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ORIGINAL ARTICLE

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Computer aided manufacturing planning for mass customization: part 2, automated setup planning

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Abstract Setup planning plays a crucial role in CAPP to ensure product quality while maintaining acceptable manufacturing cost. The tasks of setup planning include identifying manufacturing features and corresponding manufacturing processes, determining the number of setups, part orientation, locating datum and process sequence in each setup, and selecting machine tools and fixtures. An automated setup planning technique and system has been developed based on not only the tolerance analysis, but also the manufacturing resource capability analysis. The automated setup planning is divided into two levels: setup planning in single part level and in machine station level. Algorithms for setup generation and process sequencing have been developed and a case study of setup planning is presented.

Keywords CAPP · CAD/CAM · Setup planning · Fixture design

1 Introduction

Setup planning plays a crucial role in CAPP (computer-aided process planning) to ensure product quality while maintaining acceptable manufacturing cost. The tasks of setup planning consist of (1) identifying manufacturing features and corresponding manufacturing processes, (2) determining the number of setups, part orientation, locating datum and process sequence in each setup, and (3) determining the machine tools and fixtures.

The purpose of setup is to locate and fix a part on a machine tool so that machining can take place. There are three setup methods used to maintain tolerances between two features: (1) machining the two features in the same setup; (2) using one feature as the locating datum and machine the other; and (3) using an intermediate locating datum to machine the two features in different setups. These three methods are denoted as setup method I, II and III, respectively. It is concluded that setup method I may consist of least manufacturing error because no locating errors are involved [6]. Setup method II consists of one more locating error and is used when two features cannot be machined in the same setup, and setup method III is used where a tolerance stack-up is formed by every setup including the two features. Hence, to reduce the locating error effect, the setup planning priority may be given to minimize the number of setups and to process the maximum number of features that can be synchronously machined in one setup.

In the research of setup planning, the analysis of 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. Extended directed graph, including feature and tolerance relationship graph (FTG) and datum and machining feature relationship graph (DMG), is used to represent part design tolerance specifications and operational tolerance relationships based on true positioning datum reference frames [8]. By the use of graphs, it is easy to track the tolerance generation routines among manufacturing processes.

Other than tolerance analysis, feature orientation, precedence constraints, kinematic analysis and force analysis have been considered in setup planning [5]. Several methodologies and algorithms have been proposed for setup planning, including a graph-matrix approach for rotational parts based on tolerance analysis [1, 4]; a hybrid-graph theory, accompanied by matrix theory to aid setup plan generation that was carried out on a 3-axis vertical

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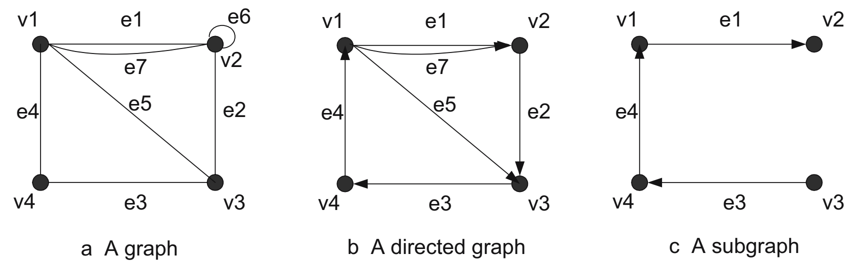


Fig. 1 Graph examples. **a** A graph. **b** A directed graph. **c** A subgraph

milling center [7]; 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) [3]; and a graph-based analysis and seven setup planning principles defined to minimize machining error stack-up under a true positioning GD&T scheme [8]. Among 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. Hence, setup planning is constrained by the fixture to be applied. But most researchers circumvent this problem by focusing on either setup planning or fixture design [4].

This paper presents a systematic strategy on automated setup planning for non-rotational parts with the utilization of flexible manufacturing resources. Three technical points are included: (1) graph theory is applied to describe FTG and DMG, where the part design tolerance specification and operational tolerance relationships are presented in setup planning; (2) setup planning of a single part is defined as transforming FTG to DMG based on tolerance and manufacturing resource capability analyses as well as the best practice in industry; and (3) in order to utilize manufacturing resource capability effectively, the setup planning is extended to the station level by the use of multi-part fixtures and multi-axis machine tools. The graph theory and its application in setup planning is first discussed in Sect. 2. In Sect. 3, the problem of setup planning is formulated as a mathematical problem of transforming FTG to DMG. Tolerance analysis, manufacturing resource capability modeling and utilization, and industry practice are taken into consideration. In Sect. 4, a case study is carried out to show the effectiveness of the automated setup planning strategy. Finally, conclusions and a discussion are given regarding the advantages and limitations of the proposed setup planning strategy.

2 Graph theory and application in setup planning

2.1 Graph theory

A *graph* is an ordered triple $G=\{V, E, I\}$, where V is a nonempty set of elements, E is a set disjointing from the elements in V, and I is an incidence map associated with each element of E [2]. Elements of V are called vertices of G, and elements of E are called edges of G. Figure 1 shows a general graph. If all the elements in E connect ordered pairs of vertices, then G is called a *directed* graph, as shown in Fig. 1b. For two vertices v1 and v2, if edge e1 is the only edge joining them, we write I(e1)=v1v2. A set of two or more edges that have the same vertices is called a set of *multiple* or *parallel* edges, like the edges e1 and e7 in Fig. 1a. An edge whose two ends are the same is called a *loop* at the common vertex, such as the edge e6 in Fig. 1a.

