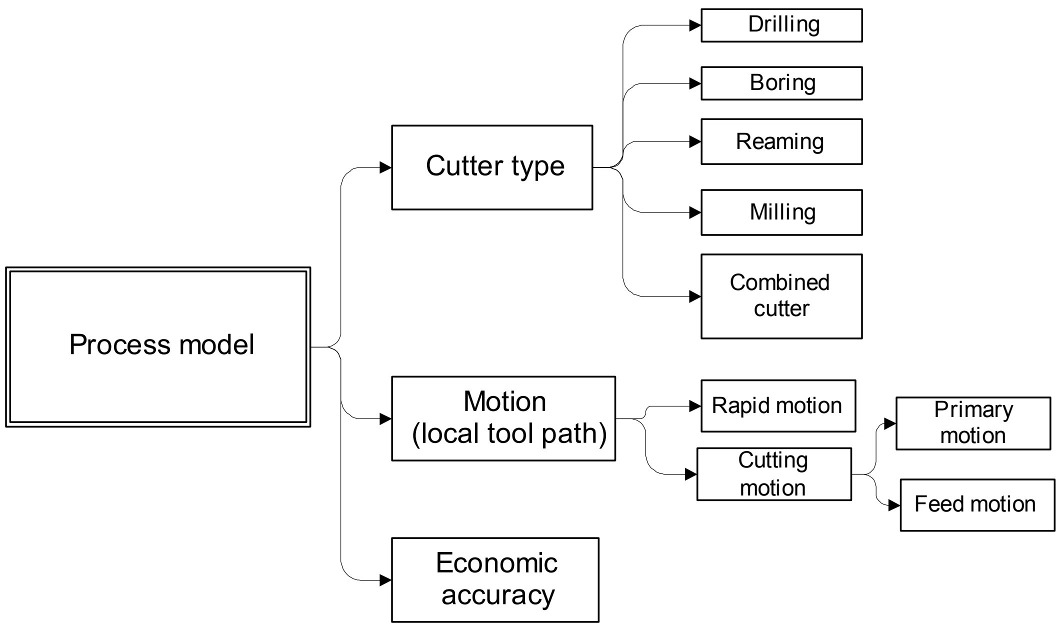


Figure 4. 7 Process model information structure

Using the process model, it is expected that a user can add new cutting tool descriptions and corresponding toolpath descriptions to the process model easily. This challenge is discussed in two ways: First, establish extensible cutter and toolpath representations so that users may easily add their own customized cutter and toolpath descriptions. Second, some validation should be made to ensure that customized cutting tools and toolpaths such as the toolpath simulation are valid in practice.

4.2.2 Cutter description

The geometry of cutters can be represented by their vertical profiles. Vertical profiles represent the shape of a maximum cross-section of cutting tools and are composed of segments and segment joints. Figure 4.8 shows the cutter used in the process "milling a flat surface," in which a standard milling tool is used. Figure 4.8(b) is the cutter's solid model and Figure 4.8(c) is its vertical profile. The cutter's dimension is driven by the flat surface's parameters.

Several functional descriptions are imposed on the segments and segment joints, as shown in Table 4.4(b). The segments are defined as cutting edges or non-cutting edges. It is assumed that one cutting edge can only machine one surface of a feature in the process. Table 4.4 shows the constraints on the segments and segment joints in the milling tool's vertical profile, which are listed in clockwise order. Each segment or segment joint has a description of its dimension range.

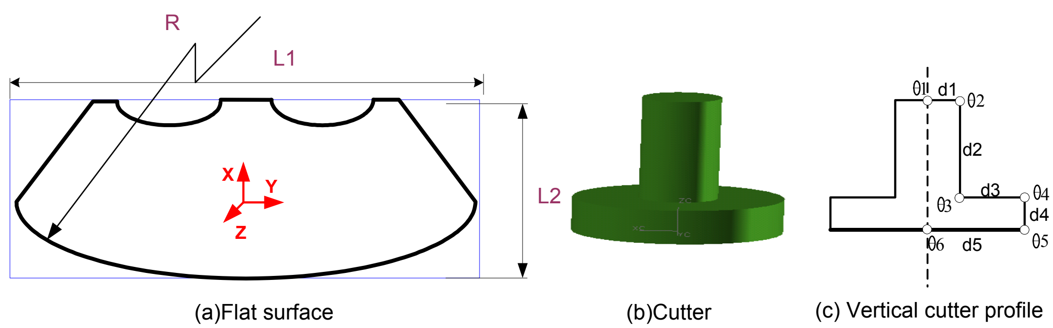


Figure 4. 8 The cutter for milling a flat surface

Table 4. 4 Representation of the cutter for milling a flat surface

(a) Tool constraints (in clockwise order)

Component Type	Para-meter	Constraints	Values	Relationships with feature parameters
Segment joint	θ_1		$\theta_1 = 0^\circ$, Profile start point	
Line segment	d_1	Non-cutting edge	$d_1 = 1/3d5$	
Segment joint	θ_2		$\theta_2 = 90^\circ$	
Line segment	d_2	Non-cutting edge	$d_2 = 30mm$	
Segment joint	θ_3		$\theta_3 = 270^\circ$	
Line segment	d_3	Non-cutting edge	$d_3 = d_5 - d_1$	
Segment joint	θ_4		$\theta_4 = 90^\circ$	
Line segment	d_4	Non-cutting edge	$d_4 = 5mm$	
Segment joint	θ_5		$\theta_5 = 90^\circ$	
Line segment	d_5	Cutting edge	$d_5 > \text{Minimum}(L_1/2\ ,\ L_2/2)$	L_1, L_2
Segment joint	θ_4		$\theta_4 = 0^\circ$, Profile end point	

(b) Constraints keywords

Component type	Constraints		Segment symbol
	Parameters	Type	
Line segment	d	Length of line	Cutting
Arc segment	r_1 r_2 θ	radius of major axis radius of minor axis angle of arc	Non-cutting
Segment joint	θ	Angle of joint	○

Using the same mechanism as for the above milling tool, the cutters used for combined features can also be represented by vertical profiles. The combined feature's parameters can drive the cutter parameters as well. Therefore, when the combined feature's parameters change, the cutters in the feature manufacturing strategies may change accordingly. Figure 4.9 shows the cutter and toolpath used to drill the mounting hole of a caliper. Figure 4.9(a) shows the parameters of a mounting hole that is "a hole with two chamfers and two surfaces" type. Figure 4.9(b) describes the vertical profile of the cutter used for drilling the hole, chamfering chamfer1, milling spotface1 and backchamfering chamfer2. Four surfaces are machined in this process. Figure 4.9(c) shows the corresponding toolpath that will be discussed in Section 4.2.3. Table 4.5 describes the cutter's vertical profile and its relationship with the feature. All the values in the table came from a BOP provided by a specific company.

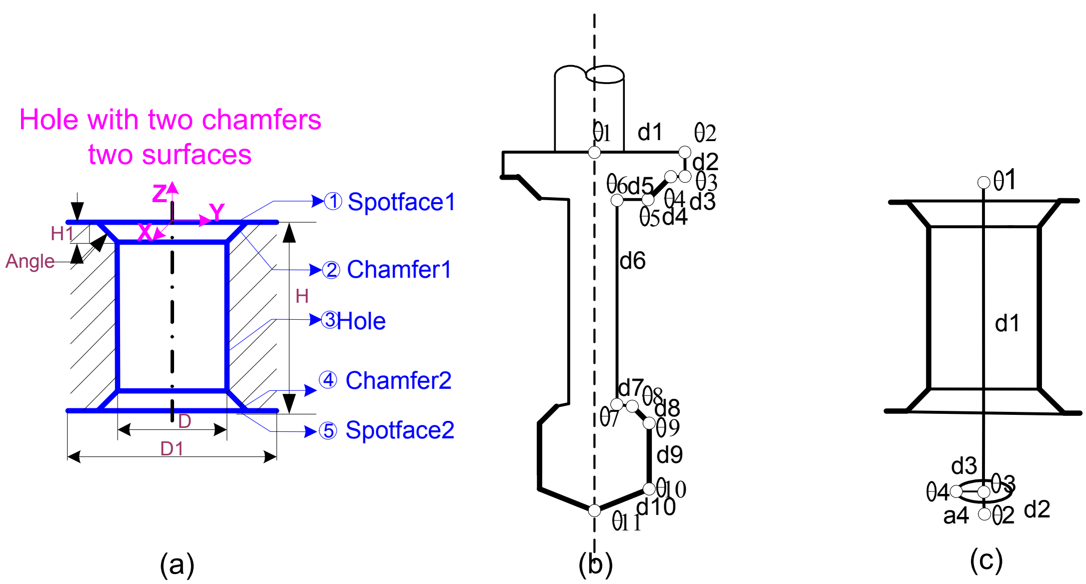


Figure 4. 9 Cutter design and toolpath design for the hole with two chamfers and two surfaces

Table 4. 5 Representation of the cutter for the hole with two chamfers and two surfaces (in clockwise order)

Component Type	Parameters	Constraints	Values	Relationship with feature parameters
Segment joint	θ_1		$\theta_1 = 0^\circ$, Profile start point	
Line segment	d_1	Non-cutting edge	$d_1 = D1/2 + 2$	D_1
Segment joint	θ_2		$\theta_2 = 90^\circ$	
Line segment	d_2	Non-cutting edge	$d_2 = 5mm$	
Segment joint	θ_3		$\theta_3 = 90^\circ$	
Line segment	d_3	Cutting edge	$d_3 = d_1 - D/2 - H_1$	D_1, H_1
Segment joint	θ_4		$\theta_4 = 315^\circ$	Angle
Line segment	d_4	Cutting edge	$d_4 = \sqrt{2}H1$	H_1
Segment joint	θ_5		$\theta_5 = 45^\circ$	
Line segment	d_5	Non-cutting edge	$d_5 > D/6$	
Segment joint	θ_6		$\theta_6 = 270^\circ$	
Line segment	d_6	Non-cutting edge	$d_6 = H+3$	H
Segment joint	θ_7		$\theta_7 = 270^\circ$	
Line segment	d_7	Non-cutting edge	$d_7 = D/6 - H_1$	
Segment joint	θ_8		$\theta_8 = 45^\circ$	
Line segment	d_8	Cutting edge	$d_8 = \sqrt{2}H1$	H_1
Segment joint	θ_9		$\theta_9 = 45^\circ$	
Line segment	d_9	Cutting edge	$d_9 = H/2$	H
Segment joint	θ_{10}		$\theta_{10} = 60^\circ$	
Line segment	d_{10}	Cutting edge	$d_{10} = \sqrt{3}d9$	
Segment joint	θ_{11}		Profile end point	

4.2.3 Toolpath description

In the process model, the cutter type determines the basic cutting motion types of machine tools, which are divided into primary motion and feed motion. Both types can be represented mathematically. The cutter parameters and the feature parameters determine the machine motion parameters. Table 4.6(a) shows the parameter-driven relationship between the feature shown in Figure 4.9, its cutter, and its toolpath. Table 4.6(b) shows the mathematical representation of cutting motions. The design of the toolpath template is also based on the BOP.

Table 4. 6 Toolpath representation

(a) Toolpath description (in clockwise order)

Component Type	Para-meter	Motion type	Values	Cut
Segment joint	θ_1		$\theta_1 = 0^\circ$, start point	
Line segment	d_{12}	Linear feed motion	$d_{12} = H+H1+d_9+0.5d_{10}$	Drilling hole, chamfer1, Spotface1
Segment joint	θ_2		$\theta_2 = 180^\circ$	
Line segment	d_{23}	Rapid motion	$d_{23} = 3+H_1$	
Segment joint	θ_3		$\theta_3 = 270^\circ$	
Line segment	d_{34}	Rapid motion	$d_{34} = H_1$	
Arc segment	r_4	Circular feed motion	$r_4 = H_1$	Backchamfer2
Segment joint	θ_4		$\theta_4 = 0^\circ$	
Line segment	d_{43}	Rapid motion	$d_{43} = d_{34}$	
Segment joint	θ3		θ3 =270˚	
Line segment	d_{31}	Rapid motion	d31 = H- H_1+3	

(b) Mathematic representation of cutting motion

Motions (provided by machine tool)			Mathematic representation
Rapid	Linear motion		$P_1 = P+(P_2-P_1)t$, P_1 is the start point vector, P_2 is the end point vector t is within [0,1]
Cutting	Primary motion	Cutter rotates along its central line	
	Feed motion	Linear feed motion	$P_1 = P+(P_2-P_1)t$, P_1 is the start point vector, P_2 is the end point vector t is within [0,1]
		Circular feed motion	$P= [M(t)]P_1 +R$ P_1 is the start point vector, R is the center point vector of the arc M is the rotational matrix by R t is within[0,1]

By the use of the process model, when a new feature type is added, corresponding processes, including the requirement of cutters and machine motions, can be generated based on the shape, dimensions, and tolerances of the new feature type. When a new manufacturing resource is added, the manufacturing capability model can be renewed to provide additional solutions to meet the requirements that come from process models.

4.2.4 OIM of process information modeling

Based on the analysis of process information structure, an OIM is established to describe the parameter-driven interactions between a feature and its manufacturing processes, as shown in Figure 4.10. The transparent objects in Figure 4.10 are objects defined for the process model. The solid objects are feature objects that have interactions with objects in the process model.

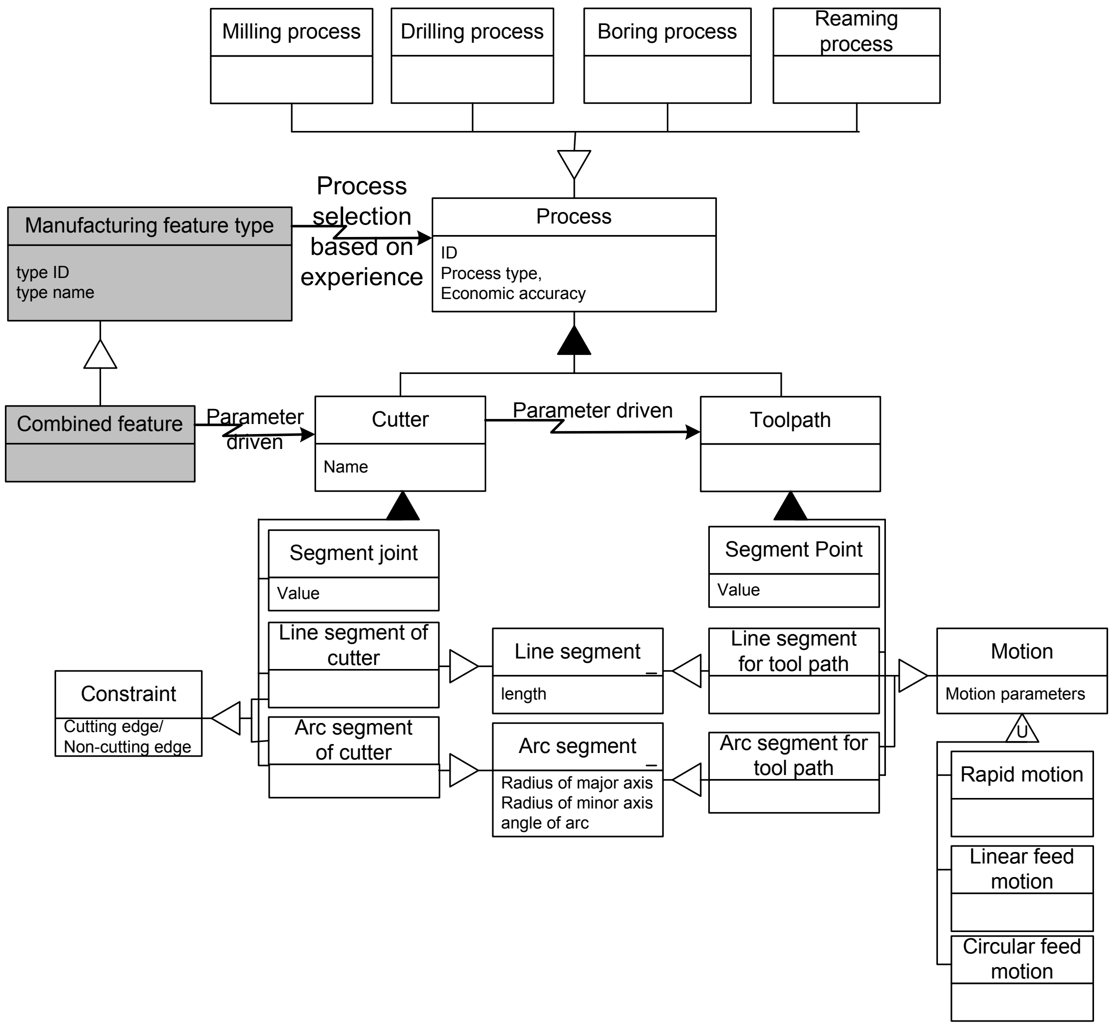


Figure 4. 10 OIM of the process model

4.3 Summary

In this chapter, combined features are defined based on the requirement of part families in the CAMP, and feature-level planning are realized by the process model that represents the fundamental characteristics of manufacturing strategies of combined features. Customized cutter and toolpath descriptions are studied in depth.

Chapter 5: Manufacturing Resource Capability Information Modeling

During the manufacturing planning activities in the CAMP, the optimal utilization of flexible manufacturing resources including cutters, machine tools, and fixtures, will increase production throughput and decrease manufacturing costs. Hence, the information content of manufacturing resource capabilities should be properly identified and represented in the CAMP so that engineers can manipulate them to make the accurate choices. Three resource capabilities: shape, dimension and precision, position and orientation capabilities are discussed in this chapter. The architecture to enable the integration of manufacturing resource capabilities to the CAMP is proposed as well.

5.1 Manufacturing resource capabilities

Parts are composed of features, which are associated with sequences of manufacturing processes. For ordinary processes, the regular manufacturing resources are machine tools, fixtures, and cutters. The interrelation of these resources constitutes three capabilities: feature shape capability, feature dimension and precision capability, and feature position and orientation capability (Zhang, Y., 1999). In this research, the capabilities are, respectively, modeled in three classes: shape capability class, dimension and precision capability class, and position and orientation capability class. These classes represent the commonality of the manufacturing resource objects. Because the planning is carried out on feature-by-feature basis, manufacturing resource capabilities will be mapped into part design specifications, including feature form, feature precision, and feature position and orientation, as shown in Figure 5.1.

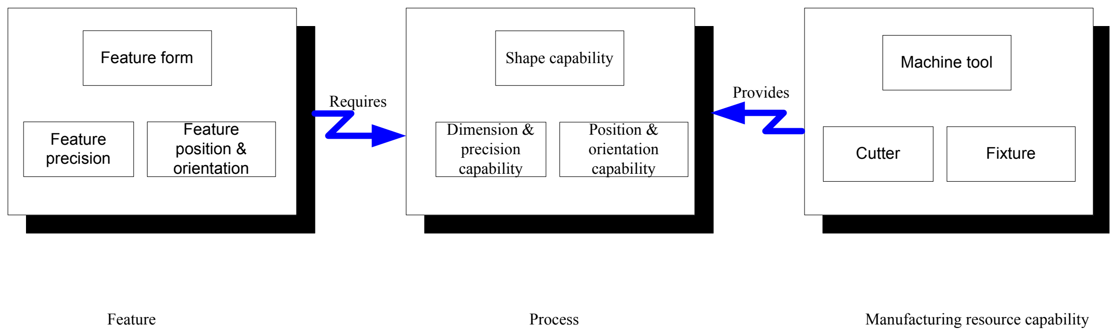
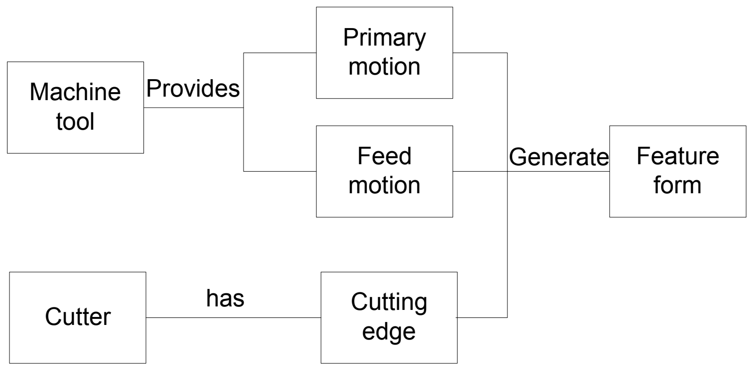


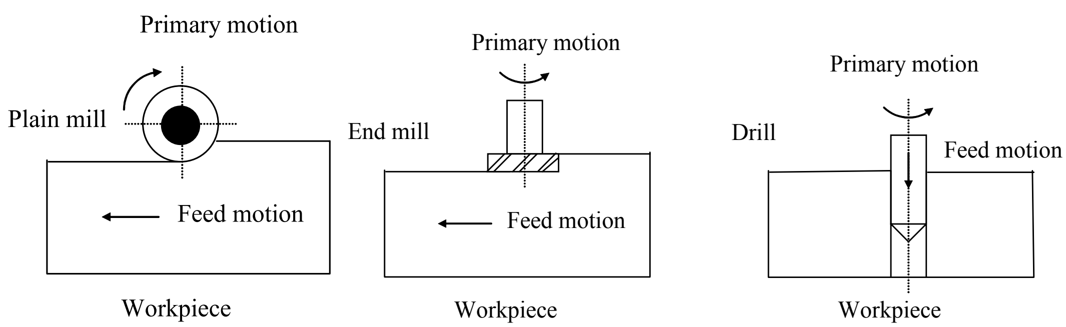
Figure 5. 1 Manufacturing resource capabilities mapped to feature's attributes

5.1.1 Shape capability

One purpose of manufacturing planning is to generate detailed NC codes for a desired part shape and feature forms. It involves three elements: the primary motion and feed motion that are provided by the machine tools, and the working edge of the cutters (Halevi, 1995). Sometimes the primary motion acts on parts and the feed motion acts on cutters, such as a typical lathe or a boring mill. In other cases, the primary motion acts on cutters and the feed motion acts on parts. The interactive relationships among a machine tool's primary motion, feed motion, and cutters' working edge express the capability of generating part shape and feature forms, as shown in Figure 5.2(a). In this research, non-rotational parts are always mounted on fixtures, and fixtures are installed on the worktables of machine tools. Therefore, in the manufacturing of non-rotational parts, the primary motion always acts on the cutters. The feed motions may act on either the non-rotational parts or the cutters. Figure 5.2(b) shows three cases of machine tool motions in the machining of non-rotational parts. Among them the feed motion acts on the cutters in the drilling process, while also acting on the part in the milling process.



(a) Feature form-generating process



(b) Cases of machining motion

Figure 5. 2 Feature form and shape generating processes

Usually, more than one machining process is suitable for cutting one feature form. In other words, a certain feature form could be produced by multiple combinations of primary motion and feed motion, which are provided by machine tools and cutters. Take a three-axis milling machine as an example: Figure 5.3 displays many-to-many relationships among the machine tool, cutters, and feature form.

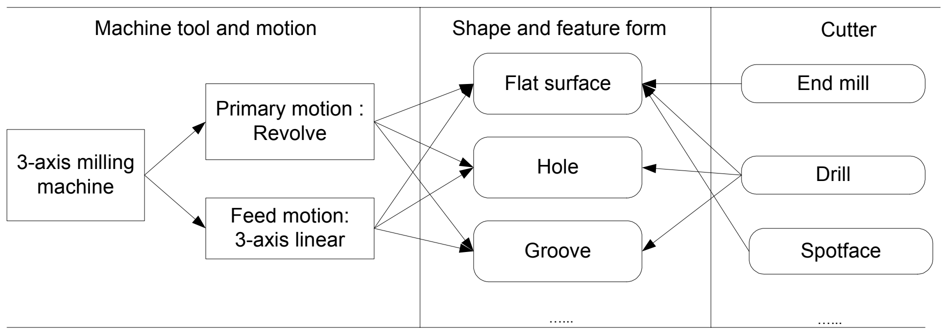


Figure 5. 3 Many-to-many relationships in shape capability analysis

In order to describe and maintain the many-to-many relationships, a shape capability class model is established, in which the machine tool's motions and cutters are included and associated with feature forms by the use of the process class. If several machine tools can provide the same motions, they are capable of producing the same feature form. Because it is easy to describe the machine tool's motions, the update and maintenance of the relationship among features, feature manufacturing strategies, cutters and machine tools becomes more convenient. Several widely used machine tools' motions are listed in Table 5.1, in which following machine tool types are illustrated: HMM, a horizontal milling machine, VMM, a vertical milling machine, HMC, a horizontal machining center and VMC, a vertical machining center. The shape capability class is shown in Figure 5.4.