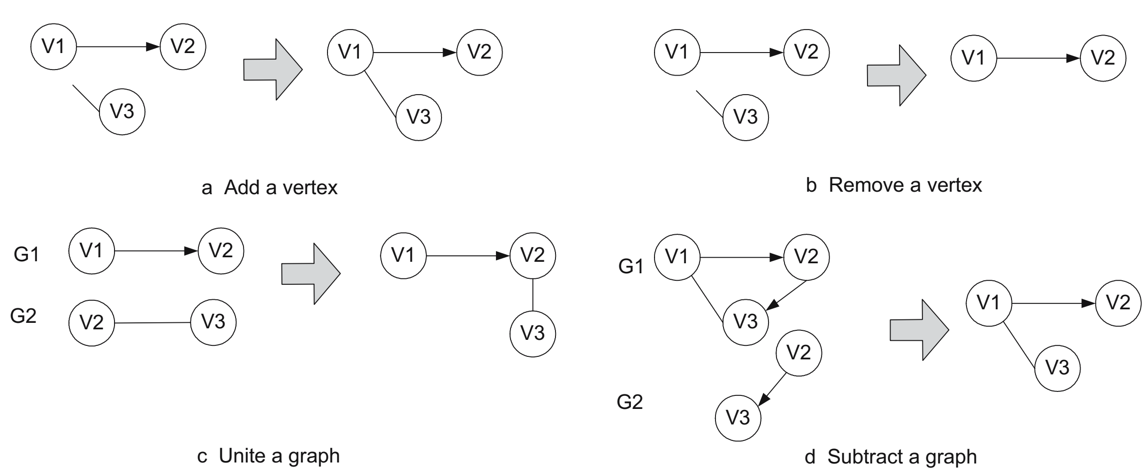


Fig. 2 Main operations in graph theory. **a** Add a vertex. **b** Remove a vertex. **c** Unite a graph. **d** Subtract a graph

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 may consist of subgraphs. A graph H is called 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 1c shows a subgraph of Fig. 1b.

Let G be a graph and $v \in V$. 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, 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,

$$d(v) = d^-(v) + d^+(v) + d^0(v) \tag{1}$$

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

A *walk* in a graph G is an alternating sequence W: $v_0e_1v_1e_2v_2e_{3\ldots}v_ne_n$ of vertices and edges beginning and ending with vertices in which $v_{i\text{-}1}$ 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 and circuit are useful in setup sequencing and process sequencing.

New graphs can be generated by the use of the 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 Fig. 2.

2.2 Feature tolerance relationship graph (FTG)

Part information is composed of the information of features and feature relationships. It can be represented by FTG. The relationships are the dimensions and tolerance

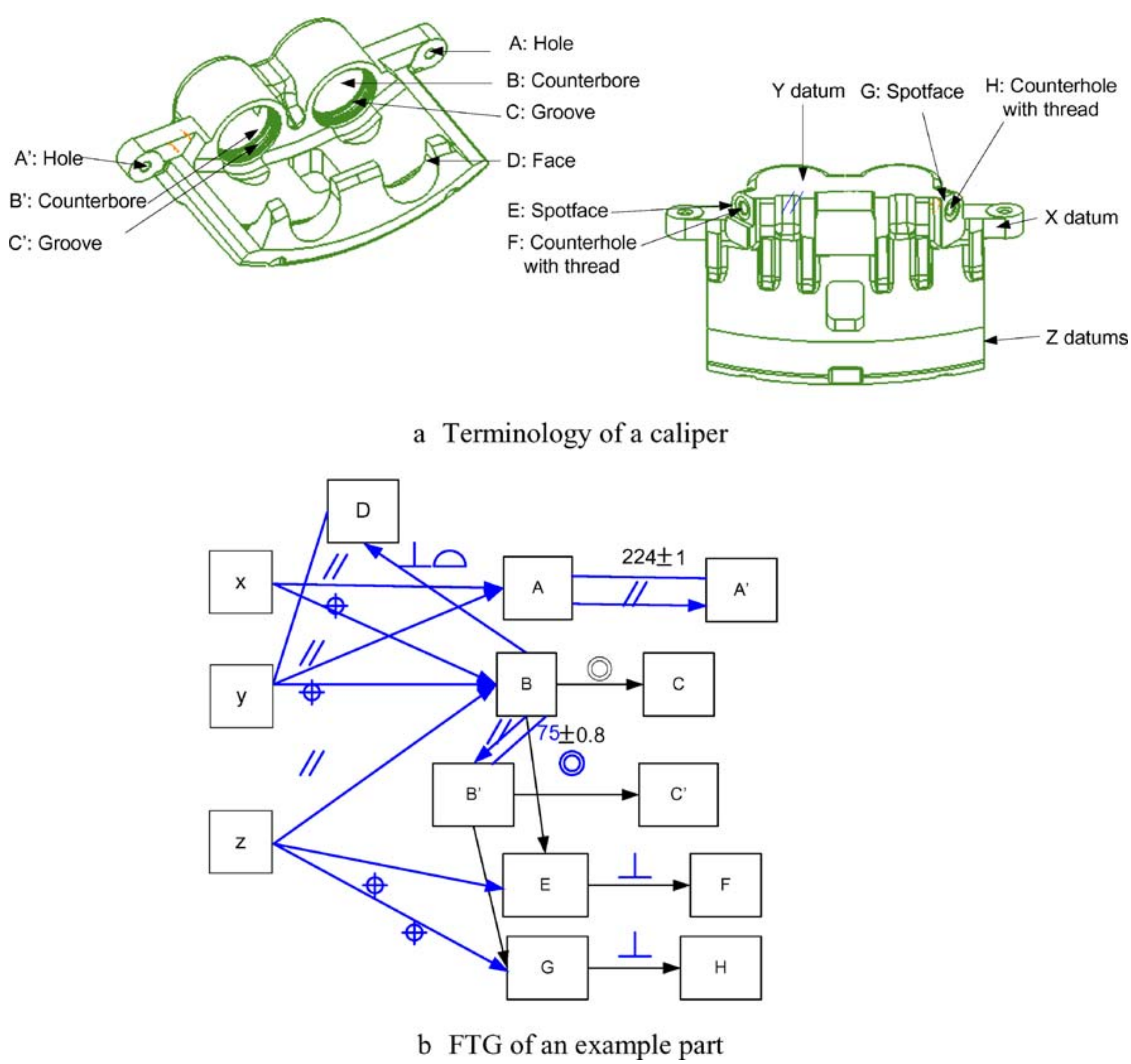


Fig. 3 FTG of a simplified caliper. **a** Terminology of a caliper. **b** FTG of an example part

specifications between features. In FTG, the vertices represent features, the edges represent dimensions and tolerances between features, and the incident maps represent the relationship types and values. Among them, a pair of unordered vertices represents the dimension tolerances, and a pair of ordered vertices represents the positional and orientation tolerances. In many cases, there may exist more than one tolerance between two features. Hence, FTG of a part is a graph with undirected edge, directed edge, and multiple edges; it is not only a simple graph. The following is a mathematical representation of FTG:

$$G_{FTG} = \{F, T\} \tag{2}$$

where: $F=\{f_1, f_2, \ldots, f_n\}$ is a nonempty set of vertices of FTG. Each vertex represents one feature; $T=\{t_1, t_2, \ldots, t_m\}$ is a set of edges of FTG with relationship defined by $t_j=\{f_i, f_k, t_{\text{type}}, t_{\text{value}}\}$. Each edge associated with the features is 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 it is a positional or orientation tolerance, the edge is a directed edge and the first feature is the datum feature of the tolerance.

Figure 3a shows the terminology of a simplified caliper part in the automotive industry. Figure 3b shows it's FTG that clearly expresses the relationships between features. *X*, *Y*, and *Z* are pre-defined datum surfaces that are mutually perpendicular to each other. Features *A* and *A*' are two holes that are used to mount calipers on the brake system. There exists a dimension tolerance between them and a 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, as shown in Fig. 3b. Hence, there are multiple edges between *A* and *A*', and *B* and *B*'.

Since features are associated with particular manufacturing methods, each of them may consist of several processes and the process may have its own tool approaching directions. Therefore FTG is extended to link feature manufacturing processes onto the features. For a particular part, it's FTG is unique, but it may have several extended FTG since one feature may have alternative manufacturing methods. As a result, the task of setup planning is to design setups that perform all the manufacturing processes linked onto the features in the FTG. Figure 4 shows extended FTGs of the caliper example.

The extended FTG is mathematically represented as follows:

$$G^E_{FTG} = \{F, T\} \tag{3}$$

where $F=\{f_1, f_2, \ldots, f_n\}$ is the feature set of a part. Each feature has its own manufacturing processes $f=\{p_{i1}, \ldots, p_{i0}\}$. The definition of T is the same as FTG.

2.3 Datum and machining feature relationship graph (DMG)

Setup planning is to determine how many setups are needed to machine a part, what the datum features are in each setup, and how many processes 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 requirement between

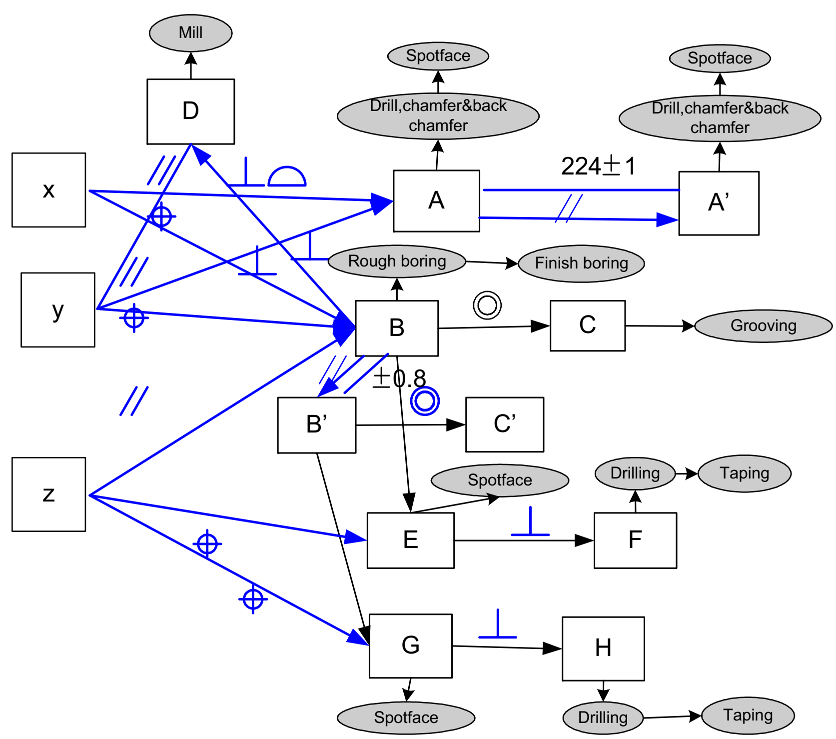


Fig. 4 FTG with the consideration of feature's processes

features, the errors caused by the manufacturing processes should also be recorded.

The information of setup planning can be represented by the relationship between datum features and manufacturing features, which is called DMG. A DMG includes one or many sub-graphs and each sub-graph represents one setup. In DMG, 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 5 shows DMG of the example caliper. With the use of DMG, it is easy to track back the machining error stack-up [3].

The mathematical representation of DMG is as follows:

$$G_{DMG} = \left\{ G^s_{DMG1}, G^s_{DMG2}, \ldots, G^s_{DMGn} \right\} \quad (4)$$

$$G^s_{DMG} = \{ D, F, Er \} \quad (5)$$

where D={D_1,D_2,D_3} represents the datum features; F={f_1,...f_m} is the feature set and associated by the processes, f_i={p_{i1} ,..., p_{i0}} and Er_j={f_i, f_k, er_{type}, er_{value}} represents the error specifications. It is true that $f_i \subset D \cup F$, $f_k \subset F$. DMG is composed of sub-graphs that represent individual setups. Each setup consists of datum features, manufacturing features and machining errors generated in the setup. er_{type} is the same as t_{type} defined in Eq. 2.

3 Automated setup planning

In this paper, automated setup planning is divided in two sub-tasks: setup planning in part level and in station level in which fixtures and machine tools are selected to machine several parts sequentially on machine tools. Moreover, setup planning and fixture design are two close modules. Fixture planning may provide locating datum information to help generation of the DMG. Station level setup planning can give part orientation, and part layout on fixture bases to facilitate fixture structural design. When fixture planning information is not available, the best of practice of similar parts can be used to help setup planning. Figure 6 shows the architecture of automated setup planning.