Table 5. 1 Machine tool motions

Machine tool type	Process type	Primary motions	Feed motions
HMM VMM HMC VMC	Milling	Cutter revolves	2-axis linear motions
	Drilling, boring, Reaming		Along cutter axis
	Grooving … …		2-axis circular motions … …

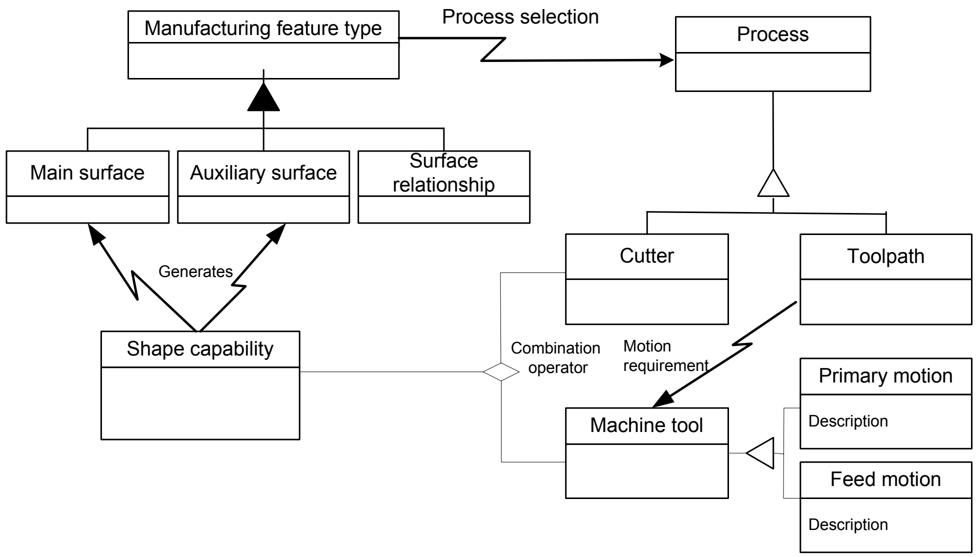


Figure 5. 4 Shape capability information model

5.1.2 Dimension and precision capability

Dimension and precision are the second important aspect of part specifications. Since no manufacturing resources can produce absolutely precise geometry, shape deviation, dimension deviation and surface roughness always exist. Every combination of machine tool, fixture, and cutter will assure a certain range of dimension, dimension tolerance, surface finish, form tolerance, position and orientation tolerance. In Zhang's research, they are classified into three subclasses: dimension capability, precision capability, and surface finish capability (Zhang, Y., 1999). It is pointed out that dimension and precision modeling is a very complicated domain. There are a lot of intricate and unpredictable reasons that cause different kinds of deviations (Halevi, 1995). Therefore, the experience in part families' BOP becomes quite precious, and it can be used as a reference to ensure the dimension precision in part manufacturing.

1. Dimension capability

Dimension capability is the means to measure the maximum and minimum dimensional range of a workpiece and its features. It is primarily derived from the working space of machine tools, cutters, and fixtures. (Zhang, Y., 1999) For example, the dimension capability of a horizontal machine tool is the diameters of its round workbench, which at the same time constrain the fixtures' dimensions. A machine tool's dimension capability is defined as the attribute of a machine tool class, as shown in Figure 5.6. Cutters can be classified into two types: scattered dimensional series (i.e., drill, reamer, etc) and free dimensional cutters (i.e., milling cutters). The dimensional limitation of a feature could be inferred from its cutters. The Cutter dimension capability is defined as the constraint used to drive the cutter templates to generate cutters.

2. Precision capability

Precision capability is designed to allow manufacturing planning systems to select appropriate manufacturing resources, in order to satisfy precision requirements in features and feature relationships. The source that causes precision errors has been discussed in Zhang's research (Zhang, Y., 1999). In this research, the part families' BOP is the most important reference for selecting machine tools, fixtures, and cutters that have the same precision specifications as those in the BOP.

3. Surface finish capability

Surface finish depends on machining methods, cutting condition, cutting tool material, and workpiece material. It is assumed in this research that the manufacturing methods from part families' BOP will ensure the surface finish requirement.

5.1.3 Position and orientation capability

Most mechanical parts consist of more than one feature, and they are usually in different normal directions. Some of them have complex position and orientation relationships, such as perpendicularity, angularity, parallelism, position, concentricity, circular runout, and total runout. If all features could be machined in one setup, the position and orientation tolerance requirements could be satisfied by the machine tool itself. Otherwise, they must be guaranteed by a certain combination of machine tools and fixtures. In other words, the capability to generate feature position and orientation is obtained by the combination of the machine tool and fixtures.

1. Position capability

There are four coordinates established in the CAMP: the machine tool coordinate, the fixture coordinate, the part coordinate, and the feature coordinate. A feature's position in a machine tool coordinate $P^{CS_{machine}}$ is transformed as:

$$P^{CS_{machine}} = [T_{CS_{machine}}^{CS_{fixture}}] \times [T_{CS_{fixture}}^{CS_{part}}] \times [T_{CS_{part}}^{CS_{feature}}] \times P^{CS_{feature}} \qquad \text{(Equation 5.1)}$$

$[T_{CS_{machine}}^{CS_{fixture}}]$ is the transformation matrix from $CS_{fixture}$ to $CS_{machine}$; $[T_{CS_{fixture}}^{CS_{part}}]$ is the transformation matrix from CS_{part} to $CS_{fixture}$; $[T_{CS_{part}}^{CS_{feature}}]$ is the transformation matrix from

$CS_{feature}$ to CS_{part}. (See Figure 5.5). Therefore, position capability is obtained by the combination of machine tools and fixtures.

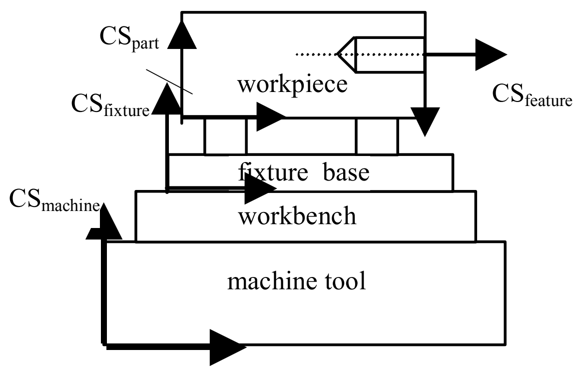


Figure 5. 5 Feature's position in machine tool's coordinate

2. Orientation capability

In the CAMP, multi-axis CNC machine tools are used to reduce the setup number so that machine error stack up can be minimized. One setup is a group of manufacturing processes that can be carried out on one fixture and one machine tool. Since the fixtures are used to hold a part onto machine tools and align manufacturing features' normal directions with the cutter approaching directions, the orientation capability is achieved by the cutter approaching directions, which are provided by the machine tool and fixtures. If more than one cutter approaching direction can be provided by the combination of machine tools and fixtures, features that have different normal direction can be machined in one setup, so that the manufacturing costs and time are greatly reduced. The strategies of setup planning should be adjusted according to the orientation capability of machine tools and fixtures. Table 5.2 shows the cutting tool axis direction (TAD) provided by several typical CNC machine tools. Figure 5.6 shows the position and orientation capability class.

Table 5. 2 TAD provided by machine tools

Machine tool type	Cutter approach direction
21/2 axis	Along Z axis of machine tool coordinates
3 axis	Along Z axis of machine tool coordinates
31/2 axis	In ZOX of machine tool coordinates
4 axis	In ZOX of machine tool coordinates

Note: In machine tool coordinate, cutter axis is defined as Z-axis.

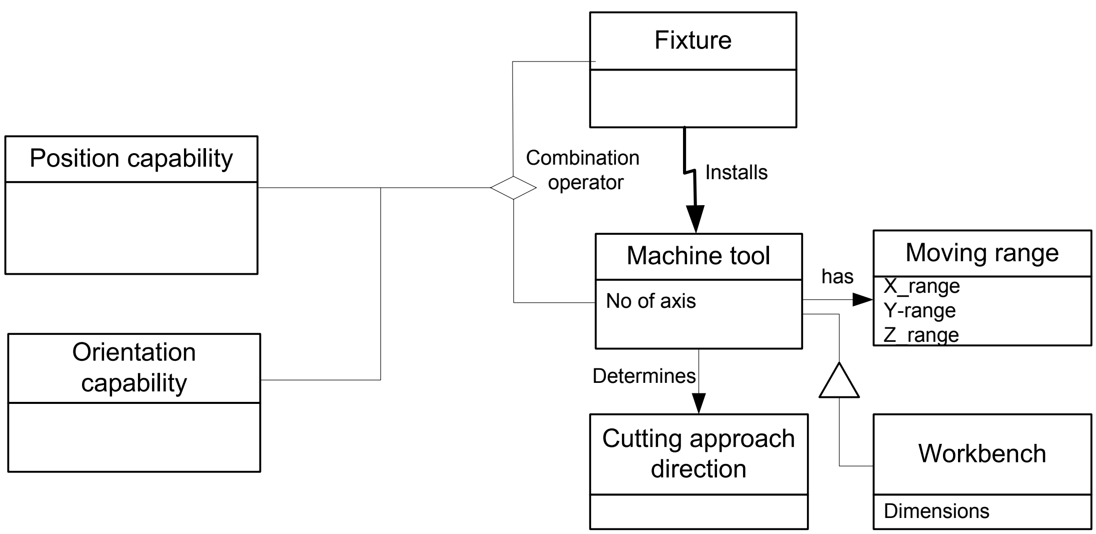


Figure 5. 6 position and orientation capability

Based on the above analysis, the information regarding manufacturing resources in BOP can be stored in the format of manufacturing resource capabilities, instead of the collection of machine tools, fixtures and cutters. Therefore, more manufacturing resources can be considered in the manufacturing planning activities.

5.2 Integration of manufacturing resource capabilities in the CAMP

As previously indicated, the tasks carried out by the CAMP are designed in three levels of planning: the feature-level, the part setup planning level and the machine-level. Therefore, the consideration of manufacturing resources is also divided into three steps, in which the effect and contribution of machine tools, fixtures and cutters are properly identified and utilized, resulting in the achievement of optimal manufacturing cost. A summary of the three levels is presented in Table 5.3.

Table 5. 3 Three levels of manufacturing resource capabilities in the CAMP

Level	Name	Objective
1	Feature manufacturing strategy determination	Selection of combination cutters and toolpath for individual features
2	Setup planning	Determination of machine tools' and fixture's capabilities
3	Manufacturing plan generation	Determination of machine tools and fixtures used in the manufacturing systems

Level 1: Determine cutters and toolpath to manufacture individual features

At this level, a feature's form, dimension, and precision attributes are taken into consideration and manufacturing resource's shape, dimension, and precision capabilities are incorporated. Based on a feature-level BOP, some candidate feature's manufacturing strategies are selected along with the cutters, toolpath, and the requirement to the machine tool's motions.

Level 2: Design the setup plans within the consideration of flexible machine tool capabilities

A feature's position and orientation attribute is achieved in this level. Therefore, position and orientation capability of manufacturing resources is considered in this level, based on the available machine tools and fixtures.

Level 3: Determine the part layout on fixtures and try to utilize machine tool capability completely to achieve minimum cycle time

Since several parts may be machined on one fixture in the CAMP, a feature's position and orientation attribute should be reconsidered in this level, as should the corresponding machine tools' moving range and worktable dimensions in order to accommodate feature's position and orientation.

The three-level integration of manufacturing resource capabilities in the CAMP are shown in Figure 5.7. By using these integration of manufacturing resource capabilities during the manufacturing planning activity, engineers can easily identify the critical factors within manufacturing resources that affect manufacturing costs and time frame of manufacturing plans, and make a quick decision on the choice of machine tools, fixtures, and cutters for specific manufacturing plans.

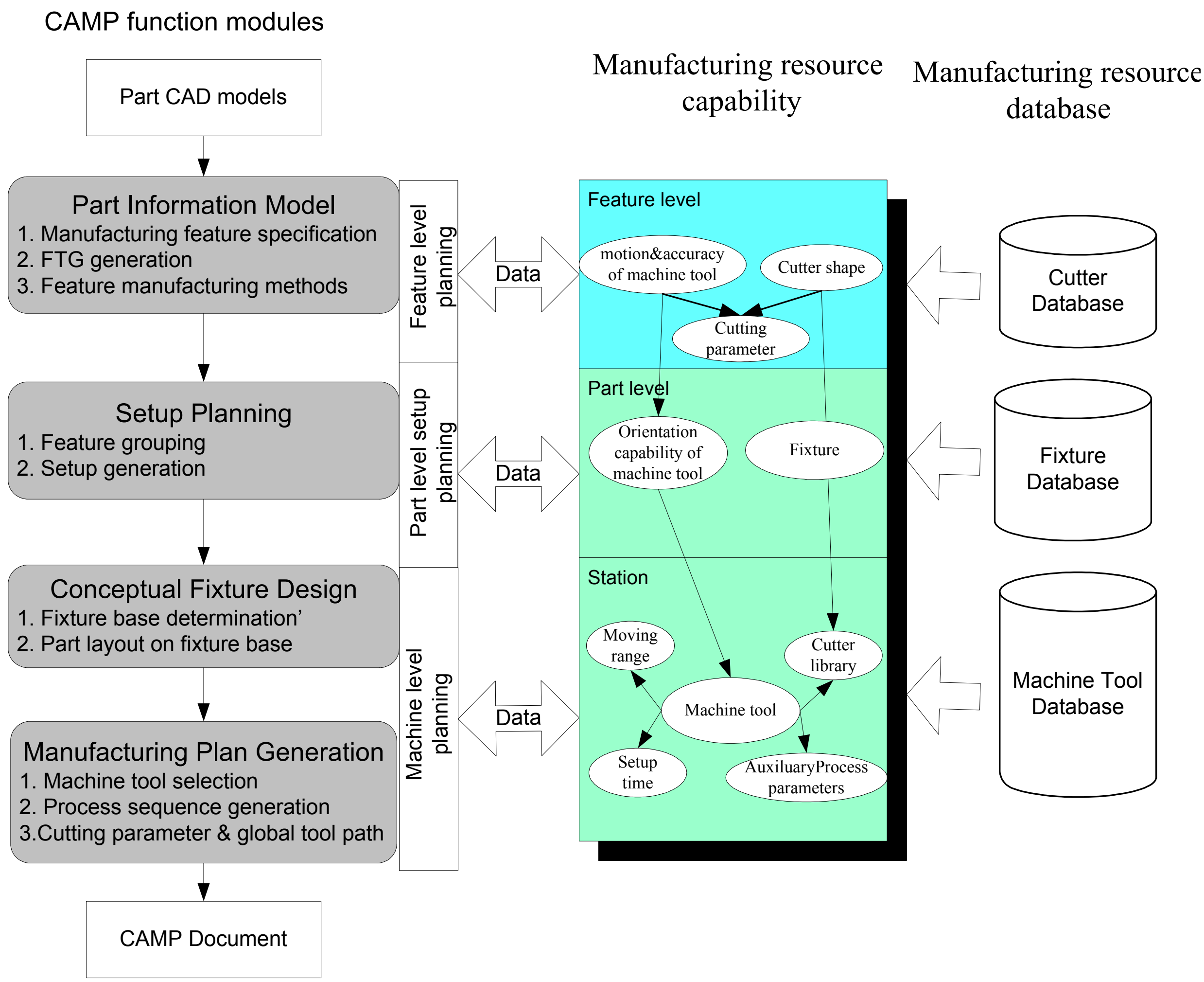


Figure 5. 7 Integration of manufacturing resource capability in the CAMP

5.3 Summary

In this chapter, three manufacturing resource capabilities: shape, dimension and precision, position and orientation capabilities have been studied in detailed and their O-O information models are established. Correspondingly, the mechanism of the integration of manufacturing resource capabilities with the CAMP has been proposed.

Chapter 6: Graph-based Setup Planning

In this chapter, part-level setup planning is discussed to determine how many setups are needed to machine a part and what kinds of manufacturing resources are involved in the manufacturing. Graph theory is applied to represent the part and setup planning information. A systematic approach is proposed for setup planning based on analyses of tolerance and manufacturing resource capabilities, along with the BOP of part families.

6.1 Setup planning methods

Setup planning plays a crucial role in manufacturing planning activities to ensure product quality while maintaining acceptable manufacturing cost. The task of setup planning is to determine the number of setups, the part orientation, locating datum, manufacturing features and the process sequence in each setup. The analysis of part information is always the starting point of setup planning. The maintenance of tolerances is the main goal of setup planning. Moreover, with the utilization of flexible manufacturing systems along with CNC techniques in industry, multiple manufacturing operations can be carried out in a single setup. Hence, manufacturing resource capabilities serve as the major constraints that influence setup planning strategies. Finally, precedence constraints should be applied to determine the sequence of the setup and the process sequence in each setup so that the optimal manufacturing time and costs can be achieved.

The information dealt with in the setup planning includes part design specifications and setup planning information. As discussed in Chapter 3, part design information is composed of combined features and the relationships between combined features. The relationships between features are those position and orientation tolerance specifications that consist of datum and target features. These tolerance relationships in part design are many-to-many relationships. On the other hand, information in one setup includes datum features and machining features. Datum features are used to generate datum reference frames, reference coordinate systems, to secure other features in the same part (Zhang, Y., 2001). In most cases, datum features can serve as locating features. Therefore, the information in setup planning can be represented by the relationships among datum features and machining features. They also have many-to-many relationships.

Graph theory has been proven a good tool for representing many-to-many relationships. A graph consists of two sets: a finite set V of elements, called vertices, and a finite set E of elements, called edges. Each edge is identified with a pair of vertices. Part information can be described by a FTG, in which features are represented by vertex and tolerances are represented by edges of FTG. On the other hand, setup information is described by a DMG, in which datum features and machining features are the vertex. The relationships between datum features and machining features are the specified tolerances and errors in each setup. These errors consist of locating errors, cutting tool errors, other deterministic errors, and random errors (Rong, 1999). Hence, the task of setup planning is to transform FTG into DMG and to ensure that the errors in setups do not exceed tolerance specifications.

In order to maintain tolerances between two features within the specified span, three setup methods are used: (Ⅰ) machining the two features in the same setup; (Ⅱ) using one feature as the locating datum and machine the other; (Ⅲ) using an intermediate locating datum to machine the two features in different setups. It is concluded (Rong, 1999) that setup method I consists of the least machining errors because it has no locating errors. Setup method II consists of locating errors, and less accuracy is usually produced than those obtained using setup method I. However, it is still regarded as a good method when the two features cannot be machined in the same setup. Setup method III is the least desired setup method. A tolerance stackup is formed by every setup including the two features. If the tolerance is tight, setup method III should be avoided.

Hence, tolerance information in part design should be considered the first priority when choosing the setup methods. The following principles are derived for the setup planning:

- Select the maximum number of features that can be synchronously machined. This will reduce the number of critical tolerances between features belonging to different setups;
- Keep the number of setups as low as possible so that manufacturing costs can be minimized.

In addition to tolerance issues in setup planning, manufacturing resource capabilities are important constraints in the generation of setups. Although as many features as possible are suggested to be machined in one setup, the machine tool available may not have the capabilities to execute all the processes. Therefore, manufacturing resource capabilities should be taken into consideration in setup planning.

Except for the generation of setups, the sequence of setups and sequence of processes in each setup should be determined in setup planning. Precedence constraints are applied to determine the above-mentioned sequence. The precedence constraints can be divided in two groups: physical constraints, which determine the feasibility of a setup and process sequence, and economical rules, which help to generate optimal solutions.

In the CAMP, parts in the same family have similar features and feature tolerance relationships. Hence, similar setup planning strategies may be applied by the use of similar manufacturing resource capabilities and similar precedence constraints. The setup planning in mass customization will be carried out in two ways: One is to automatically design setup plans for part families and store them in BOP; here optimum process sequence and parameters are determined based on tolerance analysis and manufacturing resource capability analysis. The other means is to extract existing setup plans from a part family's BOP and revise them manually to suit the new part design. A procedure of setup planning for mass customization is shown in Figure 6.1. The input information is feature-based part information that is represented by FTG. BOP of setup plans is represented by DMG and stored in databases. If a family's BOP doesn't exist, automated setup planning will be carried out based on tolerance analysis, manufacturing resource capability analysis, and the application of precedence constraints. The application of graph theory and information representation of FTG and DMG will be discussed in Section 6.2.

Automated setup planning will be discussed in Section 6.3, and a summary of the research on setup planning will be given in Section 6.4.

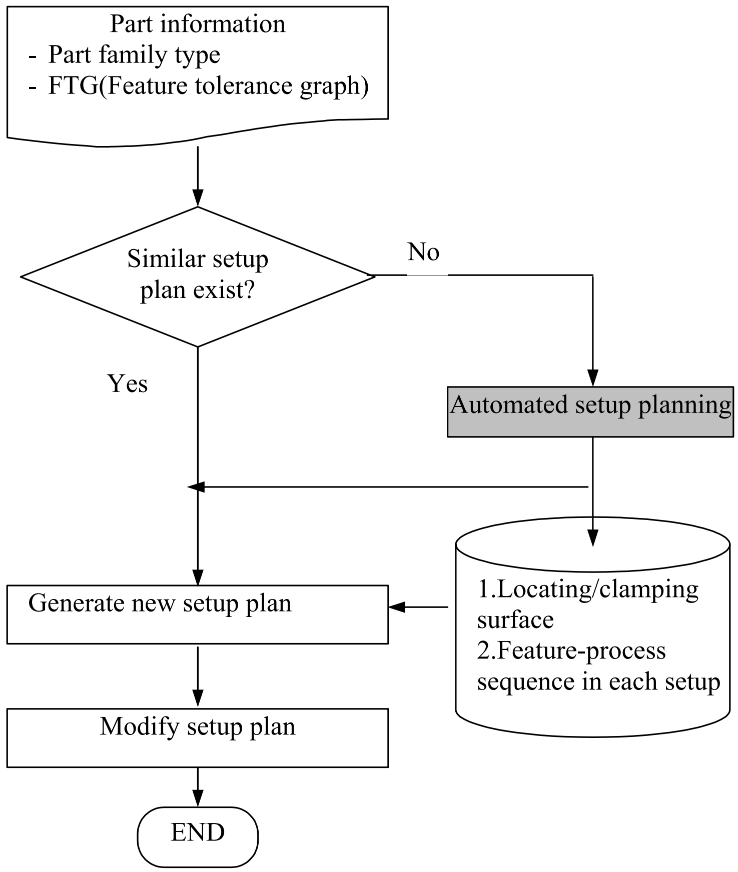


Figure 6. 1 Procedure of setup planning

6.2 Graph theory, FTG and DMG

6.2.1 Basic concepts of graph theory

A *graph* is an ordered triple G = {V, E, I}, where V is a nonempty set of vertices of G; E is a set disjoint from the elements in V, which represents the edges of G; and I is an incidence map that associates with each element of E. Figure 6.2(a) shows a general graph. If all the elements in E connect ordered pair of vertices, then G is called a *directed* graph, as shown in Figure 6.2(b). For two vertices v1 and v2, if edge e1 is the only edge joining them, then I(e1) = v1v2. A set of two or more edges that connect the same vertices is called a set *of multiple or parallel* edges, like the edge e1 and e7 in Figure 6.2(a). An edge whose two ends are the same is called a *loop* at the common vertex, such as the edge e6 in Figure 6.2(a). A graph is *simple* if it has no loops and no multiple edges. Thus for a simple graph G, the incidence function I is one-to-one. Hence, a simple graph G may be considered as an ordered pair {V, E}. A graph H is considered as a subgraph of G if $V(H) \subseteq V(G), E(H) \subseteq E(G),$ and I_H is the restriction of I_G to $E(H)$. Figure 6.2(c) shows a subgraph of Figure 6.2(b).