Since the input and output information in setup planning for a part can be represented by FTG and DMG, respectively, the problem of setup planning is to transform the extended FTG into DMG based on tolerance and manufacturing capability analyses. Setup planning in part level 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 with tolerance relationships and suggest machining them in one setup. Locating datum of each feature group is also identified in feature grouping. 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 feature's machining processes in each setup. The 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 because of the different manufacturing resource capability utilization. In the last step, precedence constraints are applied to guide a walk through all vertices on DMG2 to determine process sequence in each setup.

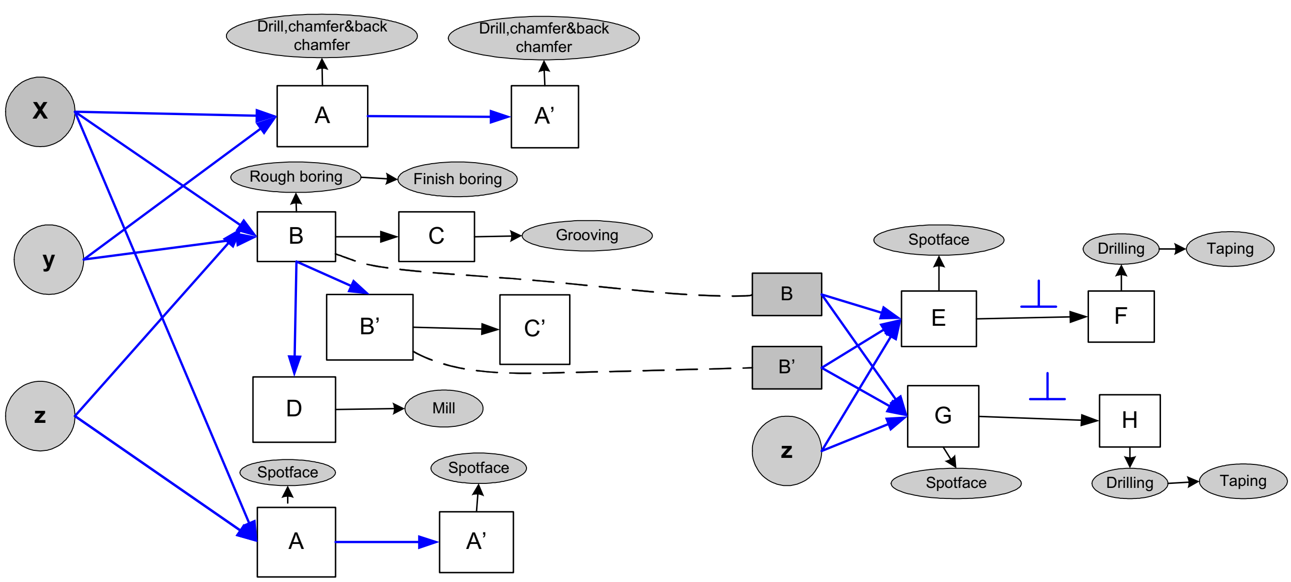
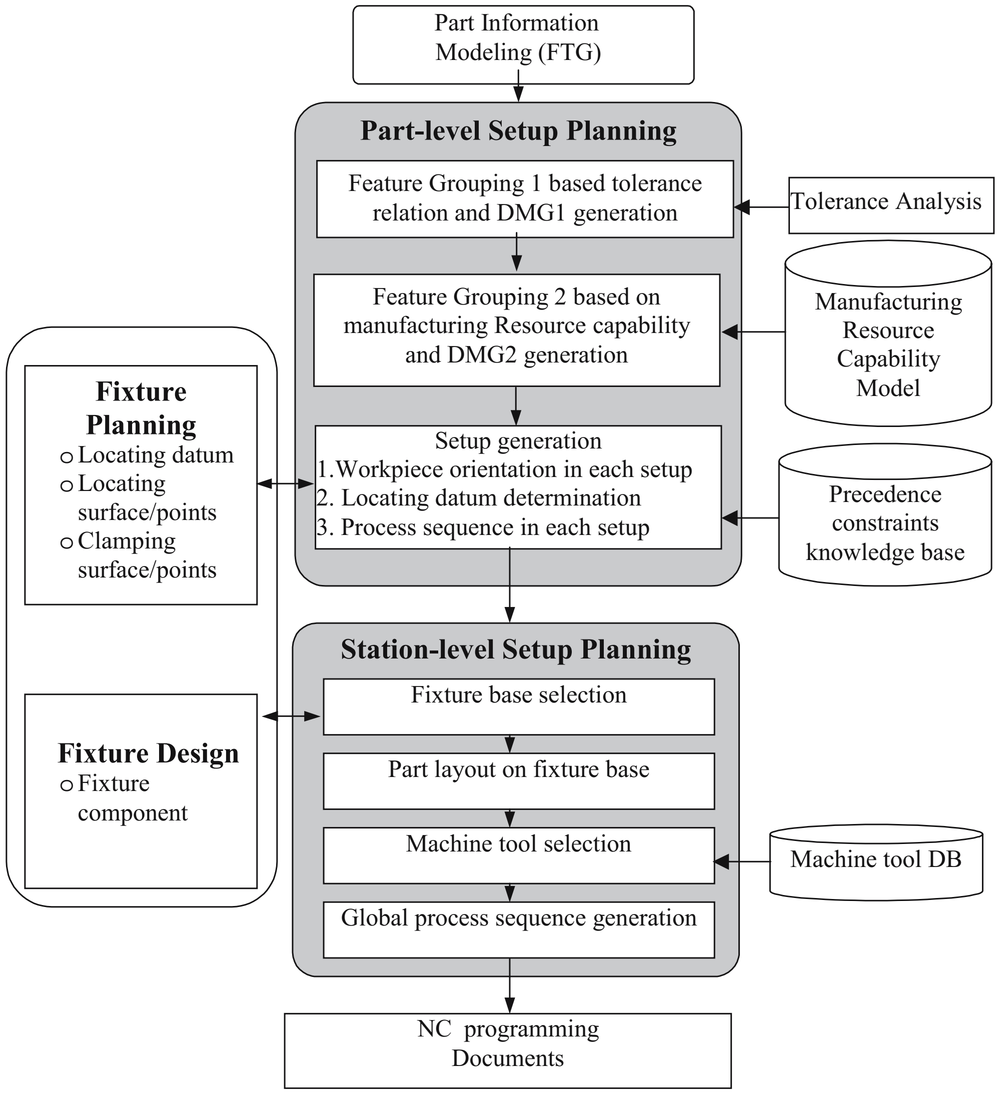


Fig. 5 DMG of caliper

Fig. 6 Overview of automated setup planning



3.1 Setup planning in part level

1. Feature grouping based on tolerance analysis
   In order to minimize the inter-setup tolerance stack-up, it is suggested to group those features with close position, orientation or profile tolerance relationship together and to be machined in one datum frame. An algorithm is developed to extract feature groups from FTG, as shown in Table 1. The basic idea is to find datum features and machining features through

Table 1 Algorithm for feature grouping based on tolerance analysis

1 /* Construct FTG of part, and calculate each vertex degree */ $d(v)=d^{-}(v)+d^{+}(v)+d^{+}(v)$

2 /*Find initial datum features */

Features whose in-degree $d^{-}(v)$ are initial datum features

3 /* Find feature group 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 1. If all the features are included in above feature groups, go to step 5 else find intermediate datum frame

2. The features in 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 as an ungrouped feature by a two-way edge.

Find chained vertices based on intermediate datum frame

Repeat 1,2,3 until all the features are grouped

5 End

calculating the degree of vertices in FTG. The in-degree of initial datum feature is 0.

By the use of the algorithm shown in Table 1, FTG is transferred into DMG1, in which initial setups have been generated, and datum features and manufacturing features that are suggested to machine in one setup are grouped into clusters.

2. Setup formation based on manufacturing resource capability
The next step of setup planning is to consider the manufacturing resource capabilities. First, features in DMG1 are attached with the manufacturing processes. Each process has its own specified tool approaching direction (TAD). Those feature processes with the same datum frame and tool access direction can be reunited into one group. The TADs are given based on part coordinate system. For the group with more than one TAD, each TAD should be considered without the violation of feature-process sequence.

Next, the machine tool capability is considered. For example, 3-1/2 axis machine tools can provide more TADs than 3-axis machine tools so that the number of setups can be reduced. Table 2 describes the algorithm of reuniting feature-processes groups based on machine tool capability.

Besides TAD, other machine tool capability measures are also considered, such as machine accuracy, table size and motion range, and combinations of fixture and cutting tool geometry. Details will be given in the next section describing station level setup planning. With these considerations, DMG1 is modified into DMG2. The setup sequencing is also determined in DMG2. The basic principle of setup sequencing is to ensure a feature to be machined before it is used as locating datum or tolerance datum of 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 sequences.

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

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

The strong constraints include:

1. Maintaining the manufacturing process sequence of each feature
2. Maintaining the operational-dependent relationship in the graph. For example, planes prior to holes and holes prior to grooves
3. Doing rough cuts first, semi and finish cuts in a prescribed order
4. 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 a surface could be combined with the cutter to drill, chamfer and back chamfer a hole so that the tool change time can be reduced.

3.2 Station level setup planning

It is known that in the overall manufacturing time, cutting time only takes up a small portion. Non-cutting time, including cutter changing time, cutter rapid traverse time and machine tool table index time, takes the most of the cycle time. Hence, in mass production, the utilization of multi-part fixtures may improve the productivity and reduce the cycle time. As shown in Fig. 7, the station level setup planning includes the following steps:

1. Select machine tools
Candidate machine tools are those that fulfilled the entire requirement of machine tool capabilities from

Table 2 Algorithm for reuniting feature-process group based on machine tool capability

1	Find the groups with the same datum features and put them into different containers
2	Put the first group in one container i into setup $i1$
	Transfer TAD of the first group into machine tool coordinate ($CS_{machine}$) and let it point to $CS_{machine}Z$ axis
3	Transfer TAD of next group into $CS_{machine}$. Is it within the machine tool TAD span?
	If yes, put current group into setup $i1$
	If no, generate new setup for current group
4	Repeat step 3 until all groups in the same container that can be machined in setup 1 are found.
5	If new setup is generated, repeat steps 2 and 3 to find feature group in the same container that can be machined in the same setup
6	Repeat steps 2,3,4 and 5 to deal with next containers i+1
7	End