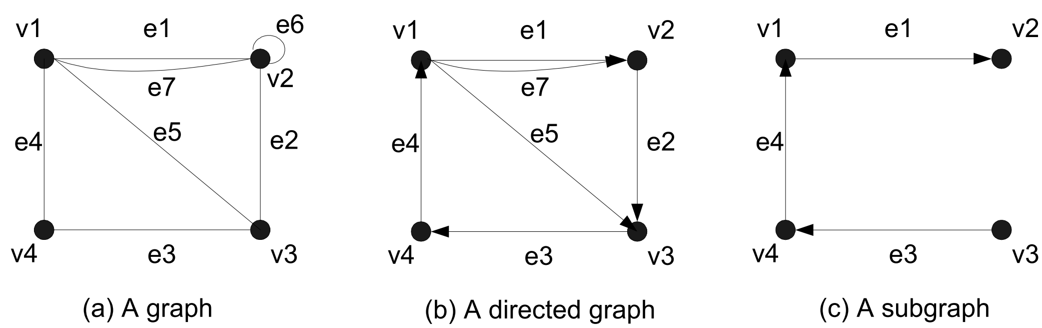


Figure 6. 2 Graph examples

Let G be a graph and v be a vertex, such that $v \in V$. The number of edges incident at v in G is called the degree of the vertex v in G and is denoted by $d(v)$. The in-degree $d^-(v)$ of v is the number of edges incident into v and the out-degree $d^+(v)$ is the number of edges incident out of v and the neutral-degree $d^0(v)$ is the number of undirected edges incident on v. A loop at v is to be counted twice in computing the neutral-degree of v. Hence:

$$d(v) = d^{-}(v) + d^{+}(v) + d^{0}(v) \qquad \text{(Equation 6.1)}$$

For example, for the vertex v2 in Figure 6.2(b), its in-degree is 2, its out-degree is 1, and neutral-degree is 0.

A *walk* in a graph G is an alternating sequence W: $v_0 e_1 v_1 e_2 v_2 e_{3\ldots} v_n e_n$ of vertices and edges beginning and ending with vertices in which v_{i-1} and v_i are the ends of e_i; the walk is *closed* if $v_0 = v_n$ and is *open* otherwise. A walk is called a *trail* if all the edges appearing in the walk are distinct. It is called a *path* if all the vertices are distinct. Thus a path in G is automatically a trail in G. The concepts of path are useful in setup sequencing and process sequencing.

New graphs can be generated by the use of operations on graphs, which include: add a vertex, remove a vertex, join two vertices, unite two graphs and subtract graph1 from graph2. Examples of these operations are shown in Figure 6.3.

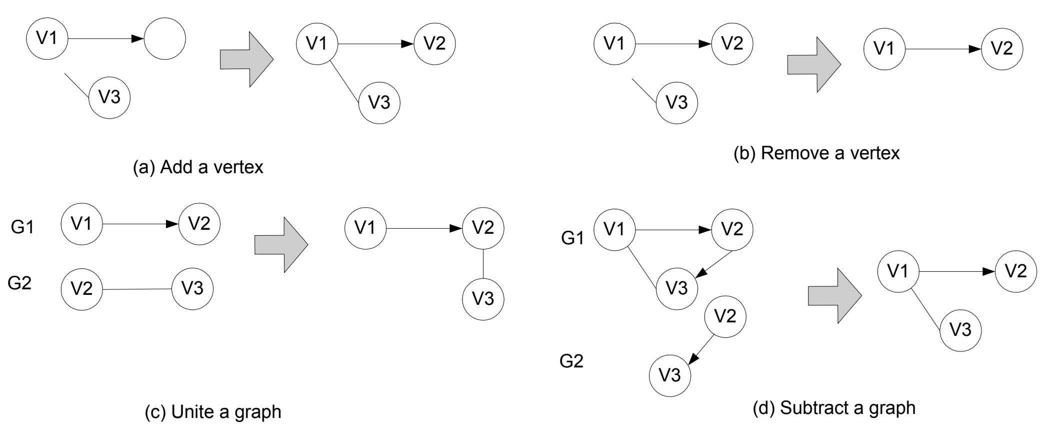


Figure 6. 3 Main operations in graph theory

Figure 6.4 shows the ORM of a graph. It is the O-O representation of a general graph. The incidentMap is an object that describes the edge attribute. In different kinds of graphs, it may have different meanings.

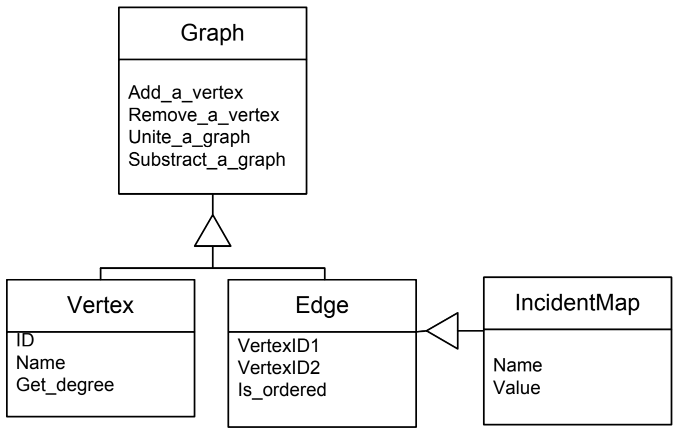


Figure 6. 4 ORM of a graph

6.2.2 Feature tolerance relationship graph (FTG)

Part information is composed of features and feature relationships. Each feature has one main surface that determines the feature's position and orientation in the part coordinate. Auxiliary surfaces of features have position and orientation relationships with the main surface. Hence, the feature relationships in part information is considered in two levels: the relationships between features, and the relationship between surfaces in one feature, which has been discussed in Chapter 4.

The relationships between features are the dimensions and tolerance specifications between the main surfaces of the features. FTG is used to represent these relationships, in which vertices represent features, edges represent dimensions and tolerances between features, and incident maps represent the relationship types and values. Relationship types between features are shown in Table 4.3, which are the same as those between surfaces within a feature. Among them, a pair of unordered vertices represents the dimension tolerances, and a pair of ordered vertices represents the position and orientation tolerances. Sometimes, there may exist more than one tolerance between two features. Hence, a FTG of a part is a graph that has undirected edge, directed edge and multiple edges. It is not a simple graph. Following is the mathematical representation of FTG:

$$G_{FTG} = \{F, T\} \quad \text{(Equation 6.2)}$$

$$F = \{f_1, f_2, ..., f_n\} \quad \text{(Equation 6.3)}$$

$$T = \{t_1, t_2, ..., t_m\} \quad \text{(Equation 6.4)}$$

$$t_j = \{f_i, f_k, t_{type}, t_{value}\} \quad \text{(Equation 6.5)}$$

where: $f_1, f_2, ..., f_n$ is a nonempty set of vertices of a FTG; each vertex represents one feature, $t_1, t_2, ..., t_m$ is the set of edges of FTG; each edge is associated with the features and the relationship type and the relationship value. If the relationship type is a dimension with or without tolerance, the edge is an undirected edge. If the relationship type is a position or orientation tolerance, the edge is a directed edge and the first feature is the datum feature of the tolerance.

Figure 6.5 shows a FTG of the sample part in Figure 4.1, which clearly expresses the relationships between features. X, Y and Z are pre-defined datum surfaces that are mutually perpendicular to each other. Feature A and A’ are two holes that are used to mount calipers on the brake systems. There exists a dimension tolerance between them, and a certain parallelism is required. The same situation exists between B and B’. The dimension tolerance is represented by an undirected edge, and the parallelism is drawn by a directed edge. Hence, there are multiple edges between A and A’, B and B’.

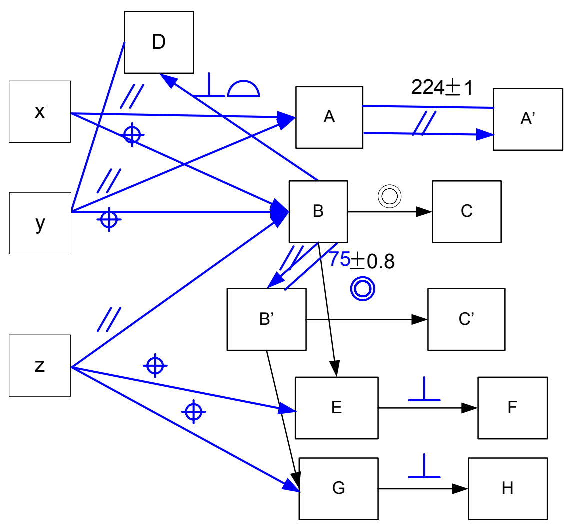


Figure 6. 5 FTG of the simplified caliper

However, features are associated with particular manufacturing strategies, each of which may consist of several processes. Each process has its own TAD. Hence, a FTG is extended to link features’ manufacturing strategies on the features. For a particular part, its FTG is unique, but it may have several extended FTGs, since one feature may have alternative manufacturing strategies. As a result, the task of setup planning is to design setups that can finish all the manufacturing processes linked to the features of a FTG. Figure 6.6 shows one of the extended FTG of the example caliper.

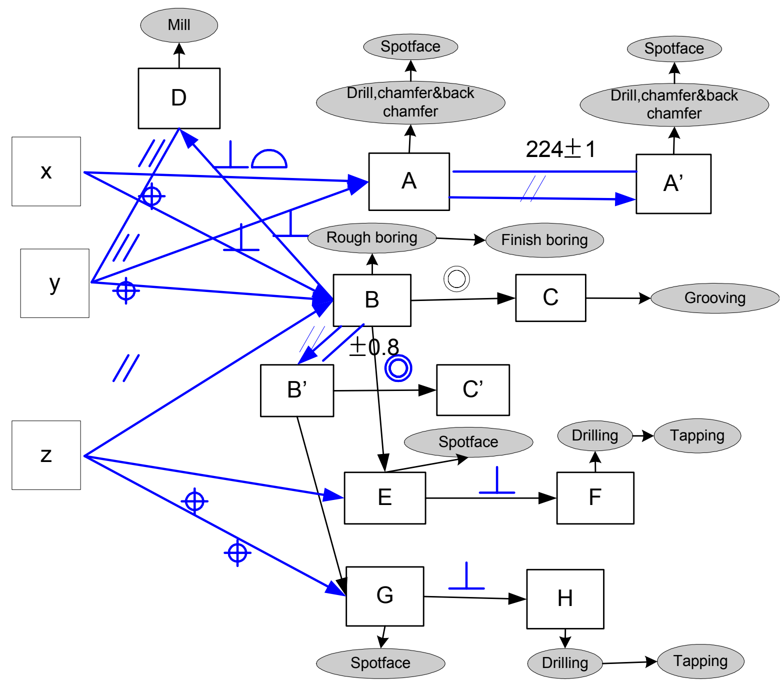


Figure 6. 6 FTG with the consideration of features' processes

Hence, an extended FTG is mathematically represented as follows:

$$G^{E}_{FTG} = \{F, T\} \quad \text{(Equation 6.6)}$$

$$F = \{f_1, f_2, ..., f_n\} \quad \text{(Equation 6.7)}$$

$$f_i = \{p_{i1}, ..., p_{io}\} \quad \text{(Equation 6.8)}$$

where: $f_1, f_2, ..., f_n$ is the feature set of a part; each feature has its own manufacturing processes $\{p_{i1}, ..., p_{io}\}$; the definition of T is the same as FTG

Figure 6.7 shows the ORM of extended FTG.

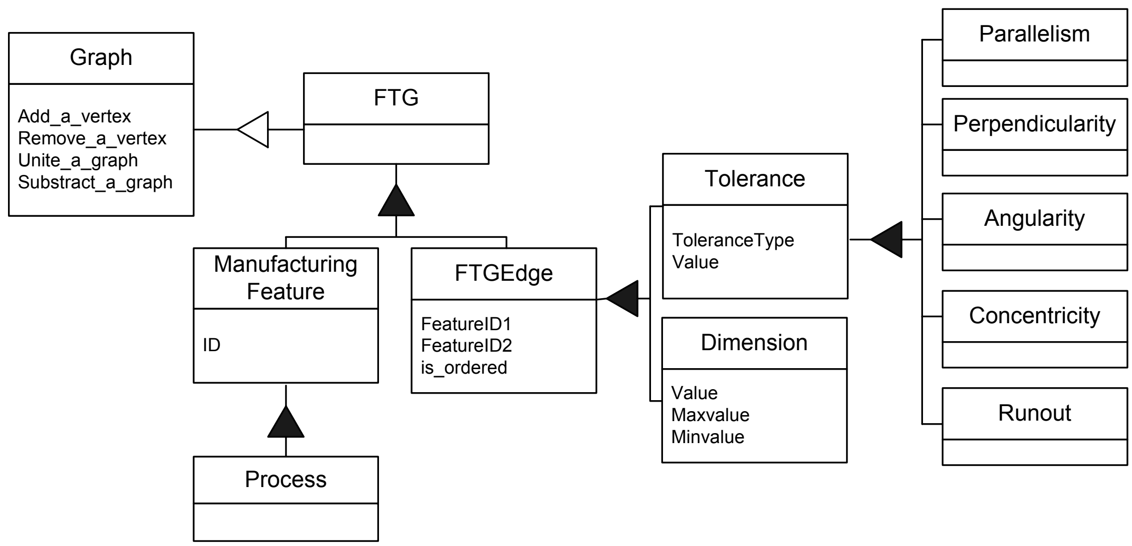


Figure 6. 7 ORM of Extended FTGs

6.2.3 Datum and machining feature relationship graph (DMG)

Setup planning is to determine how many setups are needed to machine a part, and within each setup, to determine the datum features and manufacturing features' processes that can be finished in the setup. Hence, the information of setups should include datum features, manufacturing features, and their processes. In order to fulfill the tolerance requirements between features, the errors caused by the manufacturing processes should also be recorded.

The information regarding setup planning can be represented by the relationship between datum features and manufacturing features, which is called a DMG. A DMG includes one or many subgraphs, and each subgraph represents one setup. In DMGs, vertices are classified into two sets: the datum features (gray solid vertices) and manufacturing feature (transparent vertices). An edge, which is associated with machining errors, marks the relationship between the datum feature and the target feature. A dashed line is used to connect the same feature in different setups. Figure 6.8 shows a DMG of the example caliper. By using DMGs, it is easy to track back the machining error stackup (Zhang, Y., 2001).

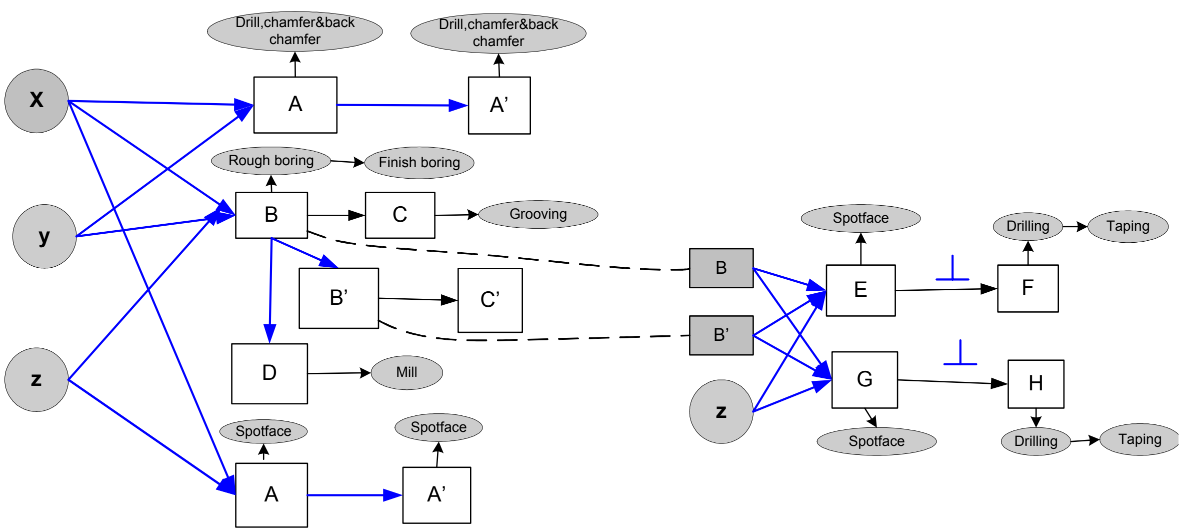


Figure 6. 8 A DMG of the caliper

The mathematical representation of DMG is as follows:

$$G_{DMG} = \{G^{s}_{DMG1}, G^{s}_{DMG2}, ..., G^{s}_{DMGn}\} \qquad \text{(Equation 6.9)}$$

$$G^{s}_{DMG} = \{D, F, Er\} \qquad \text{(Equation 6.10)}$$

$$D = \{D_1, D_2, D3\ \} \qquad \text{(Equation 6.11)}$$

$$F = \{f_1, ..., f_m\}$$ (Equation 6.12)

$$f_i = \{p_{i1}, ..., p_{io}\}$$ (Equation 6.13)

$$Er_j = \{f_i, f_k, er_{type}, er_{value}\} \text{ , } where f_i \subset D \cup F, f_k \subset F$$ (Equation 6.14)

where: DMG is composed of subgraphs, each of which represents one setup. A setup consists of datum features, manufacturing features, and machining errors generated in the setup. The er_{type} is the same as t_{type} defined in Equation 6.5.

Figure 6.9 shows the ORM of DMG.

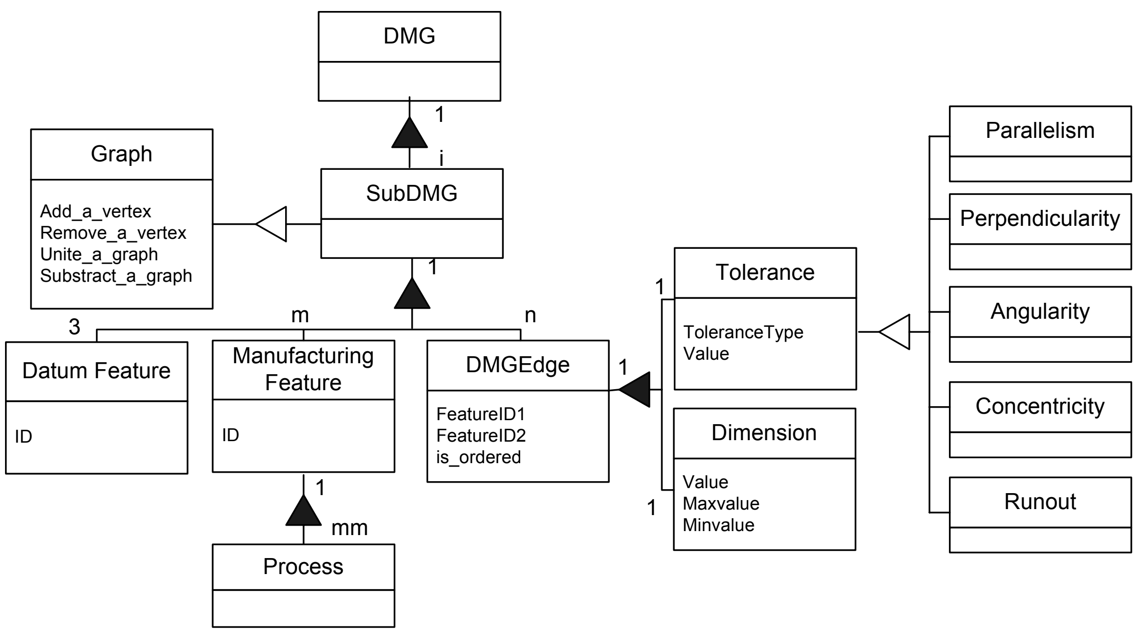


Figure 6. 9 ORM of DMGs

6.3 Automated setup planning

Since the input and output information in setup planning can be represented by FTGs and DMGs respectively, the problem of setup planning is to transform an extended FTG into DMGs based on tolerance analysis and manufacturing capability analysis. Figure 6.10 shows the procedure of automated setup planning, which is carried out in three steps: feature grouping, setup generation, setup and process sequencing. In feature grouping, tolerance analysis is carried out to identify those features in FTG that have tolerance relationships and to suggest machining them in one setup. The locating datum of each feature group is also identified in the feature grouping step. The information generated in this step is represented by DMG1, which is a rough description of setup plans. In the second step, it is the manufacturing resource capabilities that finally determine the number of setup needed, the setup sequence, workpiece orientation, features, and the sequence of the features' machining processes in each setup. This information is represented by DMG2, which is the final result of setup plans. The tolerance relationships in each setup are clearly shown in DMG2. Different manufacturing resource capabilities may lead to different setup plans, resulting in different manufacturing resource capability utilization. As discussed in Chapter 5, manufacturing resource position and orientation capability are mainly utilized in setup planning. In the last step, precedence constraints are applied to generate a walk through all vertices on DMG2 in order to determine setup sequence and process sequence in each setup.

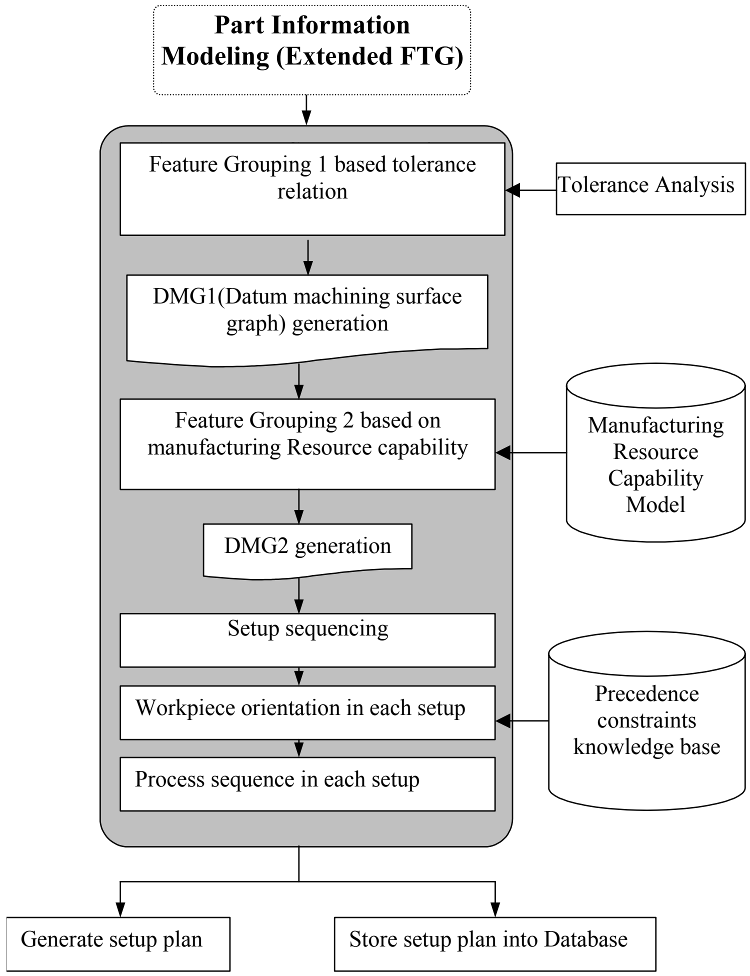


Figure 6. 10 Procedure of automatic setup planning

6.3.1 Feature grouping based on tolerance analysis

In order to minimize the inter-setup tolerance stackup, it is suggested to group those features that have close position, orientation, or profile tolerance requirement to be machined in one datum frame. An algorithm is developed to extract feature groups from FTG, as shown in Table 6.1. The basic idea is to calculate the degree of vertices in the FTG.

Table 6. 1 Algorithm for feature grouping based on tolerance analysis

1	/* Construct the FTG of a part, and calculate the degree of each vertex */ $d(v) = d^-(v) + d^+(v) + d^0(v)$
2	/*Find initial datum features */ Features whose in-degree $d^-(v) = 0$ are datum features
3	/* Find feature groups associated with initial datum features/ The chained vertices will be identified that begin with the features that have edges linked with all initial datum features whose in-degree $d^-(v) >= 3$ and end by the features whose out-degree $d^+(v) = 0$.
4	A) If all the features are included in above feature groups, go to step 5 or else find an intermediate datum frame B) The features in an intermediate datum frame should be included in found feature groups and act as the datum features of ungrouped features (one-way or directed edge) or linked an ungrouped feature by a two-way edge. Find chained vertices based on intermediate datum frame Repeat step 1, 2, 3 until all the features are grouped
5	End

For the FTG shown in Figure 6.5, in step 2, feature x, y and z are found as initial datum features. In step 3, Features A and B have three edges linking with x, y and z respectively, and feature groups (A, A'), (B, D), (B, C), (B, B', C') are identified as groups. In step 4, features E, F, G and H have not been included in the above feature groups. Hence, an intermediate datum frame is needed. Through the BOP of fixture planning, features B, B' and z are identified as the intermediate datum features and feature groups (E, F) and (G, H) are constructed. The feature groups and corresponding datum features are listed in Table 6.2.