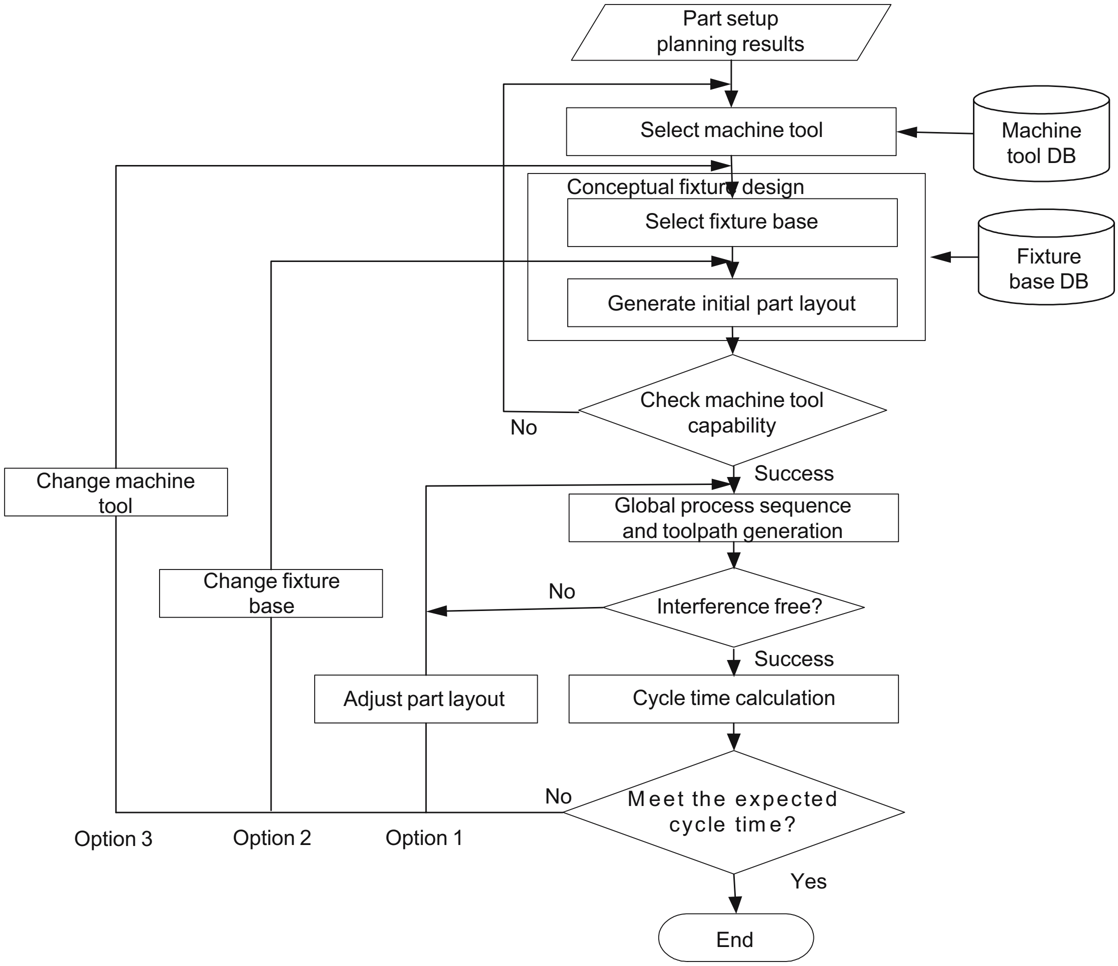


Fig. 7 Flowchart of station level setup planning

setup planning, including the number of axes of machine tools. The detailed machine tool planning is presented in the next section.

2. Conceptual fixture design and part layout design
   Fixture design issues are divided into two steps: conceptual fixture design and detail fixture design that includes the design of fixture structure and fixture components. Conceptual fixture provides ideas about what kinds of fixture bases are used and how many parts are held on the fixture bases as well as how the parts are oriented in the fixture. In mass production, it is fixture vendors who design and fabricate the real fixtures. Hence, in the setup planning level, the conceptual fixture design is emphasized. The initial solution of the conceptual fixture design can be derived from the best practice design in industry, which may include the kinds of fixture bases and the number of parts mounted on each fixture. The part position and orientation on fixture bases need to be determined, which implies how much space should be left to accommodate fixture components.

   The conceptual fixture design is considered as an extension of machine tool capabilities. There may be a mix of part level setups in one station level setup. Therefore, after generation of the initial solutions of conceptual fixture design, the machine tool capability needs to be re-evaluated:

   1. Whether it has enough space to accommodate the fixtures and parts
   2. Whether it can access all the features and finish all the required processes

   If the conditions are not satisfied, the fixture base and part layout may be reselected and adjusted, such as

Table 3 Two steps of manufacturing resource consideration in CAMP

Level	Name	Objective
1	Feature and part level setup planning	Selection of cutters and tool-path for individual feature processes and TADs
2	Setup planning in station level	Determination of the capability requirements on machine tools and fixtures and validation of the selection

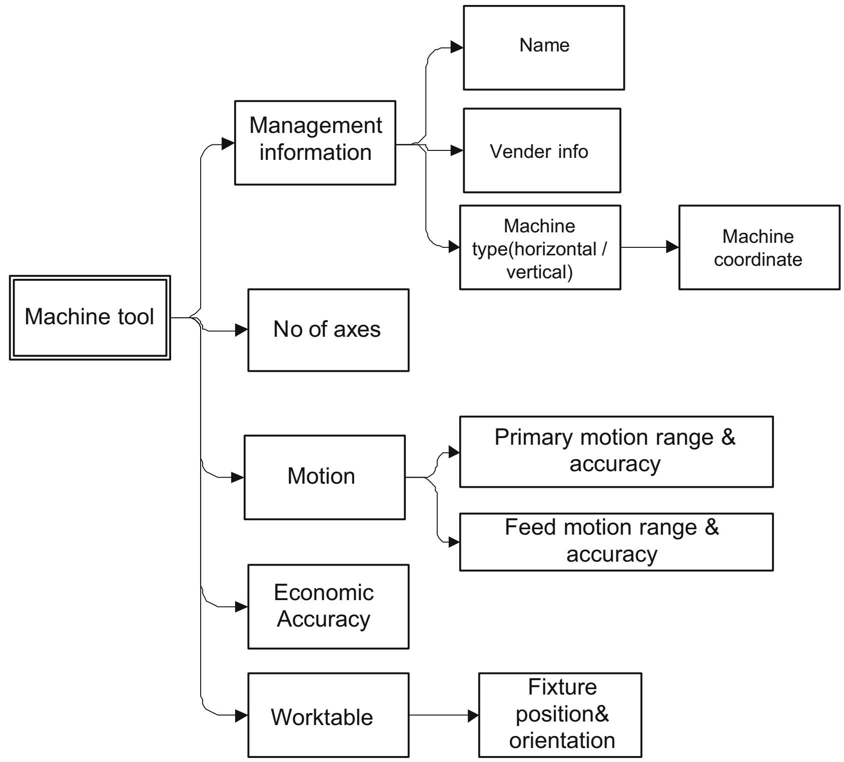


Fig. 8 Machine tool information structure

adjusting part position and orientation, or putting less parts on the fixtures, or even the machine tool is reselected.

3. Global process sequence and tool-path generation
   In order to reduce the non-cutting time on each part, the processes that use the same cutters are suggested to be carried out together in sequence. A sequence is needed for all the manufacturing processes on the multi-part fixture, and corresponding tool-paths are generated without interference from fixture components, machine tools, etc.
4. Cycle time calculation
   Cycle time is a critical factor to help choose better setup plans in mass production. Hence, the estimation of cycle time is indispensable in station level setup planning.

3.3 Manufacturing resource capability modeling

In this research, the consideration of manufacturing resources is divided into two 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 two steps is presented in Table 3.

Step 1:
Determine cutters and tool-path to manufacture individual features based on pre-defined feature-process relationships. With TAD information, the types of machine tools are determined in this step.

Step 2:
Design the setup plans with the consideration of flexible machine tool capability. Since the feature position and orientation specifications are determined in the station level setup planning, the geometry, kinematics, and accuracy capabilities of the selected machine tool and designed fixture are evaluated to ensure the processes are properly performed on all features of parts on the fixture.

By using the 2-step manufacturing resource capability analysis, the critical factors of manufacturing resources that affect the manufacturing cost and time of setup planning can be easily identified, and a quick decision can be made on the selection of machine tools and the design fixtures for

Table 4 Feature grouping based on tolerance analysis

	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*

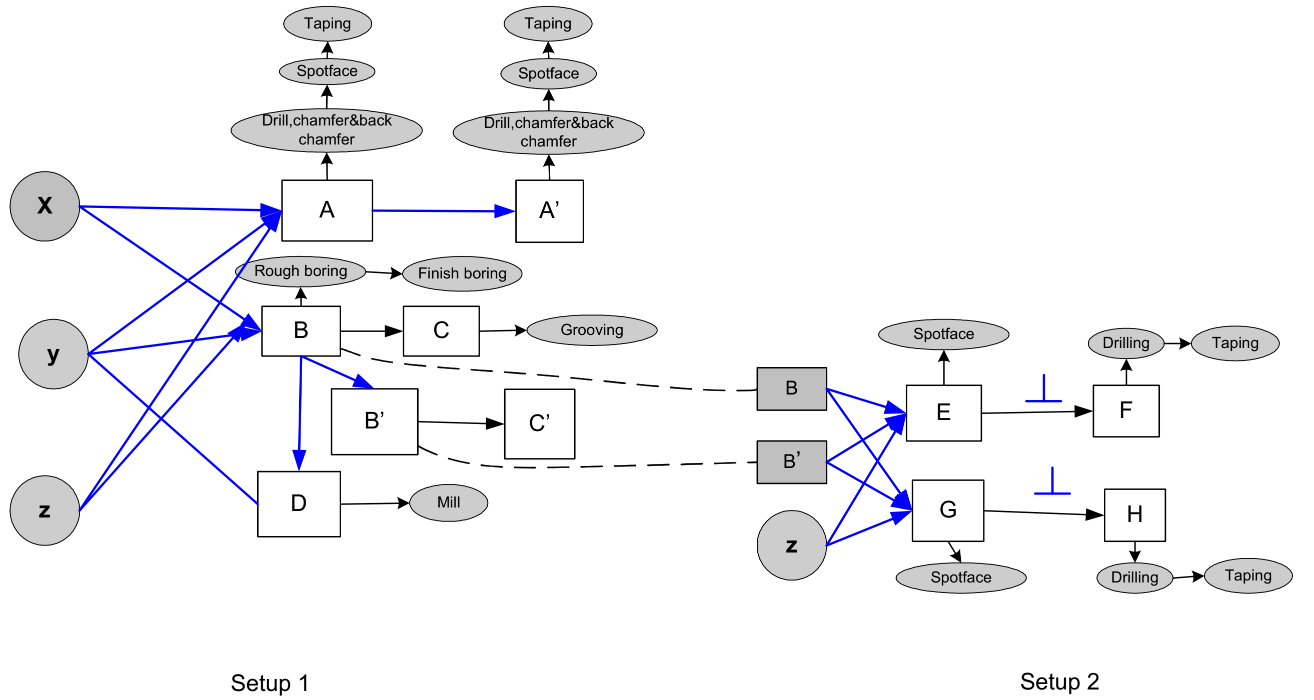


Fig. 9 DMG1 for the example part

manufacturing plans. Figure 8 shows the information structure of machine tools.

4 Case study

A sample part has been shown in Fig. 3 and it's FTG with feature's processes is shown in Fig. 4. The result from the automated setup planning algorithm follows.

4.1 DMG1 generation

With the use of the algorithm shown in Table 1, features *x*, *y*, and *z* are found as initial datum features in step 2. In step 3, features *A* and *B* have three edges linking with *x*, *y*, and *z*, and feature groups (*A*, *A*'), (*B*, *D*), (*B*, *C*), (*B*, *B*', *C*') are identified as initial groups. In step 4, features *E*, *F*, *G* and *H* are identified beyond above feature groups. Hence, an intermediate datum frame is needed. Based on the DMG rules (3-mutually perpendicular datums) and the best practice knowledge of fixture planning, features *B*, *B*' and *Z* are identified as the intermediate datum frame and feature groups (*E*, *F*) and (*G*, *H*) are constructed. The feature groups and corresponding datum frames are listed in Table 4; the DMG1 is shown in Fig. 9.

Table 5 Feature-process grouping based on tolerance analysis

	Manufacturing features	Machine tool	Datum	TAD
Group 1	*A* (Drilling, chamfer & back chamfer)	3-axis machine center	*X*,*Y*,*Z*	+*X*
	A′ (Drilling, chamfer & back chamfer)			
	B,*B′* (Rough boring, finish boring)			
	C,*C′* (Grooving)			
Group 2	*A* (Spotface)	3-axis machine	*X*,*Y*,*Z*	−*X*
	A′ (Spotface)			
	D (Milling)			
Group 3	*A* (Tapping)	3-axis machine	*X*,*Y*,*Z*	+*X* or −*X*
	A′ (Tapping)			
Group 4	*E* (Spotface)	3-axis machine	*B*,*B′*,*Z*	−0.6*Y*+0.8*Z*
	F (Drilling, Tapping)			
Group 5	*G* (Spotface)	3-axis machine	*B*,*B′*,*Z*	0.6*Y*+0.8*Z*
	H (Drilling, Tapping)			