Table 6. 2 Feature grouping of the caliper

	Manufacturing features	Datum
Group 1	A, A’	x, y, z
Group 2	B.D	x, y, z
Group 3	B, C,	x, y, z
Group 4	B’, B’, C’	x, y, z
Group 5	E, F	B, B’, z
Group 6	G, H	B, B’, z

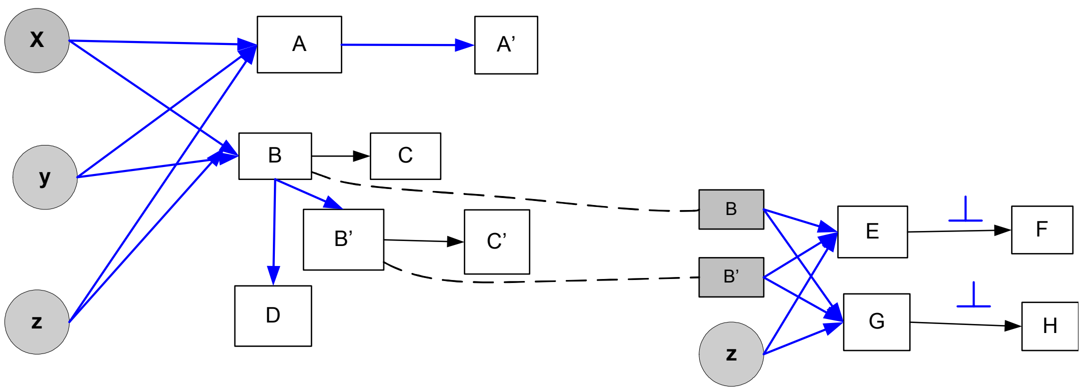


Figure 6. 11 DMG1

By the use of the algorithm shown in Table 6.1, a FTG is transferred into DMG1, in which initial setups have been generated and datum features and manufacturing features that are suggested to be machined in one setup are grouped into clusters. Figure 6.11 shows that two initial setups are generated based on the analysis of dimension and tolerance relationships between features. The manufacturing features that have the same datum features can be machined in the same setup.

6.3.2 Setup formation based on manufacturing resource capability

The next step of setup planning is to consider the manufacturing resources capabilities. First, features in DMG1 are attached with the manufacturing processes, as shown in Figure 6.12. Each process has its own TAD. Those feature processes that have similar datum frames and TAD can be reunited into one group. Table 6.3 shows the results. The TADs are given based on part coordinate systems that are pre-defined on the example part.

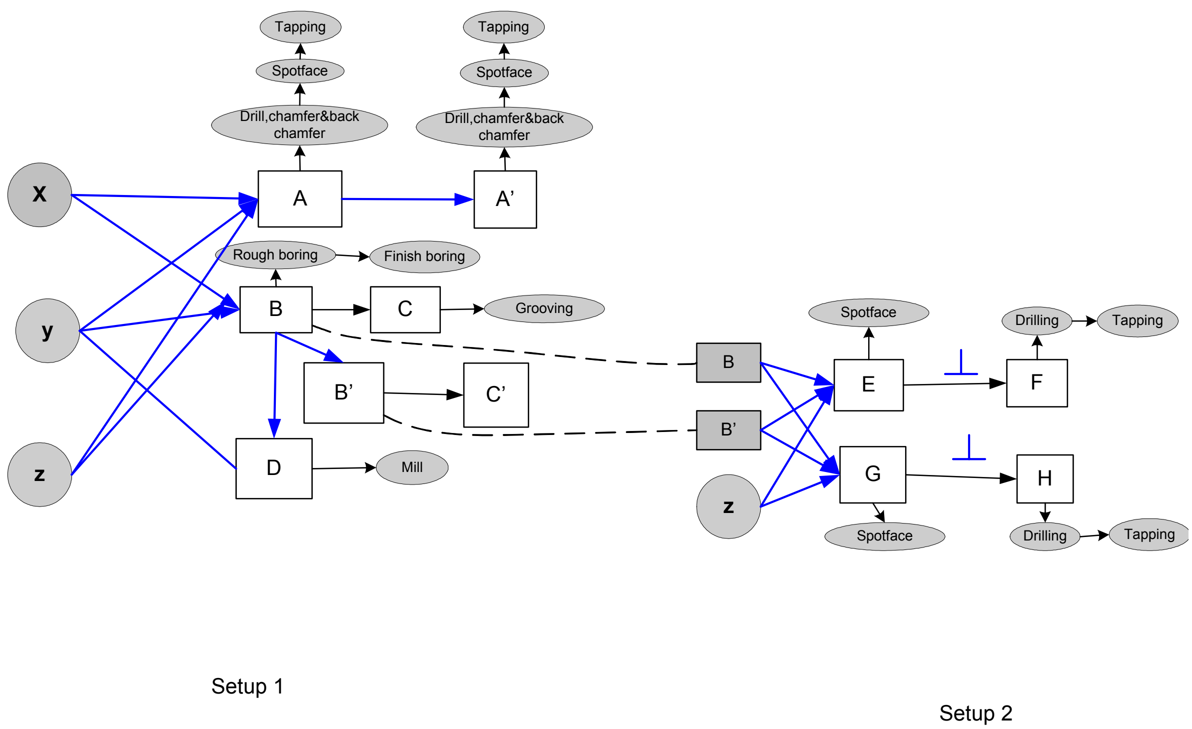


Figure 6. 12 DMG1 with processes

Table 6. 3 Feature-process grouping

	Manufacturing features	Machine tool	Datum	Tool access direction (TAD)
Group 1	A (Drilling, chamfer & back chamfer) A' (Drilling, chamfer & back chamfer) B, B' (Rough boring, finish boring) C, C' (Grooving)	3-Axis machine center	x, y, z	+X
Group 2	A (Spotface) A' (Spotface) D (milling)	3-Axis machine	x, y, z	-X
Group 3	A (tapping) A' (tapping)	3-Axis machine	x, y, z	+X or -X
Group 4	E (Spotface) F (Drilling, Tapping)	3-Axis machine	B, B', z	-0.6Y +0.8Z
Group 5	G (Spotface) H (Drilling, Tapping)	3-Axis machine	B, B', z	0.6Y +0.8Z

Note: TAD is in the sample part coordinate.

Second, manufacturing resources are selected to execute all processes in each group. As discussed in Chapter 4, the toolpath of each process generates the basic requirement to machine tool motion capability, which is shown in Table 6.3. For the example part, a 3-axis machine is the basic requirement, and therefore four setups are needed, in which group 3 can be carried out with group 2 using of the precedence constraint to maintain the feature manufacturing sequence. Figure 6.13 shows the corresponding DMG2. In a Comparison with part FTG, it can be seen that there is a perpendicular tolerance requirement between features B and D. In this solution, B and D are machined in different setups and a tolerance stackup between B and D is generated.

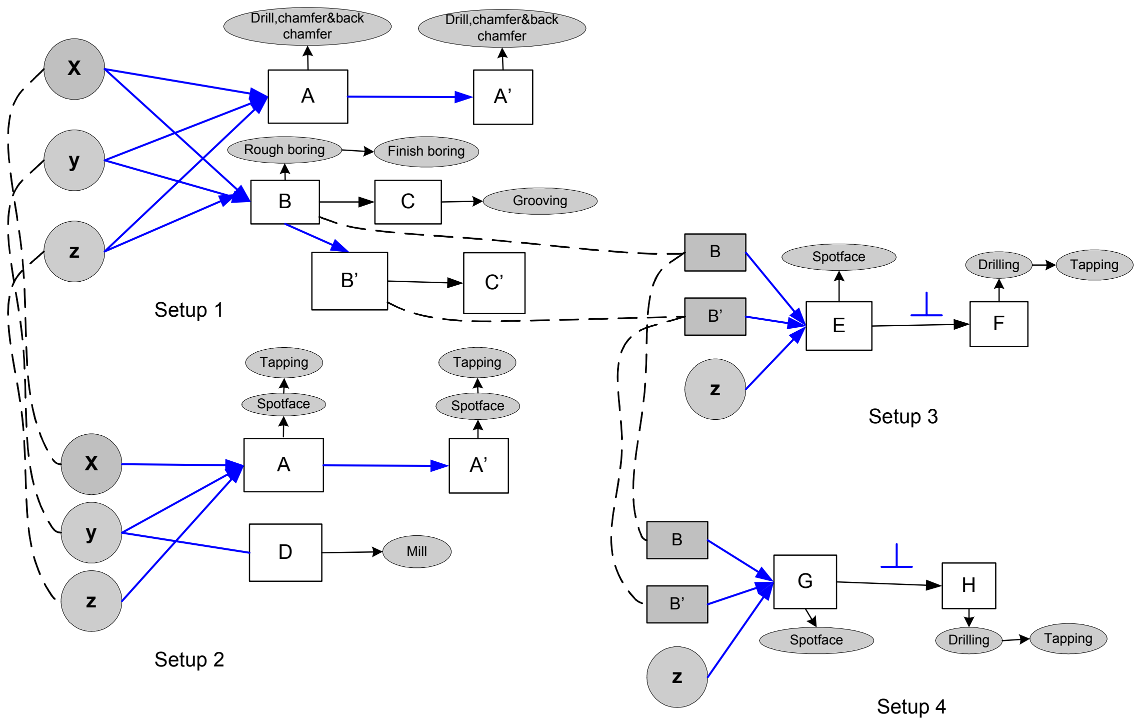


Figure 6. 13 DMG2 generation of example part (first solution)

If 3½ axis machine centers that have a table index function are selected, the setup planning will generate another solution. It is assumed that the machine tool coordinate and part coordinate overlap; group 1, 2, and 3 can be finished in one setup by indexing a machine table 180° and group 4 and 5 in another setup by indexing a machine table of 106°. The corresponding DMG2 is shown in Figure 6.14. In this solution, the number of setups has been reduced to 2 and feature B and D are machined in the same setup so that no tolerance stack-up is generated.

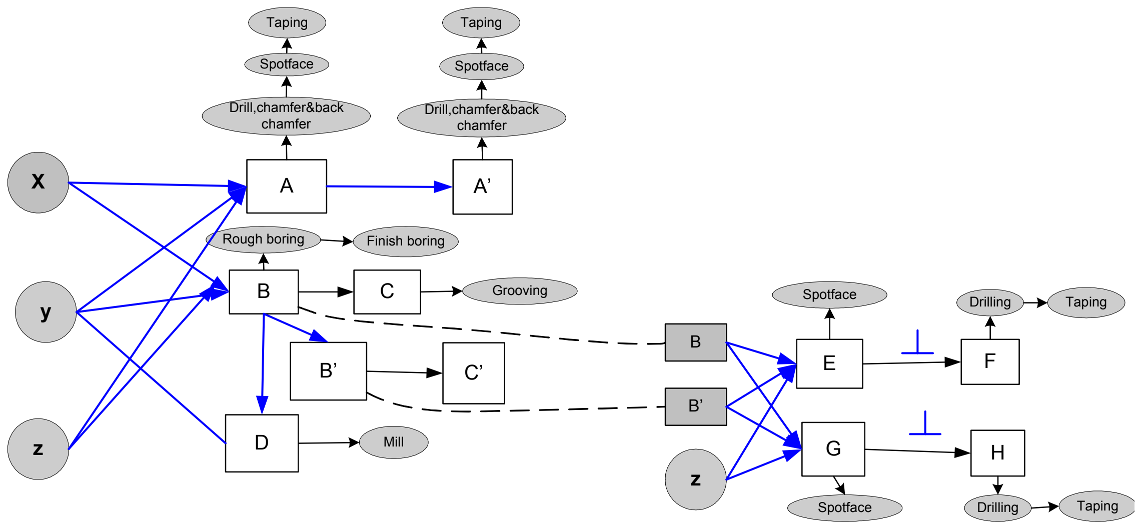


Figure 6. 14 DMG2 generation of example part (second solution)

Hence, 3½ axis machine tools can provide more TADs than 3–axis machine tools, and the number of setup can be reduced. Table 5.2 lists several typical machine tools used in real production and their TAD span. Based on that table, an algorithm for reuniting feature-processes groups based on machine tool capability is developed, as shown in Table 6.4.

Table 6. 4 Algorithm for reuniting feature-process group based on TAD

1	Find the groups that have the same datum features and put them into different containers
2	Put the first group in one container i into setup i_1 Transfer TAD of the first group into machine tool coordinate ($CS_{machine}$) and let it point to $CS_{machine}$ Z axis
3	Transfer the TAD of next group into $CS_{machine}$. Is it within the machine tool TAD span? If yes, put current group into setup i_1 If no, generate new setup for current group
4	Repeat step 3 until all the groups in the same container that can be machined in setup 1 are found.
5	If a new setup is generated, repeat step 2 and 3 to find feature groups in the same container that can be machine in the same setup
6	Repeat step 2,3,4 and 5 to deal with next containers i+1
7	End

For the groups that have more than one TAD, each TAD should be considered without violating the feature-process sequences. For example, in Table 6.4, the group3 has two TADs. But the processes in group 3 must be finished after group 2 so that group3 is united with group 2.

6.3.3 Setup sequencing and process sequencing

1. Setup sequencing

The basic principle of setup sequencing is to ensure that a feature is machined before it is used as a locating datum or a tolerance datum for other features. In this research, it is reflected in two principles:

Principle 1: The setup sequence must be arranged according to the sequence of datum features.

Principle 2: The setup sequence must be arranged according to the feature's pre-defined process sequence.

Hence, in the setup planning of the example part, there are two datum feature sets (x, y, z) and (B, B', z). Through the calculation of their degree, the in-degree of x, y, z $d^{-}(v)=0$, while $d^{-}(B)>0, d^{-}(B')>0, d^{-}(z)=0$; therefore, the setup sequence is from (x, y, z) to (B, B', z).

2. Process sequencing in each setup

The problem of process sequencing in each setup is transformed mathematically into searching for an optimal walk to traverse each vertex in the DMG2 under specified constraints. The times of passing each vertex are determined by the number of processes linked to each feature.

The constraints are classified into strong and weak constraints. The former are the first priority to achieve and cannot be violated, while the latter come from manufacturing experience and may provide optimal solutions.

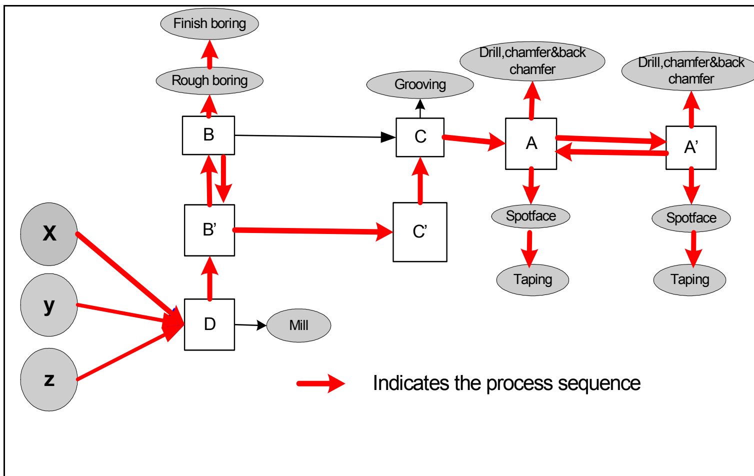
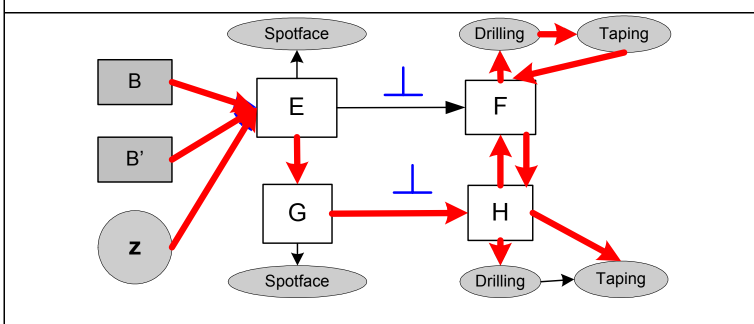
The strong constraints include:

- Maintaining the manufacturing process sequence of each feature.
- Maintaining the operational-dependent relationship in the graph, for example, planes prior to holes and holes prior to grooves.
- Doing rough cuts first, and semi and finish cuts in a prescribed order.

- Minimizing the tool change time and machine tool adjustment time (e.g., table index time).

One example of a weak constraint might be that the cutter to mill the outboard flange could be combined with the cutter to drill, chamfer and backchamfer the mounting holes so that tool change time can be reduced. Table 6.5 shows one solution of process sequencing if 3½ axis machine centers are used for the production of the example part.

Table 6. 5 A setup plan of the example caliper

<table>
<tr>
<td>
</td>
<td>Setup 1
1 Milling D
2 Rough boring B’, B
3 Finish boring B, B’
4 Grooving C’, C
5 Drilling, chamfer, back chamfer A, A’
6 Spotfacing A, A’
7 Tapping A, A’</td>
</tr>
<tr>
<td>
</td>
<td>Setup 2
1 Spotfacing E, G
2 Drilling F
3 Drilling H
4 Taping F
5 Taping H</td>
</tr>
</table>

6.4 Summary

In this chapter, the strategies of setup planning for non-rotational parts are introduced, which include automated setup planning and case-based setup planning. Graph theory is used to represent part information by FTGs and setup information by DMGs in automated setup planning. The problem of automated setup planning is transferred to change FTGs to DMGs based on tolerance analysis and manufacturing resource capability analysis. In addition, manufacturing knowledge and best practice, including precedence constraints, are summarized to determine optimal setup plans.

Chapter 7: Manufacturing Plan Generation

Manufacturing plan generation is a special step for the CAMP of mass customization. In this step, multi-part fixtures are used to maximize the utilization of machine tool capability and improve productivity. Cycle time is the critical factor used to evaluate a manufacturing plan. The part layout on the fixtures, the sequence of the processes carried out on one fixture, and the corresponding toolpath generation are the major tasks of manufacturing plan generation and will be discussed in detail.

7.1 Tasks of manufacturing plan generation

It is known that in overall cycle time, non-cutting time, including cutter change time, cutter rapid traverse time, and machine tool table index time, takes important portion. In the CAMP, in order to improve productivity and reduce cycle time, multi-part fixtures are widely used in the real production. This involves mounting several parts onto a fixture so that the processes that use the same cutters can be carried out sequentially, and non-cutting time on each part can be greatly reduced. As shown in Figure 7.1, manufacturing plan generation includes the following steps, in which machine-level decision-making strategies that abstracted from BOP are applied to achieve optimal cycle time.

1. Machine tool selection

   Candidate machine tools are those that fulfilled the entire requirement for machine tool capabilities from setup planning, including the number of axis of machine tools.

2. Conceptual fixture design and part layout design

In the CAMP, fixture design issues are divided into two steps: conceptual fixture design and detail fixture design. Conceptual fixture design provides ideas about what kinds of fixture bases are used and how many parts are held on the fixture bases. The initial solution of conceptual fixture design is derived from machine-level BOP, which includes machine tool selection, fixture base selection, and part layout on fixture bases. The part layout in BOP is based on previous detail fixture design, which determines the fixture structure and fixture components. In the meantime, necessary verifications of fixture performance are needed in detailed fixture design, such as interference free, chip shedding to avoid chip accumulation, locating accuracy, stability problems, clamping sequence, error proofing, and ergonomic issues.

The conceptual fixture design is considered an extension of machine tool capabilities. Not only can the same setups be machined on a fixture, but also the different setups are expected on the fixture. Hence, the requirement for the machine tools may be changed to accommodate bigger TAD range. As a result, the machine tool capability should be rechecked after part layout design.

3. Global process sequence and toolpath generation

In order to reduce the non-cutting time on each part, the processes that use the same cutters should be carried out sequentially. Hence, a sequence is needed for all the manufacturing processes on the multi-part fixtures. A corresponding toolpath is generated without interference with fixture components, machine tools, etc.

4. Cycle time calculation

Cycle time is the critical factor in choosing the optimal manufacturing plan in mass customization. Hence, the estimation of cycle time is indispensable for manufacturing plan generation.

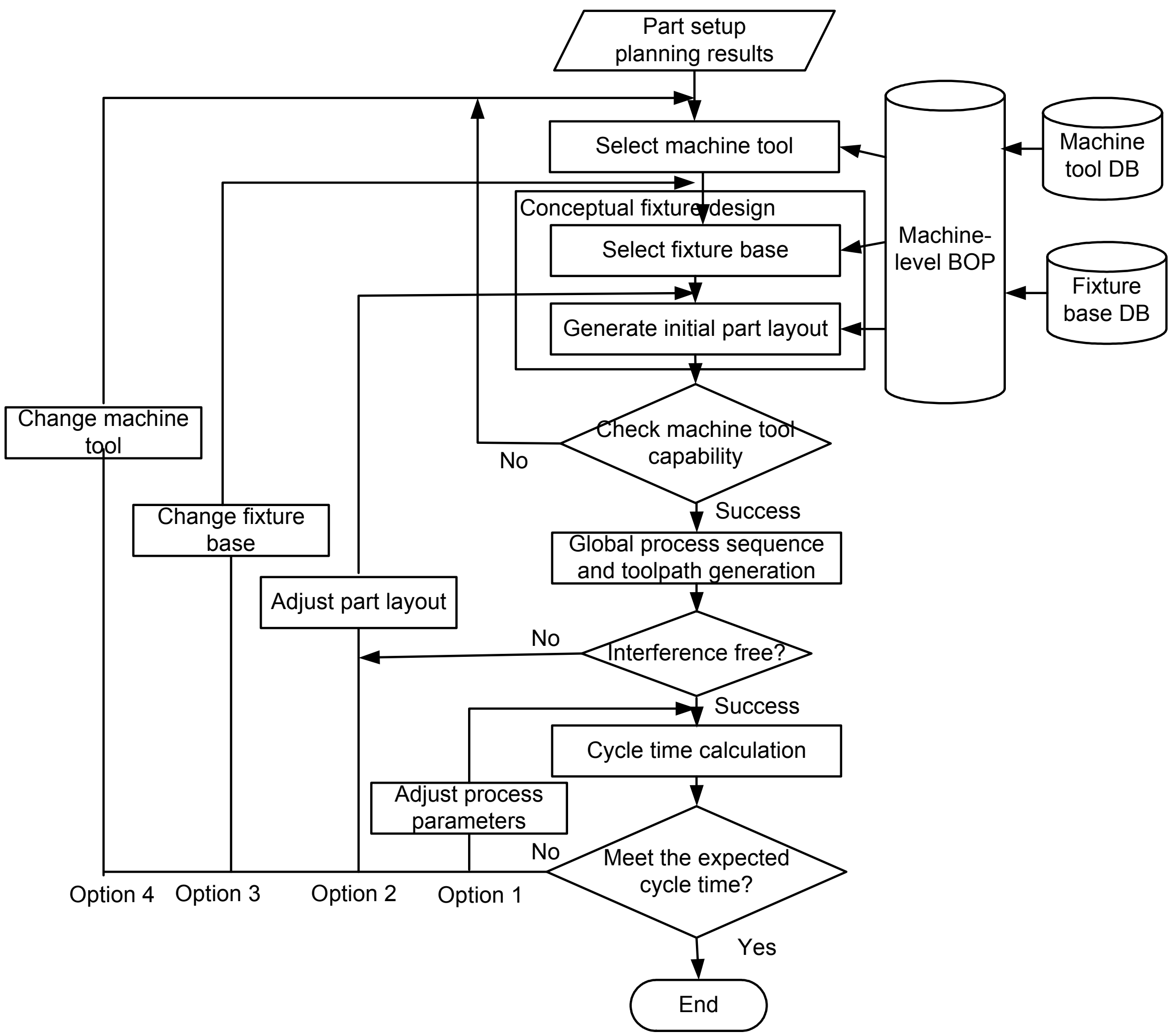
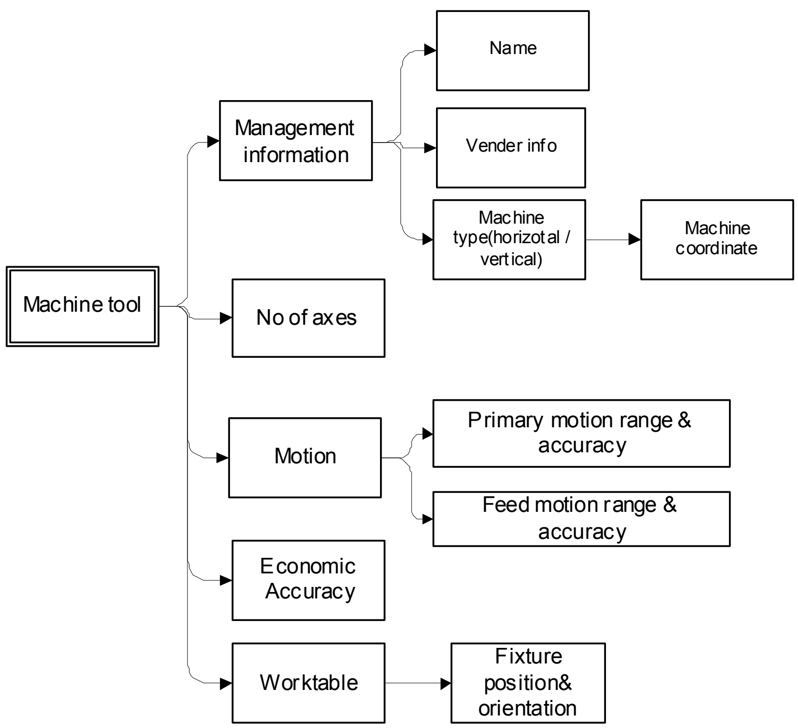


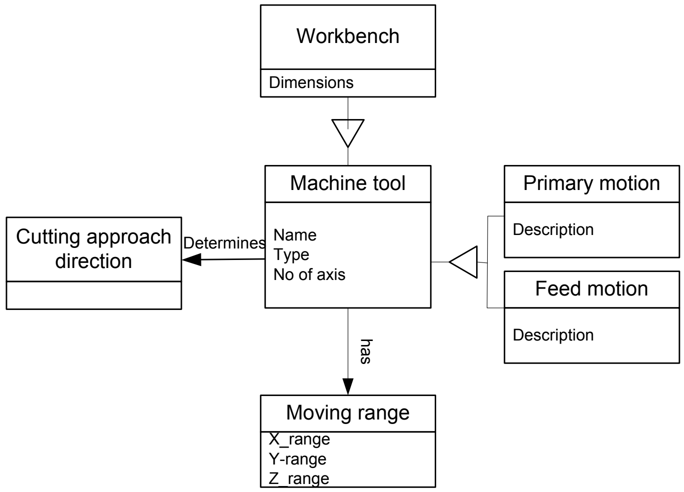
Figure 7. 1 Flowchart of manufacturing plan generation

7.2 Machine tool information modeling

In mass customization, plenty of vendors provide a variety of machine tools with similar functions. How to use machine tool specifications to make the right choice becomes a critical problem in reduce manufacturing costs. From the discussion of manufacturing resource capabilities, it is known that machine tools make a significant contribution to these capabilities. Therefore, the information of machine tools is summarized, and an O-O machine tool information model is established, as shown in Figure 7.2.



(a) Machine tool information structure



(b) ORM of machine tool information model

Figure 7. 2 Machine tool information model

7.3 Conceptual fixture design and part layout

In the CAMP, it is fixture vendors who design and fabricate the real fixtures. Hence, in conceptual fixture design stage, detail fixture structure information is not available. Manufacturing engineers have to generate a rough fixture design solution based on former fixture designs in BOP, which includes the types of fixture bases and the number of parts that are mounted on each fixture. The part position and orientation on fixture bases should be determined too, which implies how much space should be left to accommodate fixture components. As shown in Figure 7.1, the types of fixture bases and part layout on fixture bases are pre-stored in the CAMP. After the generation of the initial solutions of conceptual fixture design, the machine tool's capabilities need to be re-checked in the following:

- Whether it has enough space to accommodate the fixtures and parts

- Whether it can access all the features and finish all the required processes

If these are not satisfied, engineers may consider reselecting a fixture base or regenerating part layout, such as adjusting part position and orientation or putting fewer parts on the fixtures.

7.3.1 Fixture base types

In this research, there are four types of fixture bases involved, as shown in Figure 7.3. A flat fixture base can accommodates two parts. A round base can hold four parts. A bridge can hold four parts, two on the upper level, and two on the lower level. Tombstones offers the most variations, which have at most four faces that can hold parts; each face can hold two parts.

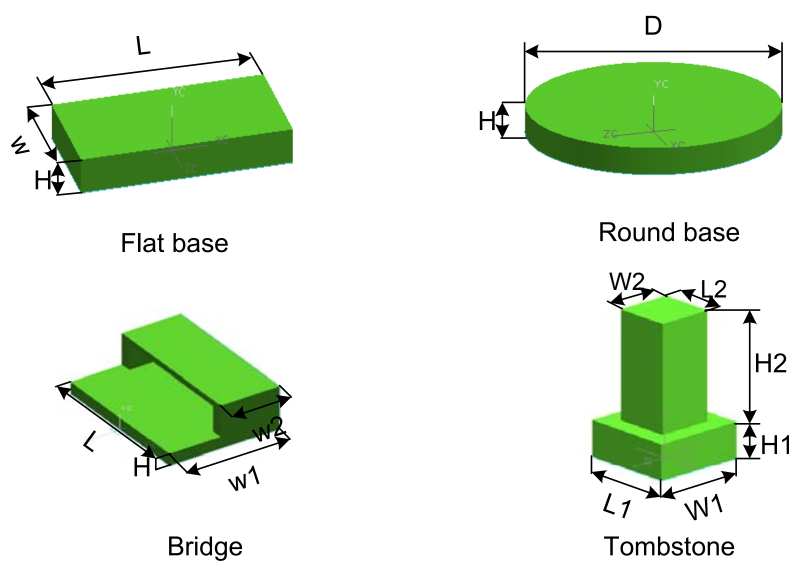


Figure 7. 3 Types of fixture bases

Each fixture base is controlled by several key dimensions, which are driven by part dimensions and pre-defined constraints that are stored in BOP. Each fixture allows different TAD of machine tools.

7.3.2 Part layout on fixture bases

The shape and dimensions of fixture bases may have lots of varieties. However, the common point is to identify the mounting surfaces that are used to hold parts through the use of fixture components. In Figure 7.3, a flat base and round base can only provide one mounting surface; a bridge provides two surfaces, and tombstone can provide at most four mounting surfaces. Hence, the problem of part layout is transferred to design the part layout on each mounting surface.

Since the number of setups to machine a part, the part orientation and the process sequence in each setup have been generated in setup planning, the issue for part layout is to determine which setup should be carried out, and how many setups should be carried out on each mounting surfaces. Although detailed information about a fixture is not available, the overall dimensions of fixture units can be deduced from BOP (Rong, 2002). Two factors are considered in this step:

1. Leave enough space between parts, and between parts and fixture bases, according to BOP of fixture design.
2. Ensure that machine tools can access the TADs of all the processes for each part.

Furthermore, machine tool capabilities are the major constraints for the part layout on fixture bases. First, the TAD of processes should be checked. If a process TAD is blocked by other parts on fixture base or by the fixture base itself, the part position and orientation should be changed. The checking algorithm has been realized as the accessibility analysis, which is available in (Kang, 2002). Second, the working range of machine tools should be re-checked, which includes that machine tool's worktable dimensions should be larger than fixture bases, and the machine tool's moving range should be enough to execute all the processes.

Figure 7.4 shows a solution of the example caliper introduced in Chapter 6. We already know that the caliper needs two setups by the use of 3½ machining centers. From the BOP of the caliper obtained from the industry, setup 1 is executed on bridges and setup 2 on tombstones. The distances between parts and parts and fixtures are derived from BOP. The TADs of processes have been checked.

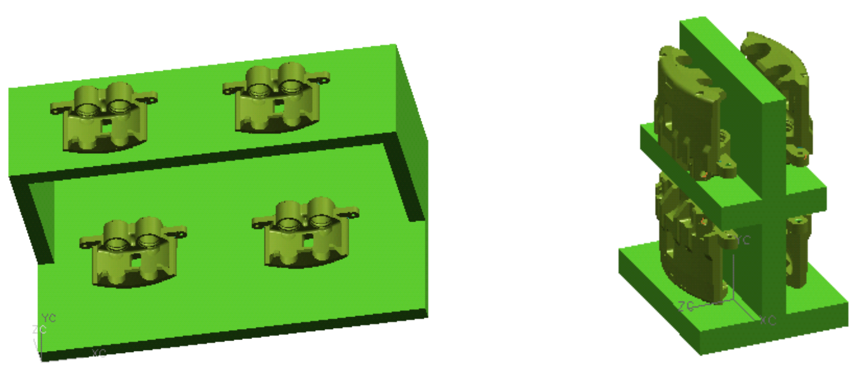


Figure 7. 4 Part layout on fixture bases

The solutions shown in Figure 7.4 can be stored as a machine-level BOP in a database for future reference; the following information should be included.

1. Fixture base type

    - Key dimensions

2. Part layout on mounting surfaces

    - Part setup, and part orientation in fixture base coordinates

- Fixture unit dimensions, including locating units and clamping unit

7.4 Global process and toolpath generation

In conceptual fixture design, the machine tools and part layout on a fixture are already determined. Therefore, the part position and orientation is transferred to the machine tool, and the processes are carried out in the machine tool's coordinate system. Corresponding toolpath is called a global toolpath.

1. Global process sequence

The main purpose of using multi-part fixtures in the CAMP is to fully utilize machine tools' capability and reduce the non-cutting time on each part. Non-cutting time includes tool change time, machine tool table index time, and tool rapid traverse time. Hence, two criteria are used to determine the global process sequence on one fixture:

- Reduce the time of tool change. All the processes that use the same cutters should be executed sequentially.
- The toolpath of those processes executed by the same cutter should be optimized to reduce the table index time and tool rapid traverse time.

Figure 7.5 shows the algorithm for global process generation.

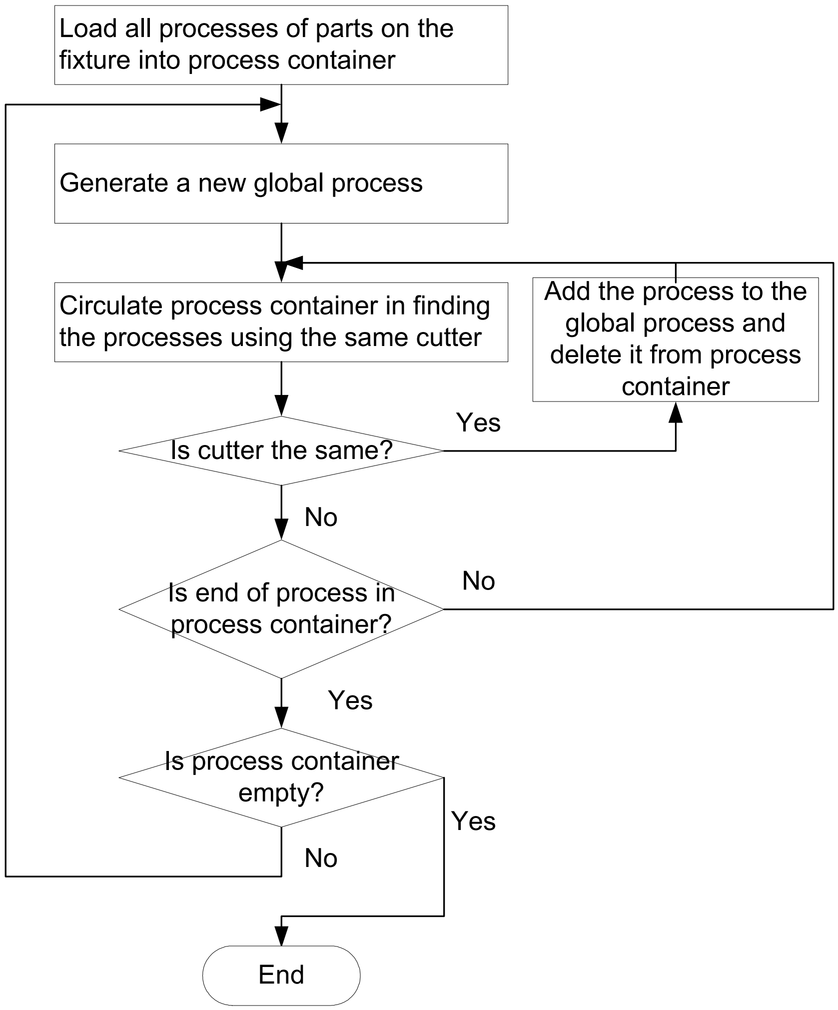


Figure 7. 5 Algorithm for global process generation

2. Global toolpath generation

Chapter 4 explained that each feature has a sequence of processes that are associated with a pre-defined toolpath. Hence, the task of global toolpath generation is to connect the processes executed by the same cutter without interference. Interference may happen between the cutter and workpieces, the cutter and fixture components, or the cutter and fixture base. At the feature-level, the pre-defined toolpath that comes from BOP also considers the interference between the cutter and workpieces, and the cutter and fixture components. Hence, at the global process level, only interference between the cutter and fixture bases are considered. Figure 7.6 shows the algorithm for global toolpath generation.

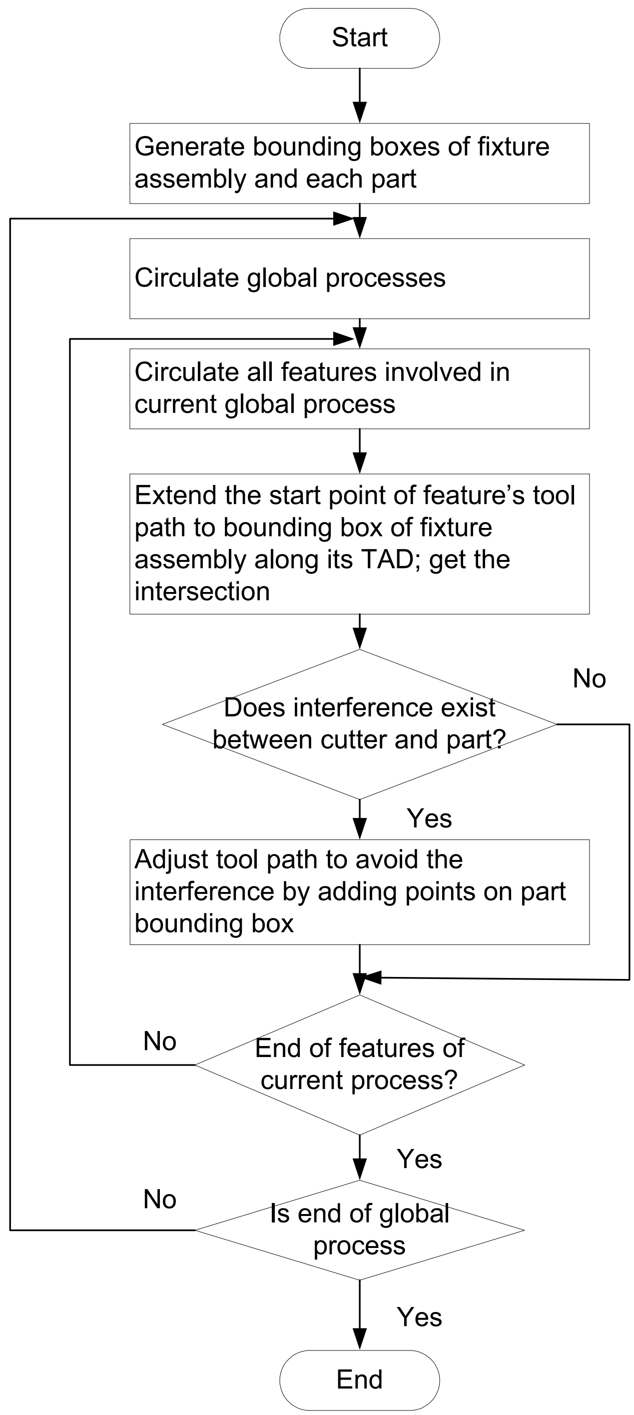


Figure 7. 6 Algorithm for global toolpath generation

7.5 Cycle time calculation

It is always of interest for engineers to find the most economical solution. Basically, process economics means determining the cost efficiency of processes. For the CAMP, it is necessary to go through a very detailed economic analysis before selecting a specific processing method. However, it is not practical to conduct a very detailed study in the manufacturing planning stage. Hence, some rough estimation is used to select the best solution. Cycle time calculation is known as the most effective determinant for mass customization.

A cycle time calculation model can be stated as:

$$T = \sum_{i=1}^{N} \left(\sum_{j=1}^{M_i} T_{process} + M_i * T_{tool\_change}\right) / P_i \qquad \text{(Equation 7.1)}$$

where

T : Cycle time for fabricating one part

N: Number of setups used to fabrication

M_i : Number of global processes in ith setup

$T_{process}$: Time of one global process finished by one cutter

T_{tool_change} : Time for changing one cutter, which is determined by specified machine tools

P_i : Number of parts machined on ith setup

In the model, the time of one process is composed of the cutting time, tool rapid traverse time, and machine tool table index time.

$$T_{process} = T_{cutting} + T_{rapid} + T_{table\_index} \quad \text{(Equation 7.2)}$$

where

$T_{cutting}$: Cutting time is associated with process types

T_{rapid} : Tool rapid traverse time, which includes the time when cutter travels from tool change position to the starting point of toolpath, the time used for its rapid motion in the toolpath of a process, and the time when the cutter returns to tool change position. The tool change position is specified in a machine manual or achieved from experiments.

T_{table_index} : Machine tool table index time is proportional to the rotational displacement of the worktable, which is specified by a machine tool manual.

7.6 Case study

In Chapter 6, a sample caliper is discussed, which has two setups generated based on the tolerance analysis and manufacturing resource capability analysis. From the BOP of the caliper family, three types of fixture bases: a flat base, a round base and a bridge were used for the setup 1. Hence, they serve as the candidate fixture bases. Table 7.1 shows the part layout, available machine tools and the corresponding cycle time. It can be concluded that the bridge is the best choice to achieve the minimum cycle time. Table 7.2 shows Mori Seiki SH633 and Kitamura Mycenter-H630i are the good candidates, which have the smaller tool change time and faster rapid federate among the candidate machine tools. The specifications of candidate machine tools are listed in Appendix B.

Table 7. 1 Candidate part layout of the caliper

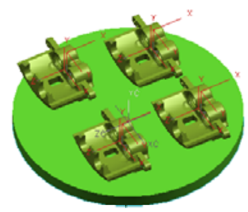
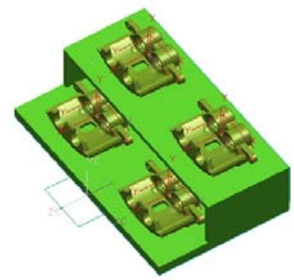
	Flat base	Round base	Bridge
			
Fixture base (mm)	L = 600, W = 250, H= 40	R = 310, H = 40,	L = 630, W1 = 400, W2 = 250, H = 120, H1= 30, L1= 15
Requirement to machine tool envelop (mm)	600×155×470	630×131×445	630×260×660
Times of tool change	6	6	6
Times of table index	2	2	2
Candidate machine tool and the corresponding cycle time on each part			
Daewoo DHM630	92.7 sec	87.95sec	87.8 sec
Mori Seiki SH633	89.1 sec	85.97 sec	85.93 sec
Kitamura Mycenter-H630i	89.6 sec	86.22 sec	86.05 sec

Table 7. 2 Detailed cycle time composition of the bridge

	Tool to tool (sec)	Table Index (sec/90°)	Rapid feedrate (m/min)	Cycle time		
				Tool change time	Table index time	Total
Daewoo DHM630	2.5	1.2	24	15	2.4	351.21
Mori Seiki SH633	0.8	2	50	4.8	4	343.73
Kitamura Mycenter-H630i	2	0.45	50	12	0.9	344.21

7.7 Summary

In this chapter, the final stage of the CAMP is studied. A O-O information model is established for machine tools. The conceptual fixture design and the part layout on fixture bases are generated based on BOP of part families. The algorithms for global process sequence and toolpath are developed and cycle time calculation are discussed as well. The above results can be documented in industry-specific formats to aid in the real production.

Chapter 8: System Implementation

PEMS (Parametric engineering manufacturing system) is a CAMP application developed for non-rotational parts. This chapter first discusses the overview architecture of PEMS, with special focus on the application of information storage technology – XML. A thorough case study of caliper is presented.

8.1 PEMS system architecture

PEMS is a CAMP system that incorporates Unigraphics CAD package to create integrated parametric CAD/CAM software for part families. The main goal of PEMS is to design manufacturing plans for mass customization quickly and effectively, based on the BOP used in industry. It is a valuable tool to help manufacturing engineers make optimal solutions on manufacturing costs. Taking into consideration the software lifecycle from design to maintenance, the development of PEMS must solve two problems:

1. The manufacturing knowledge and BOP applied in different workshops may be significantly different. Hence, in order to increase the adaptability of PEMS, the knowledge and BOP should be separated from the software itself, and a mechanism for how to use existing knowledge and BOP to generate optimal solutions should be established.

2. A variety of CAD packages and operation systems are available in today's marketplace. In order to maximize the portability of the CAMP system among different CAD packages, the PEMS system is divided and encapsulated into

modules, so that the operations on CAD packages are carried out in stand-alone modules. As a result, these modules can be reused as much as possible, and the maintenance costs of PEMS will be greatly reduced.

Figure 8.1 shows the diagram of PEMS architecture. The PEMS software contains 4 function modules: (1) The part information modeling module extracts part information from CAD packages, recognizes manufacturing features, and associates them with pre-defined manufacturing strategies; the module then generates FTG to organize feature-based part information; (2) The setup planning module can generate setup plans either based on BOP or by the automated setup planning methods; a corresponding DMG is generated in this module; (3) The conceptual fixture design module generates different part layout solutions on multiple-part fixtures; (4) The manufacturing plan generation module generates a global toolpath on each fixture base and calculates a corresponding cycle time. The Manufacturing knowledge and BOP are stored in relational databases and knowledge bases. Figure 8.2 shows the overview of database relationships, in which part type, feature type, process type and manufacturing resource type are stored. However, this kind of databases is not suitable for storing the knowledge that is specified by BOP because this knowledge is associated with specified manufacturing industry environments and does not have a unified format. In order to ensure the commonality of PEMS, XML format is used to represent this knowledge in BOP, which can be accessed by standard browsers such as the Internet Explorer. In section 8.1, XML format will be introduced and the knowledge represented by XML will be listed.

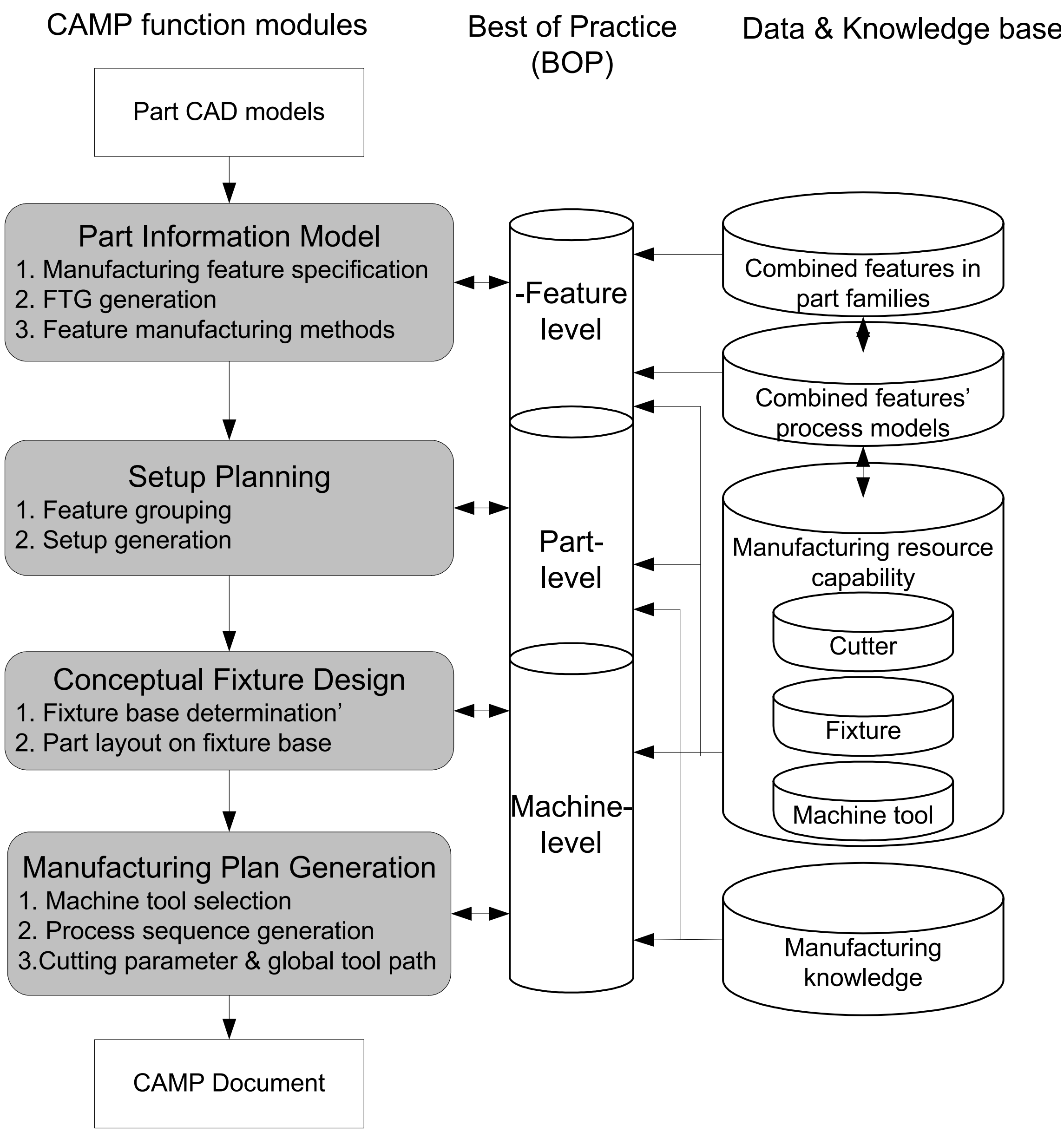


Figure 8. 1 PEMS software architecture

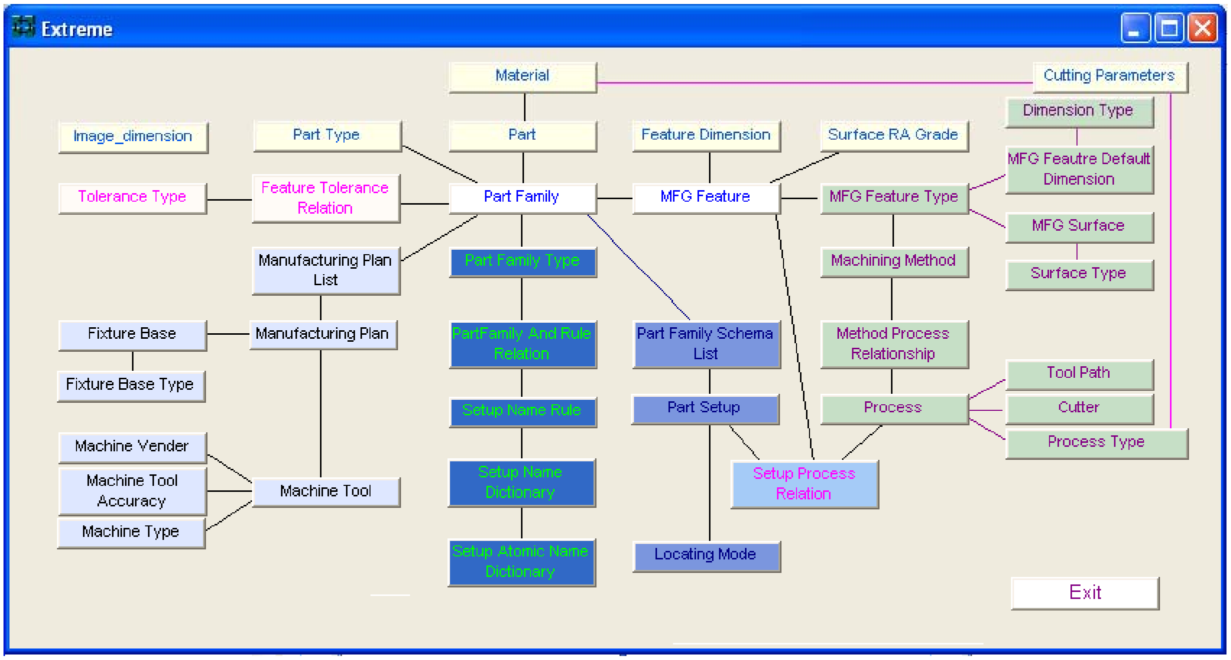
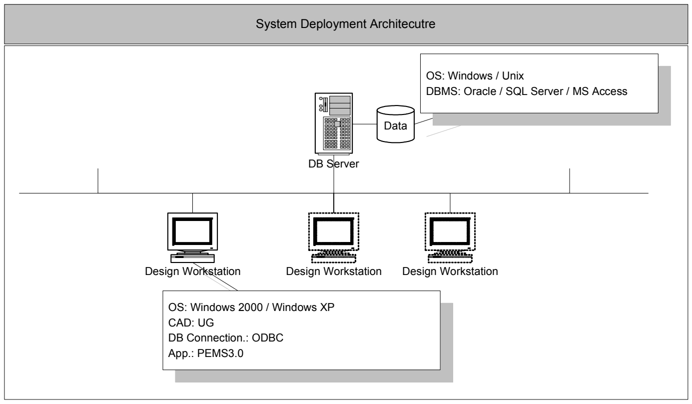
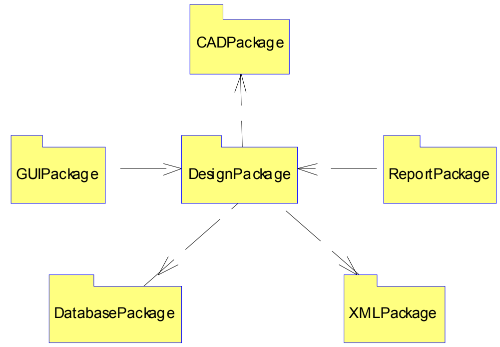


Figure 8. 2 Overview of PEMS relational databases

Figure 8.3 shows the PEMS software package design. In Figure 8.3(a), the whole system has a server-client structure, in which knowledge and databases are stored on the server side while the applications are running on the client side. By using this structure, resources in PEMS can be utilized by multiple users. Figure 8.3(b) figures out the main packages in PMES. Each package can be considered as a high-level object that consists of related low-level objects. The design package plays a key role in PEMS to control other package's activity. The CAD package deals with all the activities for CAD software. The GUI package controls the user interfaces. The database package manages databases and deal with the inquiry on databases. And the XLM package manages the knowledge of BOP and intermediate information generated by PEMS. The report package collects information in PEMS and generates documents.





(a) **(b)**

Figure 8. 3 PEMS software package design

The screenshots of PEMS are shown in Appendix D, which demonstrates the case study of the sample caliper discussed in the research.

8.2 XML in PEMS

XML format is used to define and structure the information embedded in BOP. It is derived from SGML (Standard Generalized Markup Languages). XML is designed to allow data to be formatted such that it is "machine readable." It allows users to define their own tags, thereby making it possible to share data via the web in a format that makes computer interpretation possible. XML documents can be displayed in popular web browsers like Microsoft Internet Explorer (version 5.0 or up) without any modification and programming effort. Moreover, there are many supporting tools to make the XML document available on the Internet. For programmers who must develop applications to process the XML, APIs in the most common computer language, for instance, C++ and Java, are available for data parsing and storing the database system.

In PEMS, a part family's BOP is stored in XML format, which includes three levels of information. Figure 8.4 illustrates the structure of a part family's BOP; The detailed XML for each level's BOP is shown in Appendix C.

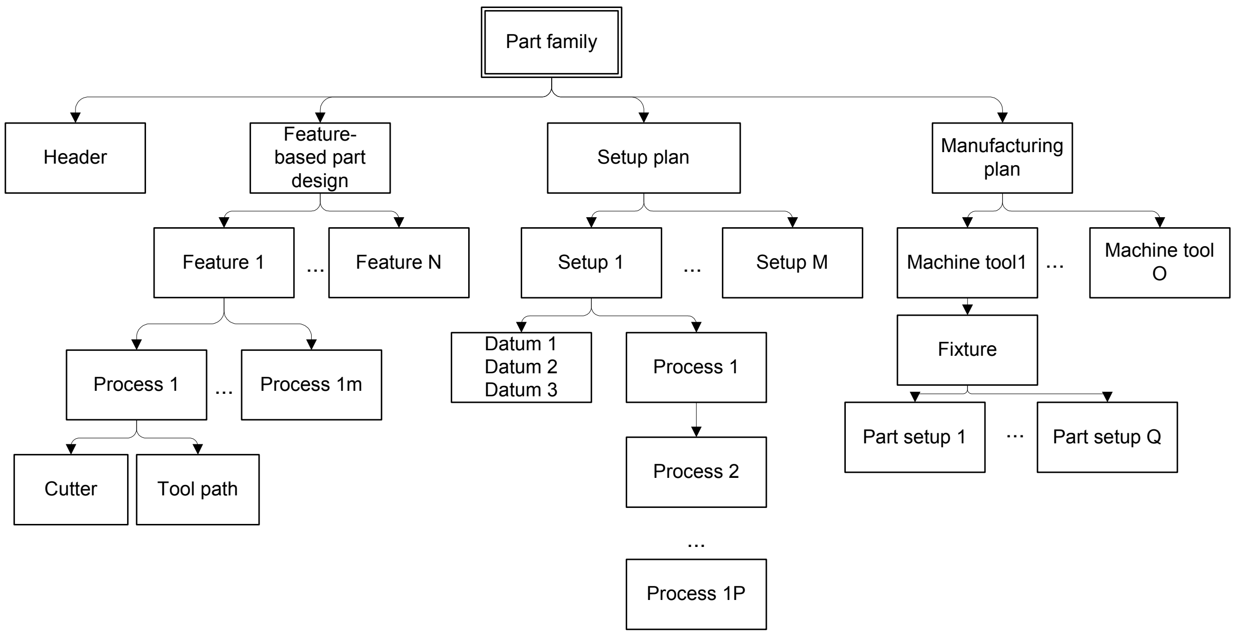


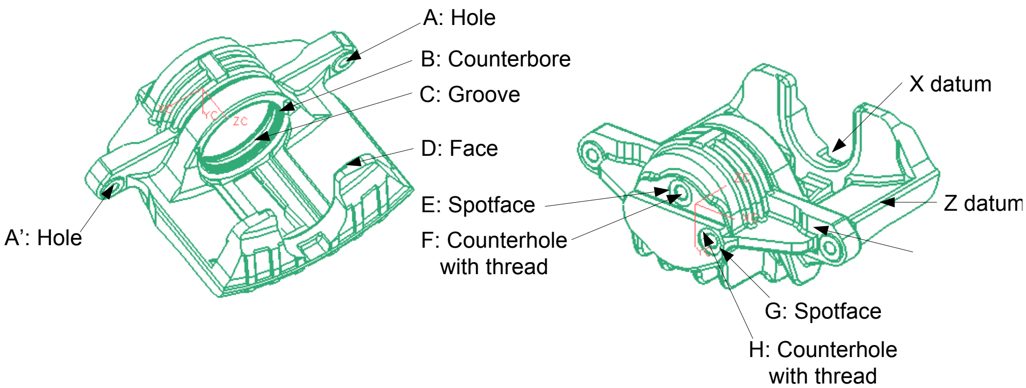
Figure 8. 4 XML structure of part family BOP

8.3 Case study

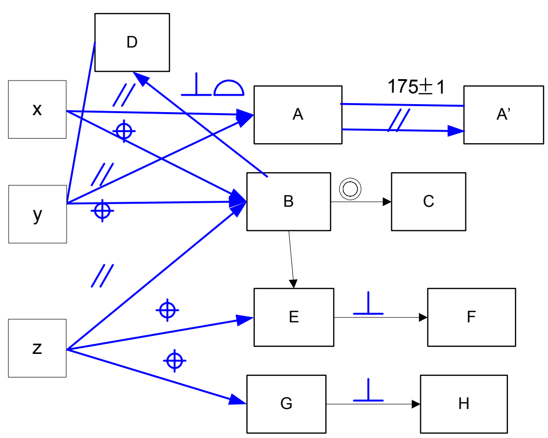
In the research, the manufacturing planning strategies are studied in three levels: feature-level, part setup planning level and machine-level, and the part families' BOP is stored in three levels too. In this section, a thorough case study of a single bore caliper is presented based on the BOP of the caliper family.

1. Feature level planning

Figure 8.5 shows the CAD model of the single bore caliper and its FTG. This single bore is in the same family as the sample caliper discussed in Chapter 4, 6, and 7. Hence, they have the same types of features, as shown in Table 8.1. Since the features E, F, G, and H in the two parts have the same parameters, the same cutters and toolpaths can be used. Figure 8.6 shows the extended FTG with manufacturing strategies linking with the features.



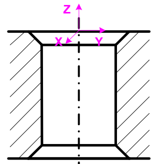
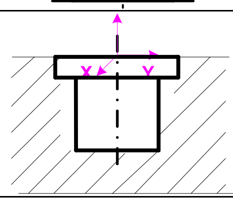
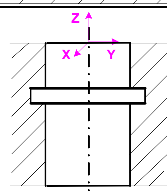
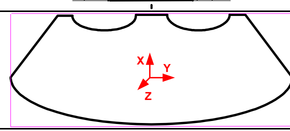
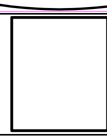
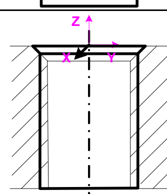
(a) Features of a single bore caliper



(b) FTG

Figure 8. 5 A singlebore caliper & Its FTG

Table 8. 1 Feature list of the calipers

ID	Feature name	Feature type	Sample caliper	Single bore caliper
A	Mounting hole		D = 8.2 D1= 28.7 H = 17 H1= 1	D = 8.2 D1= 18 H = 18 H1= 1
B	Piston bore		D = 45.05 H=29.69 D1= 48.0 H1=3.0	D = 60.52 H=35.25 D1= 65.0 H1=3.0
C	Seal groove		D= 48 H1=1.85 Distance = 10	D= 63 H1= 2 Distance = 10
D	Outboard flange		L= 162.08 W= 38.8	L= 129.35 W=41.47
E	Spotface		D= 18	D=18
F	Connector hole		D=9.04 H= 21.38	D= 9.04 H=13.14
G	Bleed hole spotface	Same as E	D=18	D=18
H	Bleeder hole	Same as F	D=9.04 H= 15.52	D=9.04 H= 15.76

Note: Unit is mm.

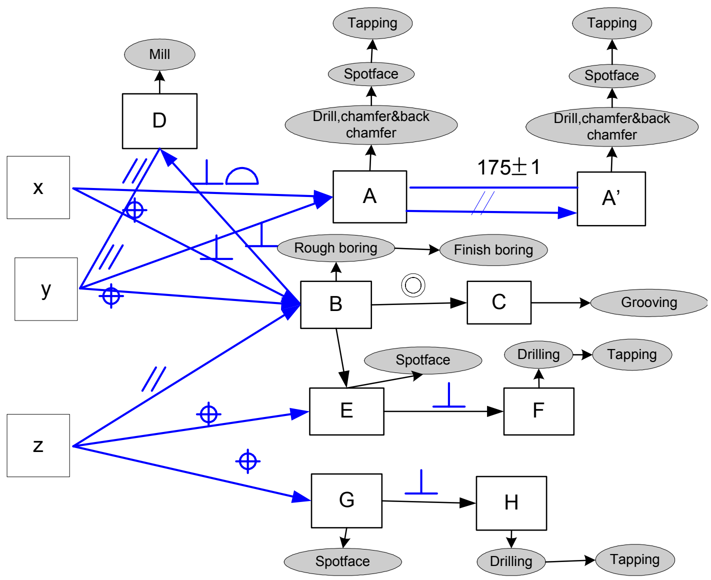


Figure 8. 6 Single bore caliper's FTG with processes

2. Part-level setup planning

First, two datum frames are identified based on the tolerance analysis, as shown in Figure 8.7. Second, features' manufacturing processes are divided into 5 groups by the use of TAD, which is shown in Table 8.2. Finally, the setups are generated based on available machine tools. If 3½ axis machine tools are used, all the features can be machined in one setup, as shown in Table 8.3. The process sequence is indicated by the arrows. Since B is the datum of E, F,G and H, the processes of B must be carried out before those of E,F, G and H.

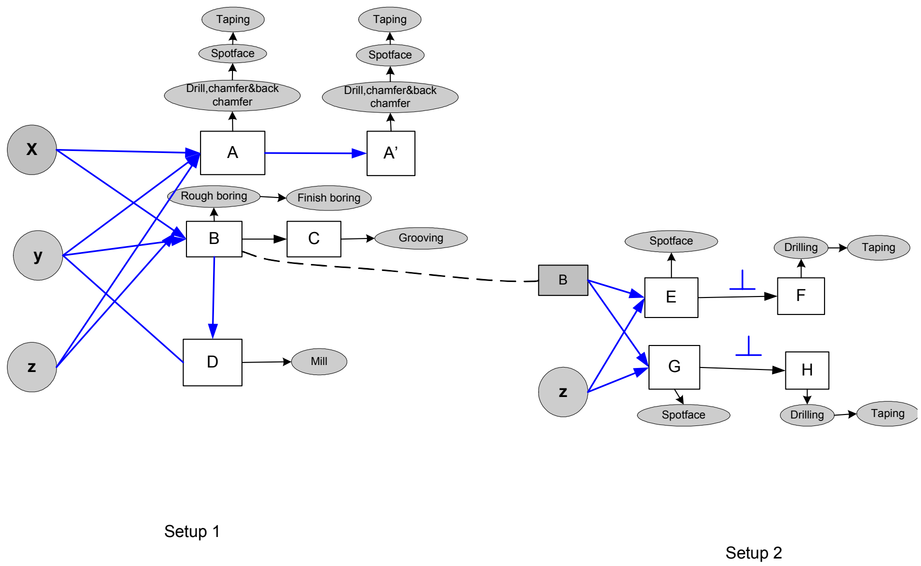


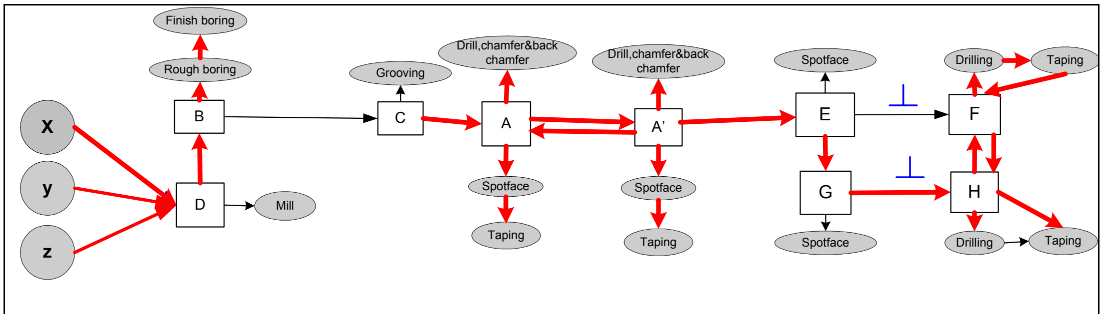
Figure 8. 7 DMG1 of the single bore caliper

Table 8. 2 Feature-process grouping of the single bore caliper based on tolerance analysis and TAD

	Manufacturing features	Machine tool	Datum	Tool access direction (TAD)
Group 1	A (Drilling, chamfer & back chamfer) A' (Drilling, chamfer & back chamfer) B (Rough boring, finish boring) C (Grooving)	3-Axis machine center	x, y, z	+X
Group 2	A (Spotface) A' (Spotface) D (milling)	3-Axis machine	x, y, z	-X
Group 3	A (tapping) A' (tapping)	3-Axis machine	x, y, z	+X or -X
Group 4	E (Spotface) F (Drilling, Tapping)	3-Axis machine	B, z	-X
Group 5	G (Spotface) H (Drilling, Tapping)	3-Axis machine	B, z	-X

Note: TAD is in the single bore caliper's coordinate.

Table 8. 3 A setup plan of the single bore caliper by using of 3½ axis machine tools

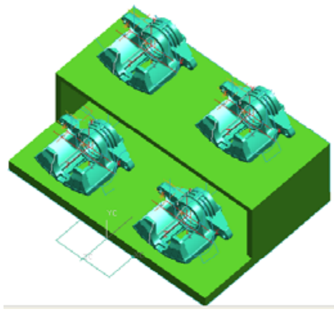


1	Milling D
2	Rough boring B
3	Finish boring B
4	Grooving C
5	Drilling, chamfer, back chamfer A, A’
6	Spotfacing A, A’
8	Tapping A, A’
9	Spotfacing E, G
10	Drilling F
11	Drilling H
12	Taping F
13	Taping H

3. Machine-level planning

In the manufacturing plan of the sample caliper discussed in Chapter 7, a bridge and a machine tool name Mori Seiki SH633 are proven to achieve the best cycle time. Hence, this solution will also be used to the single bore caliper. Table 8.4 shows the results. Figure 8.8 shows the documents generated by PEMS.

Table 8. 4 A manufacturing plan of the single bore caliper

	Fixture base	Bridge L = 570, W1 = 400, W2 = 250, H = 150, H1= 30, L1= 15
	Requirement to machine tool's moving range (mm)	570×307×550
	Moving range	
	Machine tool	Mori Seiki SH633
	Cycle time (per part)	78 sec

PEMS V3.0			**Global Setup Plan**	
WPI, CAM Lab Copyright 2002			Name:	PEMS USER NAME
			Doc Ver:	0
Production Plan Name:				
Station 0: [Cycle Time: 311.399000 Sec]				
Fixture Name: bridge				
Machine Tool Name: Mori Seike SH630				
Process Name	**Cutter Name**	**Spindle Speed(rpm)**	**Feed Rate(mm/min)**	**Process Time(s)**
Finish Face Milling	FinishFaceMillCutter	7000	900	106.629
Rough Boring	RoughBoreTheTopHoleOfStepHoleCutter	6000	900	8.569
Rough Boring	RoughBoreBlindHoleCutter	6000	900	17.547
Combined Machining	FinishBoreBlindStepHoleCutter	5000	200	53.247
Grooving	InternalGrooveCutter	5000	200	5.124
Combined Machining	FinishDrillMillSurfaceChamferBackChamferCu	7000	200	18.22
Finish Face milling	SpotfaceMillCutter	7000	900	14.554
Tapping	TappingHolewithChamfer	4000	125	8.125
Combined Machining	FinishDrillChamferSpotfaceCutter	7000	200	52.509
Tapping	TappingHolewithChamfer	4000	125	7.775

Figure 8. 8 Document for the single bore caliper

Chapter 9: Summary

This chapter gives a summary of this research. It includes two parts: contributions and future works.

9.1 Contributions

A systematic and comprehensive study on Computer-Aided Manufacturing Planning (CAMP) is carried out in this research. The scope is for non-rotational part production in the mass customization production mode.

The characteristics of the CAMP of mass customization can be summarized as generating manufacturing plans quickly in accordance with part changes based on best-of-practice (BOP) of part families. In BOP, flexible manufacturing resources, including customized combination cutters, multi-part fixtures, and multi-axis CNC machines are widely utilized. The architecture of the CAMP of mass customization is proposed, which includes feature-based part information modeling, setup planning, conceptual fixture design and manufacturing plan generation.

A systematic information modeling technology is proposed to represent the information relationships and associativities from the system perspective. The Object-oriented Systems Analysis (OSA) approach is used as the primary tool to describe the static and dynamic characteristics of information. Therefore, the information associativities within the CAMP between part design and manufacturing planning can be properly described, so can the information in BOP of part families. A three-level decision-making mechanism is proposed by using of the systematic information modeling technology. At the feature-level, the combined features and their manufacturing strategies are defined based on part families. At the part-level, a part's information is represented by a Feature Tolerance relationship Graph (FTG), and setup planning information is described by a Datum Machining feature relationship Graph (DMG). Rules and constraints that are extracted from BOP control the transformation from a FTG to a DMG. At the system level, multi-part fixtures are utilized to reduce cycle time and to increase productivity. Part layout on multi-part fixture bases is also retrieved from BOP.

First, feature-based part information modeling is studied, based on the BOP of part families. In the CAMP, parts are grouped into part families. The parts in the same family may have similar manufacturing plans, which are composed of sequences of processes and the manufacturing resources used to carry out these processes. In the research, the definition of feature is extended to include combined features, which are associated with particular processes that are pre-defined by specific part families. FTGs are used to represent part information. Moreover, a process model, including pre-defined cutters and toolpath, is proposed as the link between features and their manufacturing strategies. The process model describe the common characteristics of manufacturing strategies, such as the description of cutters, the toolpaths, and the requirement for machine tool motion. No specific machine tools are pointed out in this phase.

Secondly, the problem of setup planning is to transfer a FTG into a DMG, which represents the tolerance relationships between datum features and machining features in the setup planning. Graph theory is utilized in automated setup planning, based on tolerance analysis and manufacturing capability analysis. In this research, manufacturing capability is expanded to 3½ and 4-axis machine tools and multi-part fixtures, so that the number of setups can be minimized and as many processes as possible can be carried in one setup. Corresponding machining time and cost may be greatly reduced. The BOP of setup plans can be generated either from cases of part families or automated setup planning.

Manufacturing plan generation is a special step for mass customization. Part layout on fixture bases, global process and toolpath generation, and cycle time calculation are discussed at this stage based on the machine-level decision-making strategies. Cycle time is used as the criterion to evaluate the manufacturing plans.

Through this research, the software named PEMS has been developed to help engineers design manufacturing plans more quickly and accurately. Multiple solutions can be generated as well, and engineers can choose optimal solutions.

9.2 Future works

In this research, only the limited aspects of fixture issues are considered. However, fixture planning and fixture design is indispensable in setup planning and should receive more study.

Multi-spindle machine tools are widely used in mass production. They can execute multiple processes at the same time, which can greatly increase productivity and reduce cycle time. The machine tool capability model should be extended to multiple spindle machine tools in the near future.

Next, some validation of the results generated by the CAMP is needed. For example, tolerance issues have not been mentioned in this research.

This research is limited to the production mode of mass customization. It is can also be extended to job and batch production with changes to manufacturing resource capability models. Corresponding manufacturing knowledge and rules should be adjusted accordingly as well.

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Appendix A: Feature types and manufacturing strategies in a caliper family

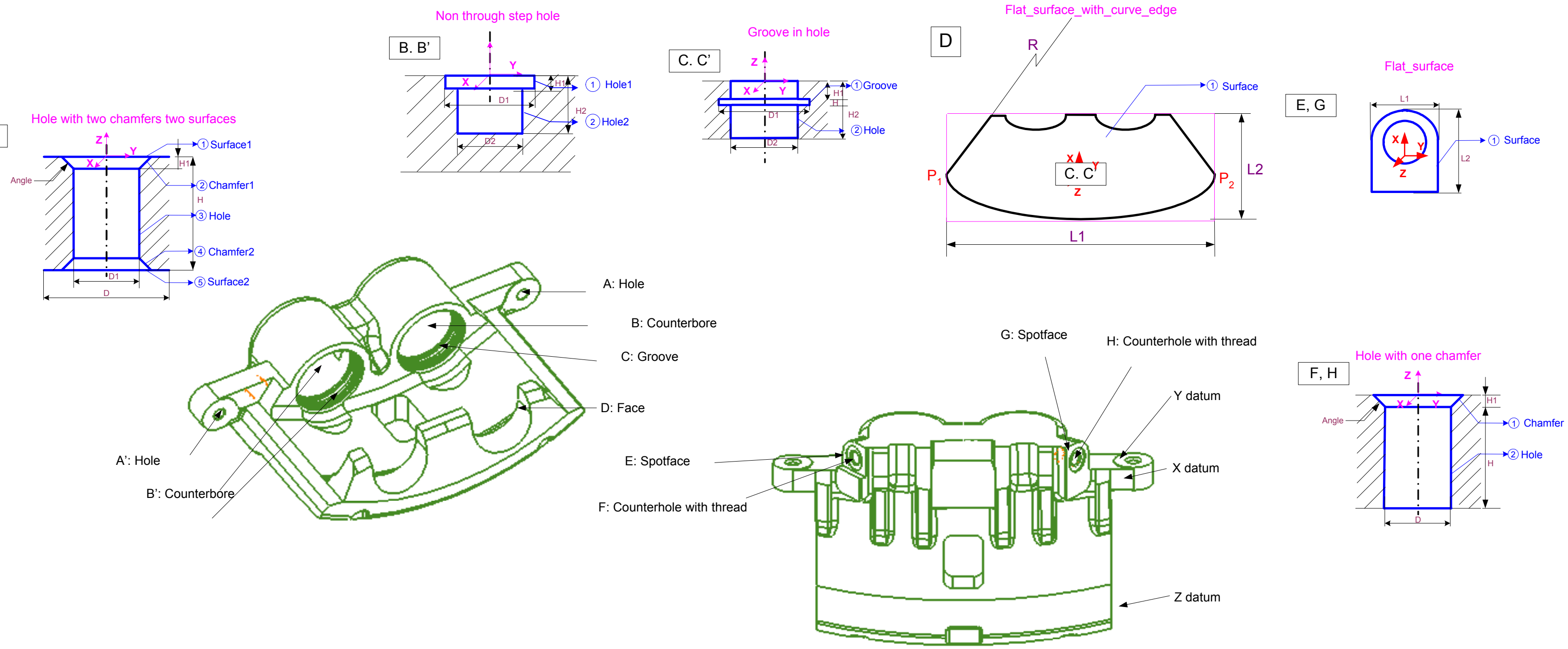
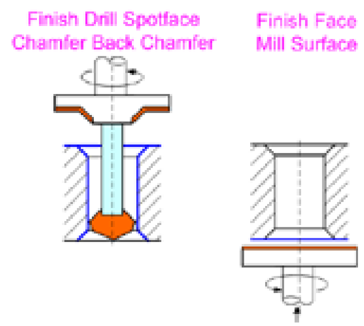
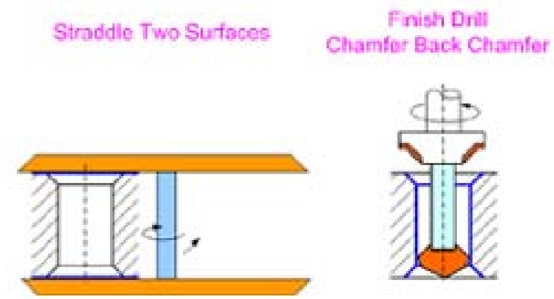
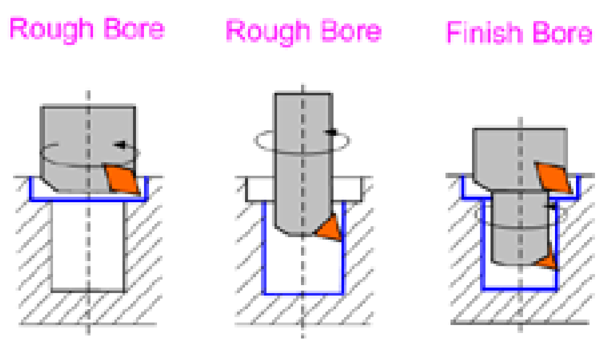
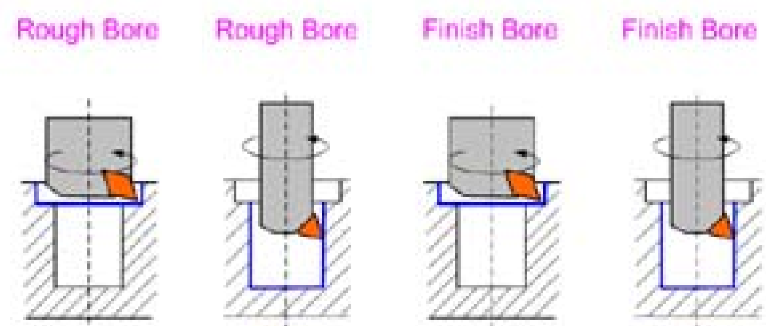
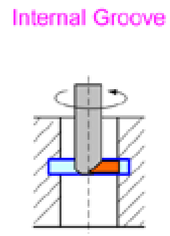
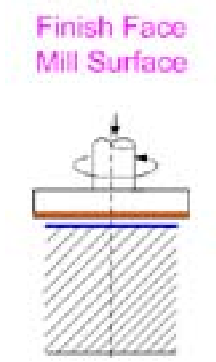
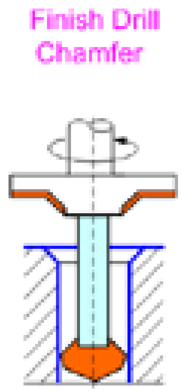
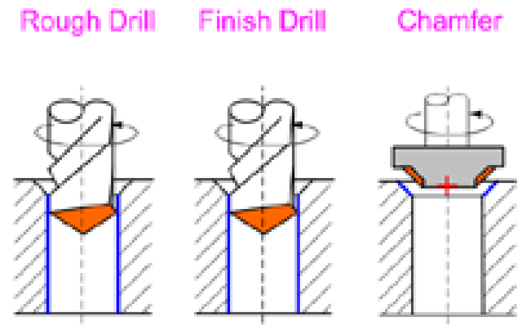


Figure A. 1 Combined feature types and parameters in a caliper family

Table A. 1 Manufacturing methods of the features of caliper family

Feature	Manufacturing methods Ⅰ	Manufacturing methods Ⅱ
Hole with two chamfers two surface		
Non through step hole		

Groove in hole		
Flat surface with curve edge		
Flat surface		

Hole with one chamfer		

Appendix B: Samples of machine tool information & capabilities

Table B. 1 Daewoo horizontal machining centers

		DHM 500	DHM 630	DHM 800
Number of axis		3½(Pallet rotation at pallet loading station)		
Axis movement X × Y ×Z (mm)		800×650 ×650	1000 ×800 ×1000	1250 ×1000 × 1000
Pallet Size (mm)		500 ×500	630 ×630	800 ×800
Pallet index speed		1.2 sec/90°		
Maximum spindle speed (rpm)		6000 rpm		
Rapid feedrate	X	24 m/min		
	Y	18 m/min		
	Z	24 m/min		
Tool shank		CAT 50		
Tool change time		2.5 sec		
Tool change position	X			
	Y			
	Z			
Controller		Fanuc 16/-MA		

Note:
X-axis travel: Longitudinal movement of column;
Y-axis travel: Vertical movement of spindle head;
Z-axis travel: Cross movement of table.

Table B. 2 Mori Seiki horizontal machining centers

		SH-403	SH-503	SH-633
Number of axis		3½(Pallet rotation at pallet loading station)		
Axis movement X × Y ×Z (mm)		560×510 ×510	630 ×600 ×850	840 ×760 ×840
Pallet Size (mm)		400 ×400	500 ×500	630 ×630
Pallet index speed		2sec/90˚		
Maximum spindle speed (rpm)		12,000	10,000	
Rapid feedrate	X	50 m/min		
	Y	50 m/min		
	Z	50 m/min		
Tool shank		CAT 40		
Tool change time		0.8 sec		
Tool change position	X			
	Y			
	Z			
Controller		Fanuc 16/-MA		

Table B. 3 Kitamura horizontal machine centers

		Mycenter-H400i	Mycenter-H500	Mycenter-H630i
Number of axis		3½(4th axis 0˚ ~ 360˚)		
Axis movement X × Y ×Z (mm)		660×610 ×560	870 ×610 ×660	1000 ×800 × 820
Pallet Size (mm)		400 ×400	500 ×500	630 ×630
Pallet index speed		0.36sec/90˚	0.45sec/90˚	
Maximum spindle speed (rpm)		13,000	12,000	
Rapid feedrate	X	50 m/min		
	Y	50 m/min		
	Z	50 m/min		
Tool shank		CAT 50		
Tool change time		1.0 sec	2.0 sec	
Tool change position	X			
	Y			
	Z			
Controller		Fanuc 16iM		

Appendix C: XML file format of BOP

1. Combined feature definition

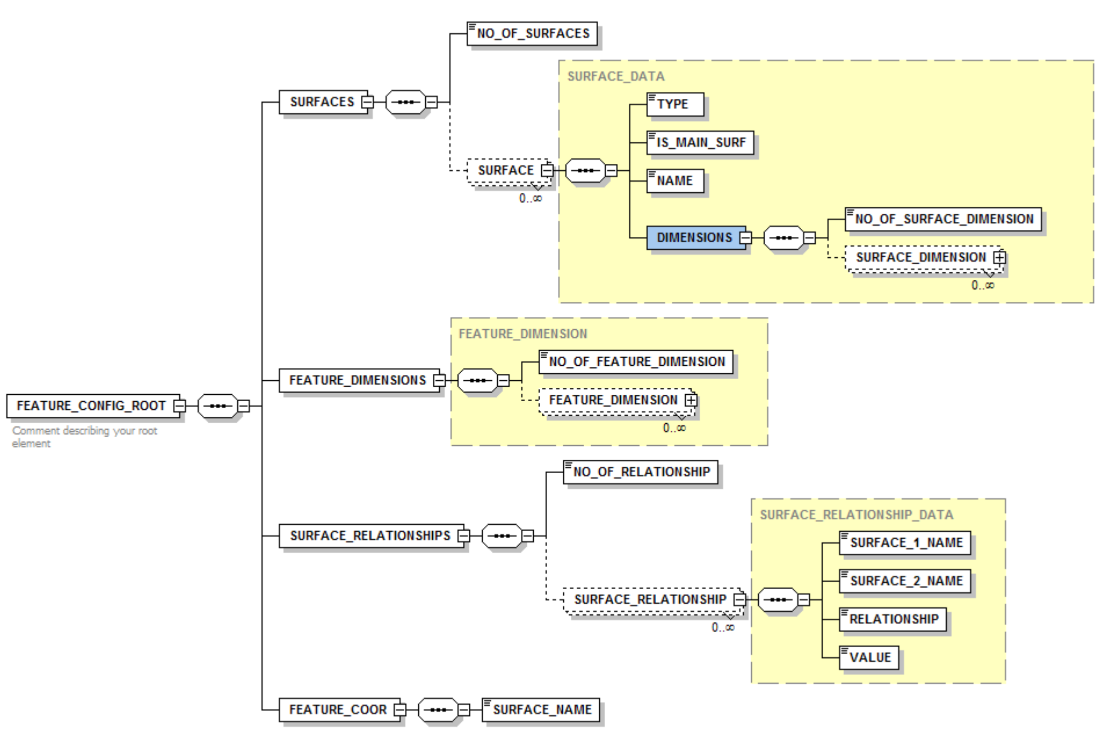


Figure C. 1 XML format for combined feature definition

2. Cutter definition

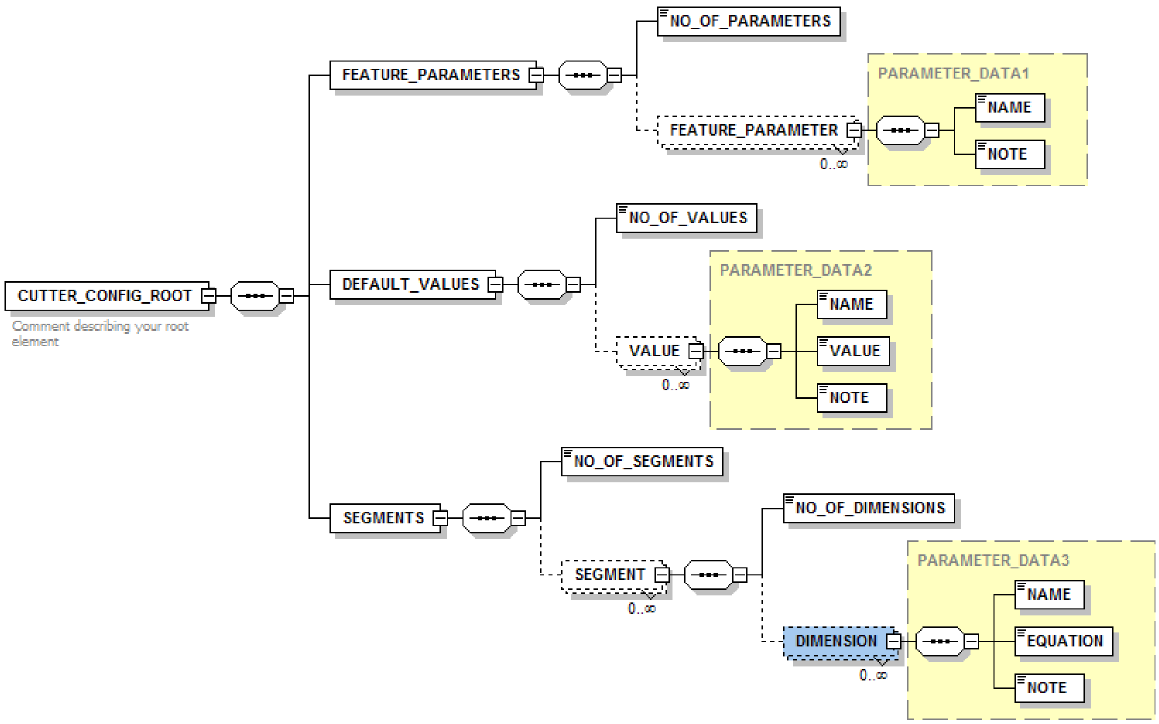


Figure C. 2 XML format for cutter definition

3. Toolpath definition

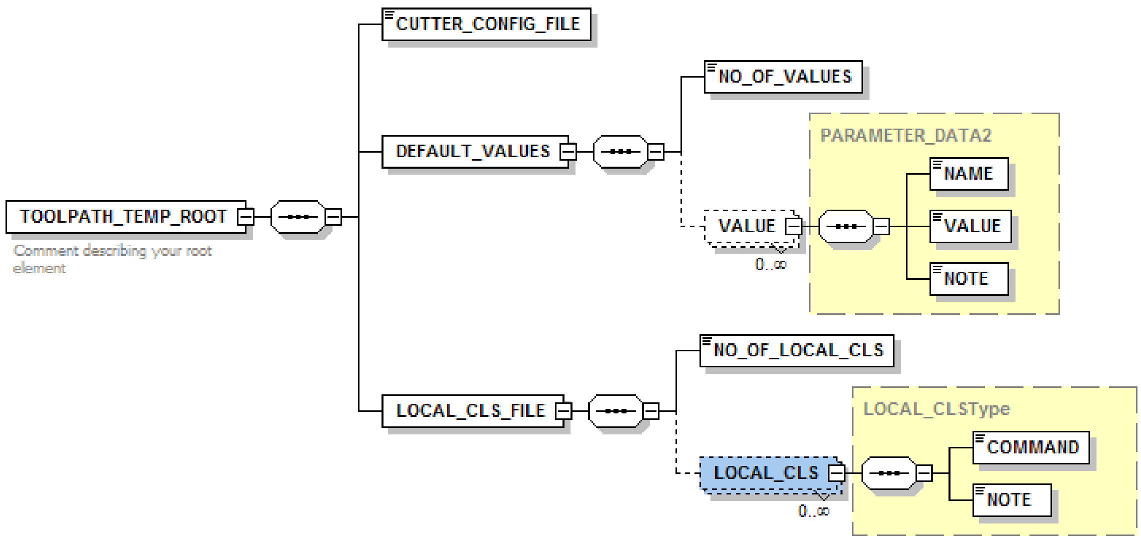


Figure C. 3 XML format for toolpath definition

4. Fixture base and part layout definition

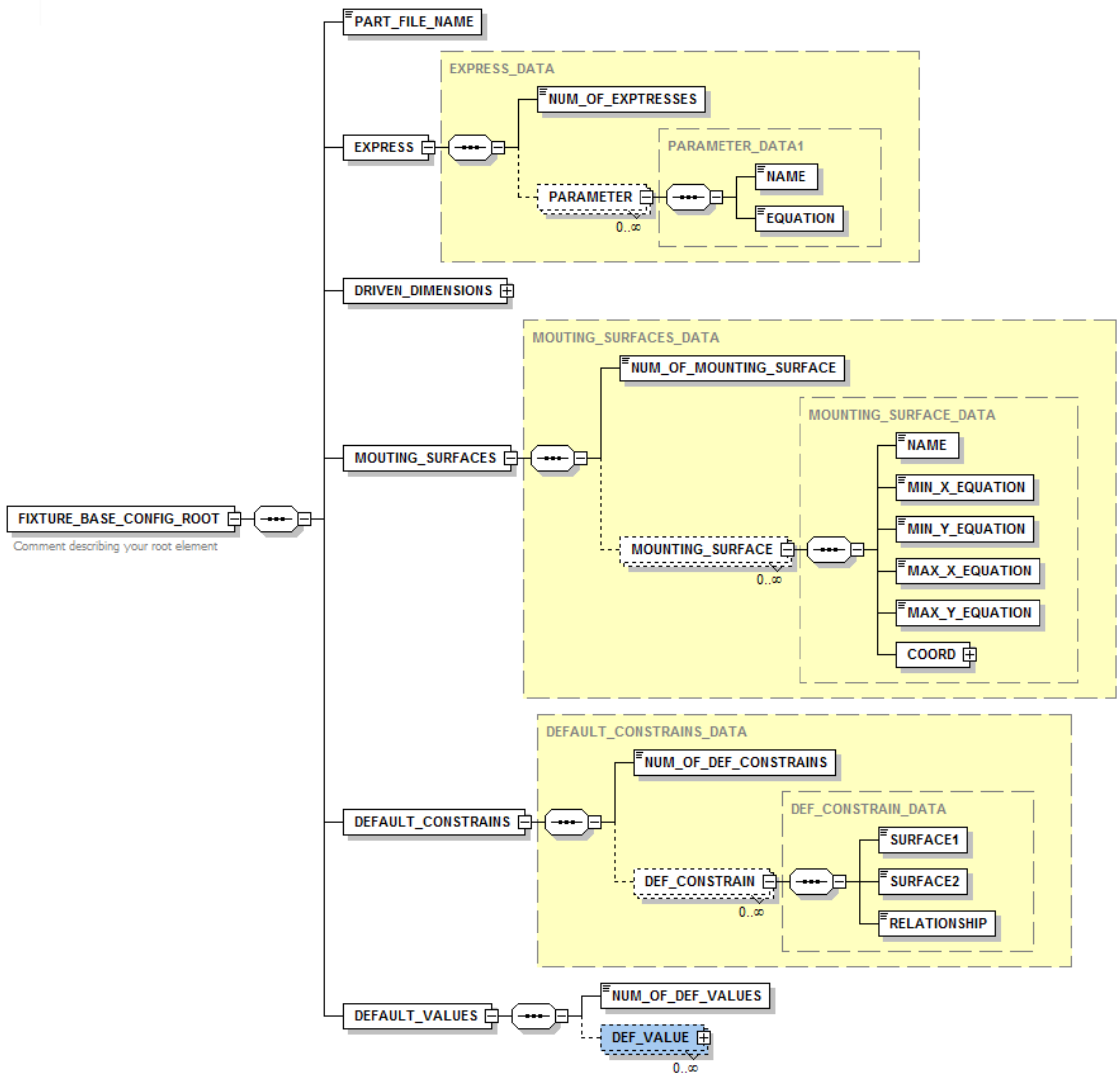


Figure C. 4 XML format for fixture base definition

Appendix D: User interface and screenshots of PEMS

Step 1: Specify part information

This is PEMS program startup screen. Before the design of a part 's manufacturing plan, its material, part family type and its CAD file should be specified by users first.

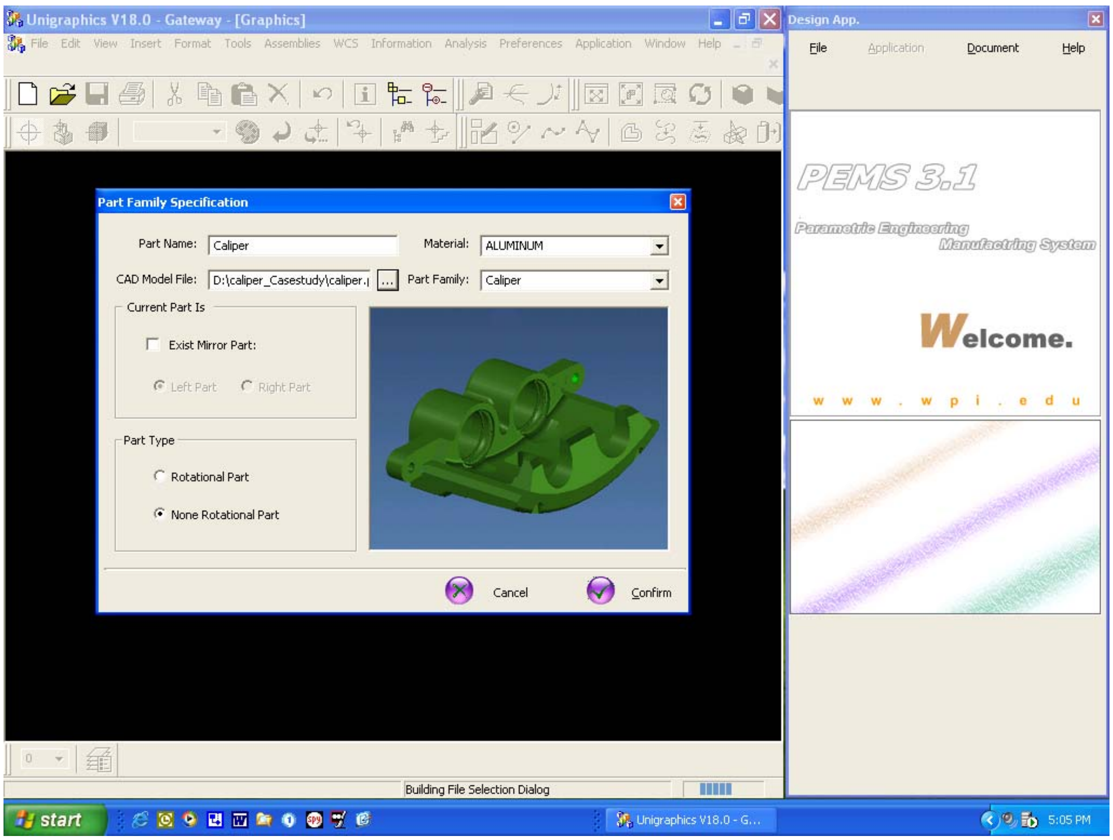


Figure D. 1 Screenshot – Startup

As a result, corresponding part family's information is retrieved from the database and shown out the right side of screen. See in Figure D.2

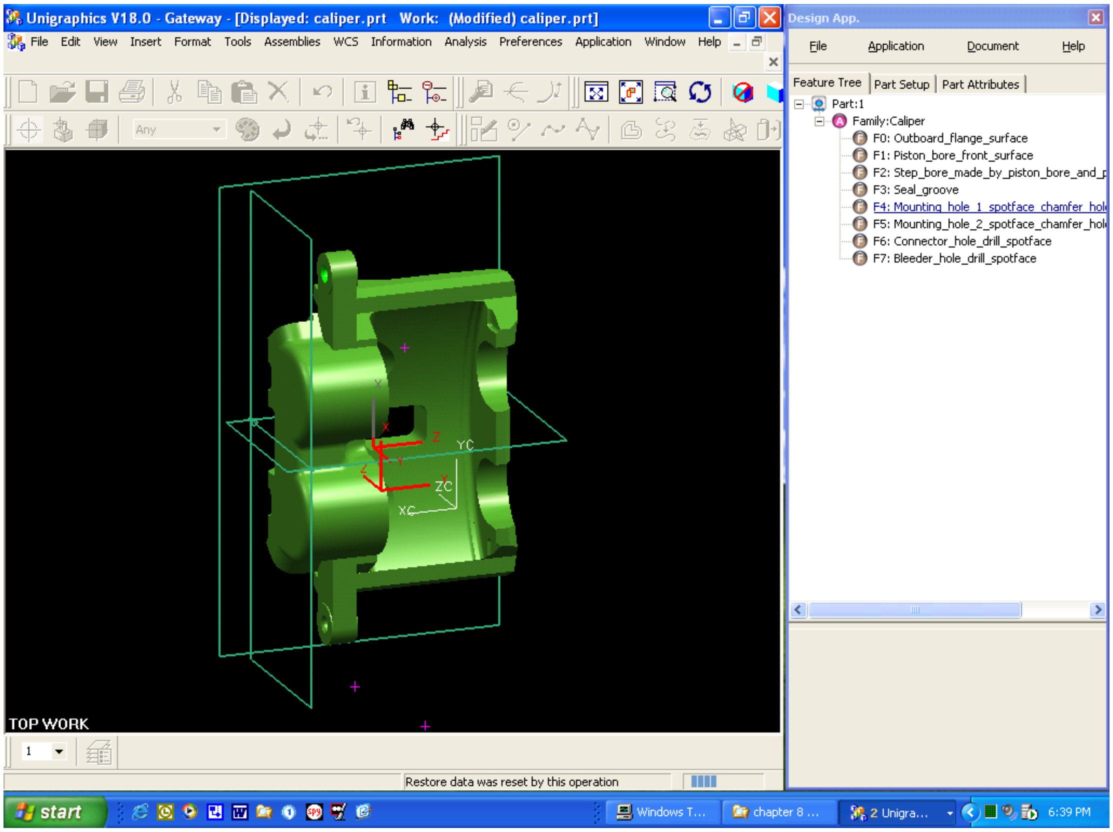


Figure D. 2 Default part family information

Step 2: Define feature information and its manufacturing strategies

Each feature on a part family tree should be recognized from the CAD model. A feature's main surface and auxiliary surfaces' parameters is recognized and a coordinate on feature is established. As shown in Figure D.3, the surfaces of feature are highlighted and its coordinate is shown in red color.

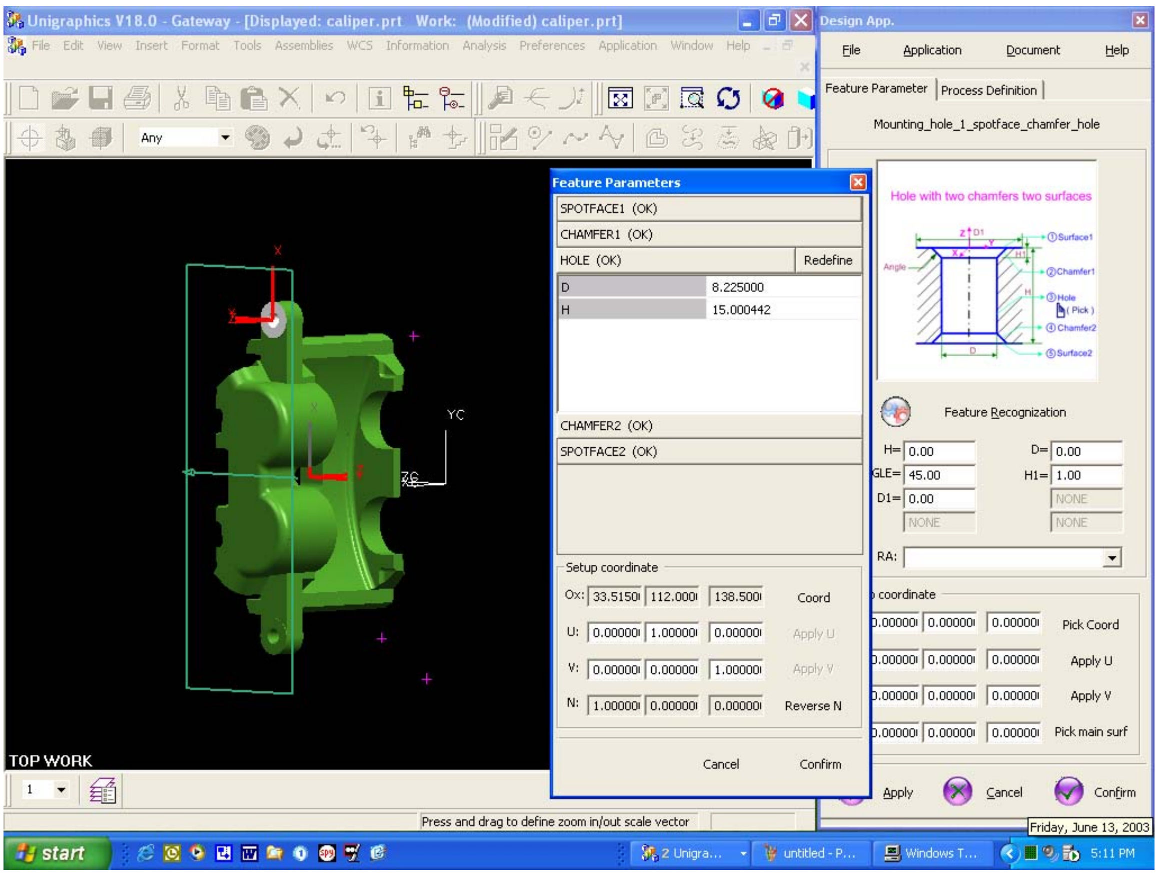


Figure D. 3 Feature recognition

After feature is recognized, its manufacturing strategies can be retrieved from the database, by which a cutter and a pre-defined toolpath are associated with the processes in the strategies and the dimensions of the cutter and the toolpath is driven by the feature's parameters.

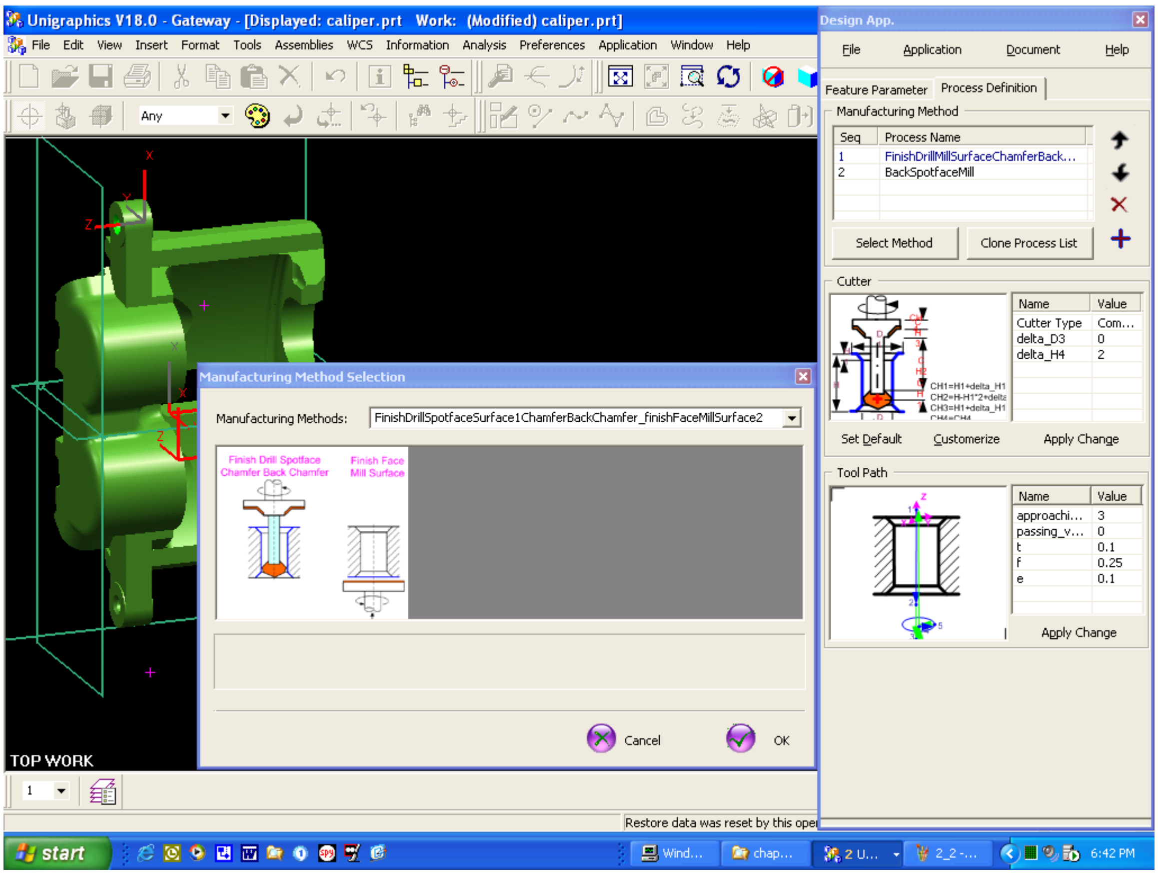


Figure D. 4 Selection of feature's manufacturing strategies

Step 3:

After all the features have been recognized and their manufacturing strategies have be determined, setup planning is carried out based on the BOP stored in database.

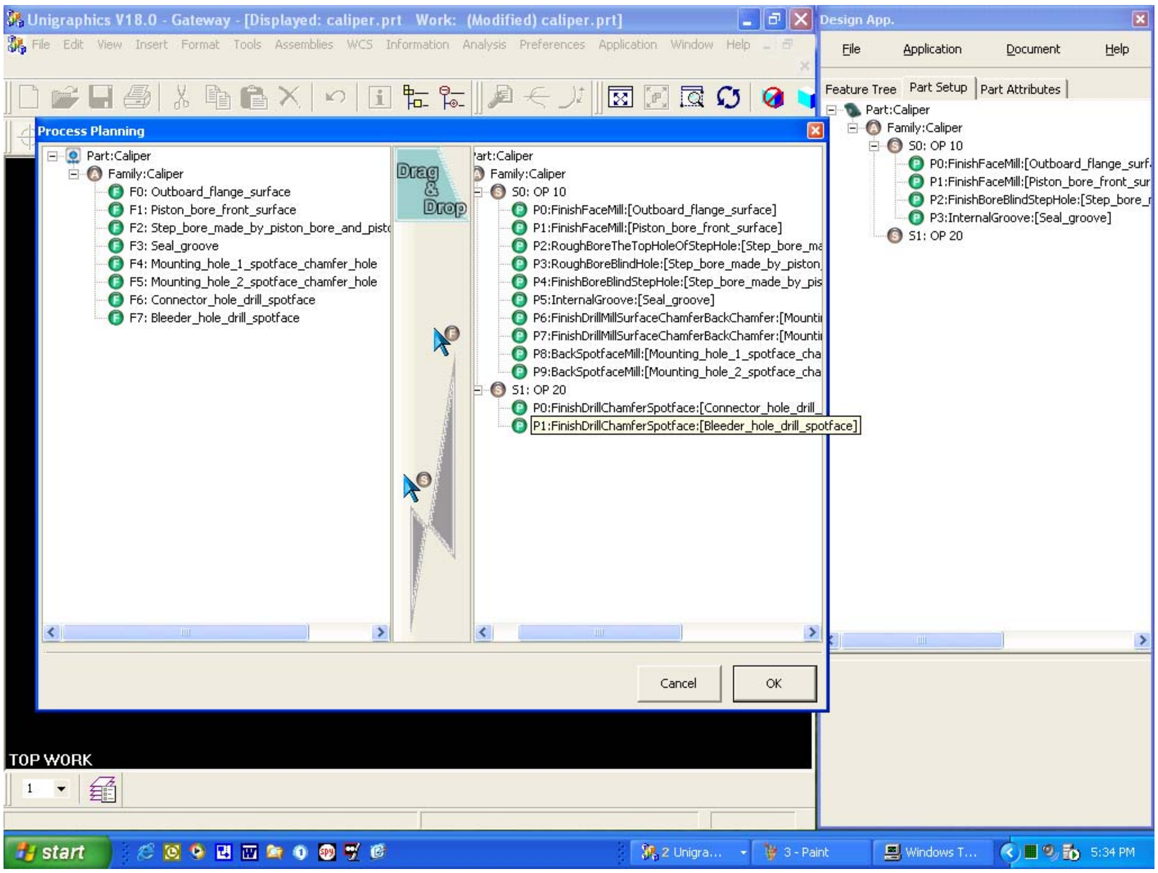


Figure D. 5 Setup planning

Step 4: Conceptual fixture design and manufacturing plan generation

Conceptual design is carried out based on the BOP. Figure D.6, Figure D.7 and Figure D.9 shows the one solution of the caliper production. Corresponding global processes and their toolpath are generated automatically. Cycle time is calculated and a toolpath simulation is shown in Figure D.8.

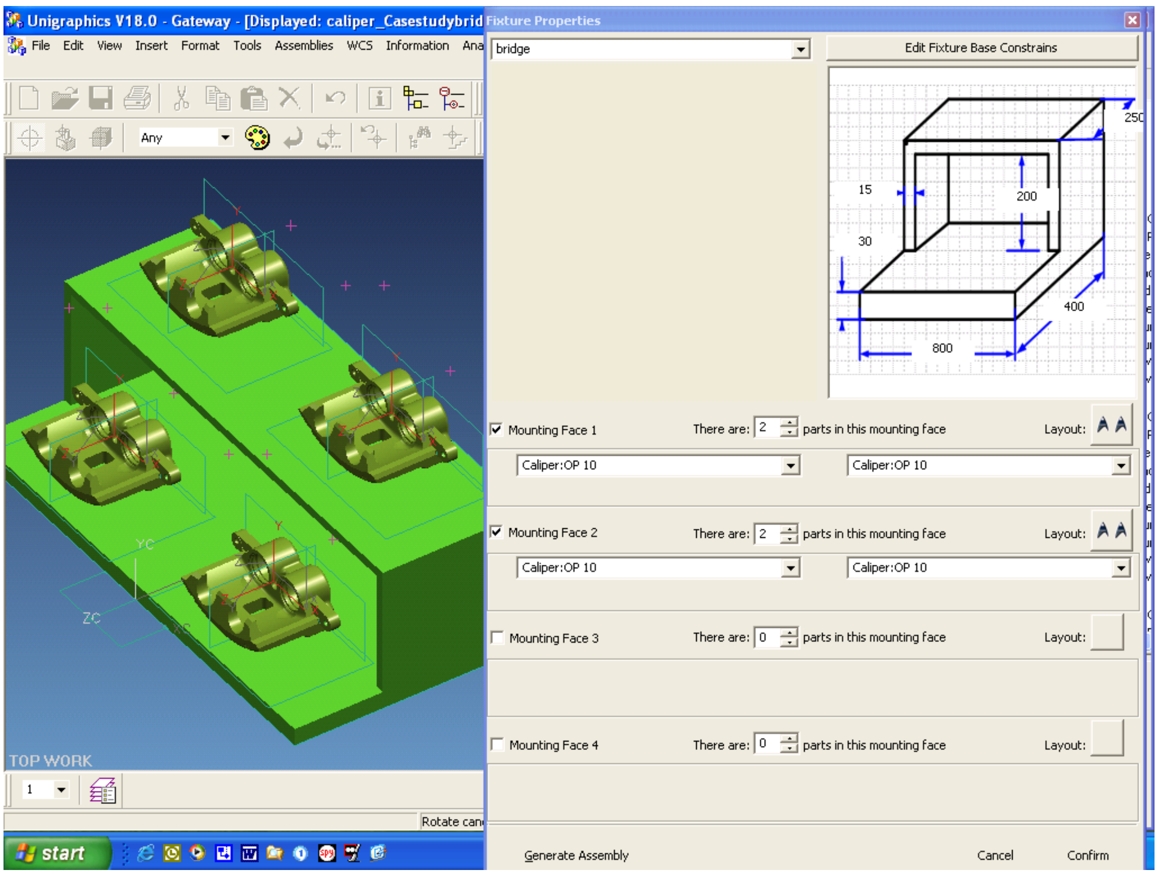


Figure D. 6 Conceptual fixture design of caliper setup 1

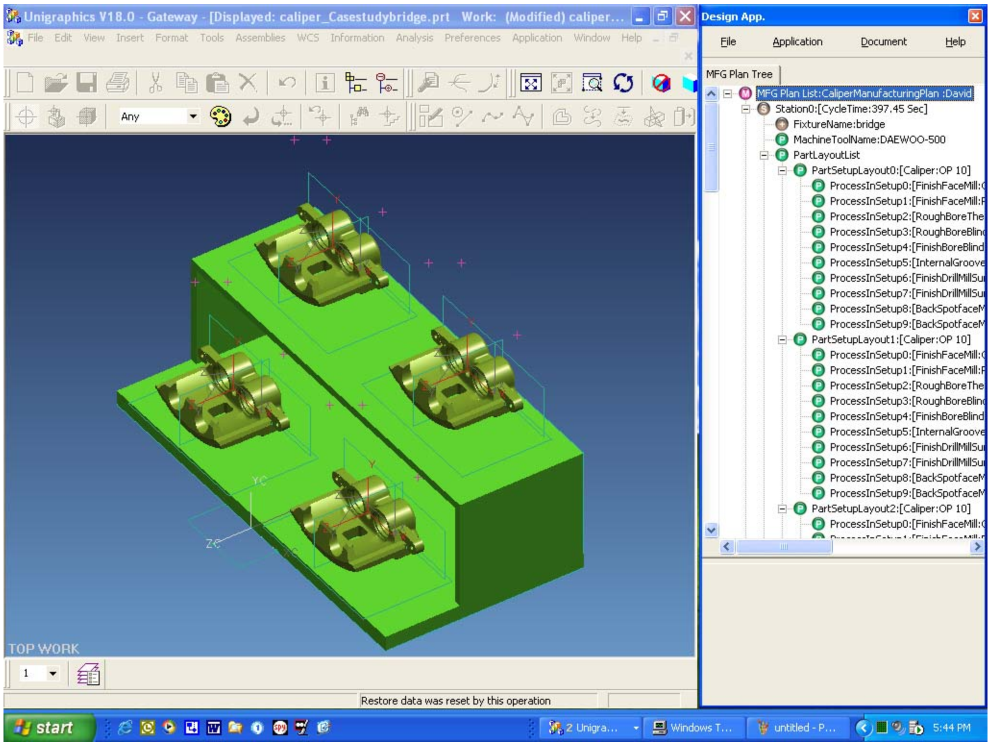


Figure D. 7 Manufacturing plan of caliper setup 1

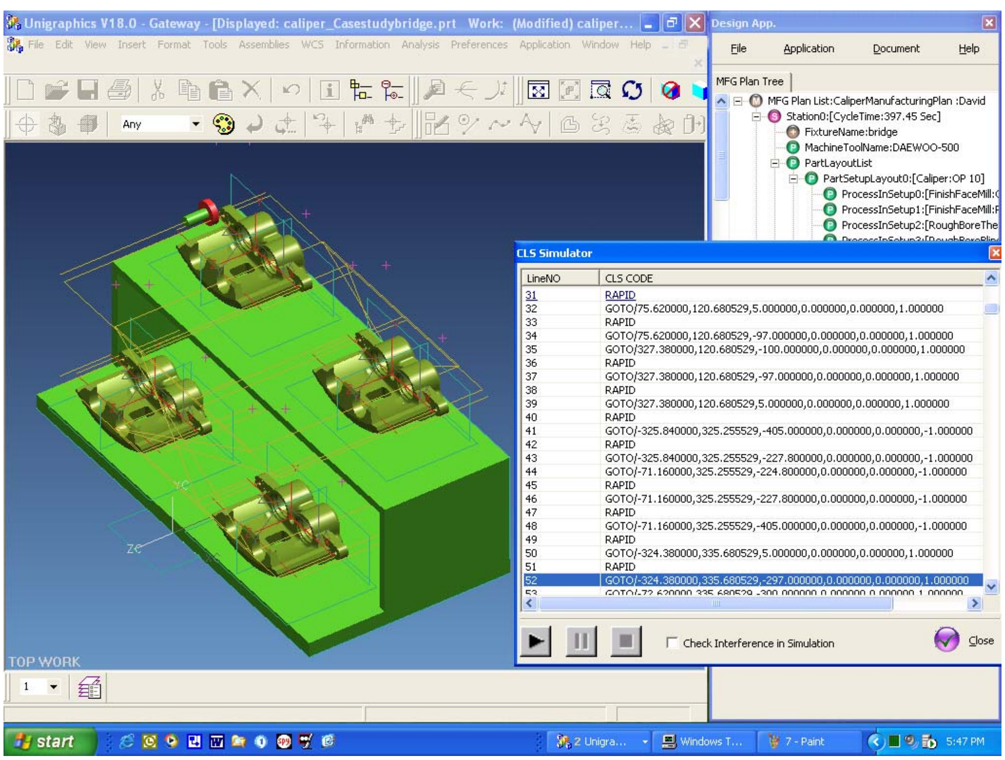


Figure D. 8 Simulation

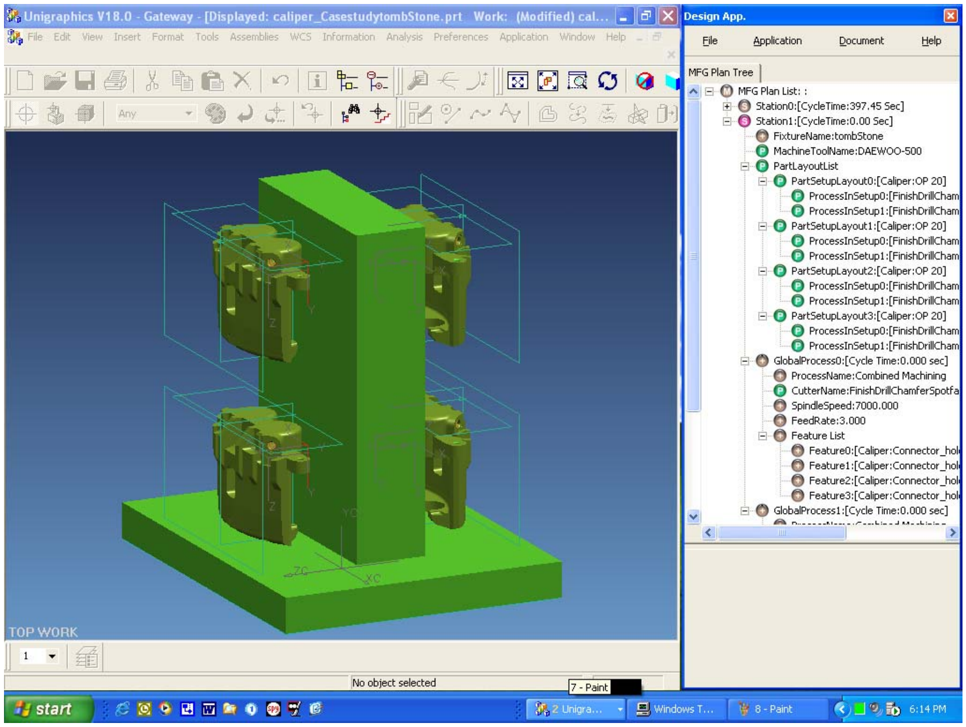


Figure D. 9 Conceptual fixture design and manufacturing plans of caliper setup 2