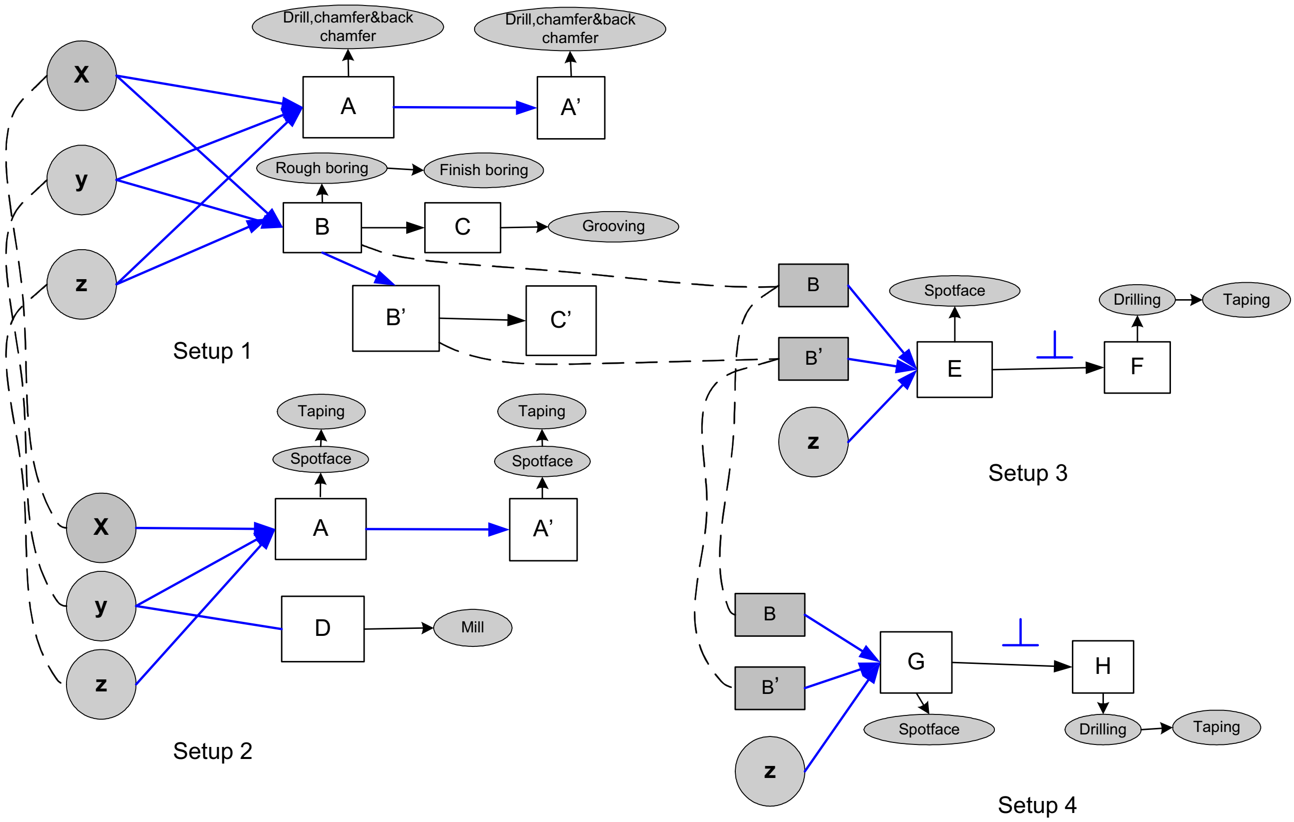


Fig. 10 DMG2 of the example part (first solution)

4.2 DMG2 generation

The next step of setup planning is to consider the manufacturing resources capabilities. First, each process in DMG1 has its own specified TAD. Those feature processes with the same datum frame and TAD can be reunited into one group. Table 5 shows the results. The TADs are given based on a part coordinate system that is pre-defined on the example part.

The manufacturing resource is selected to carry out all processes in each group. A 3-axis machine is the basic requirement. Based on TADs, four setups are needed, in

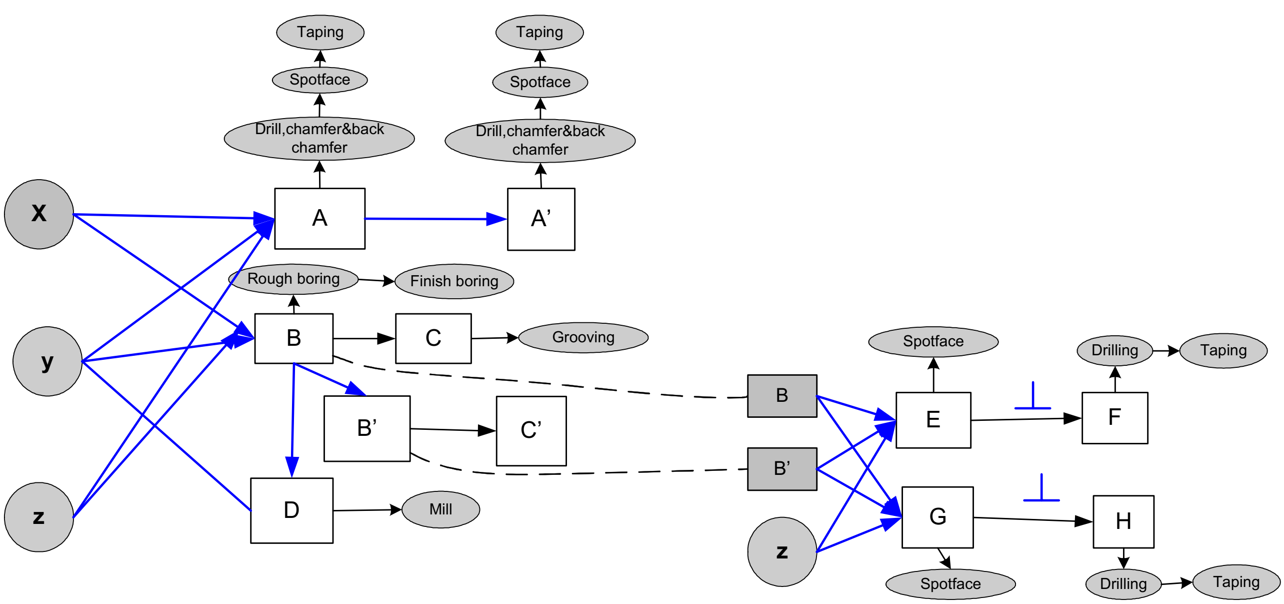
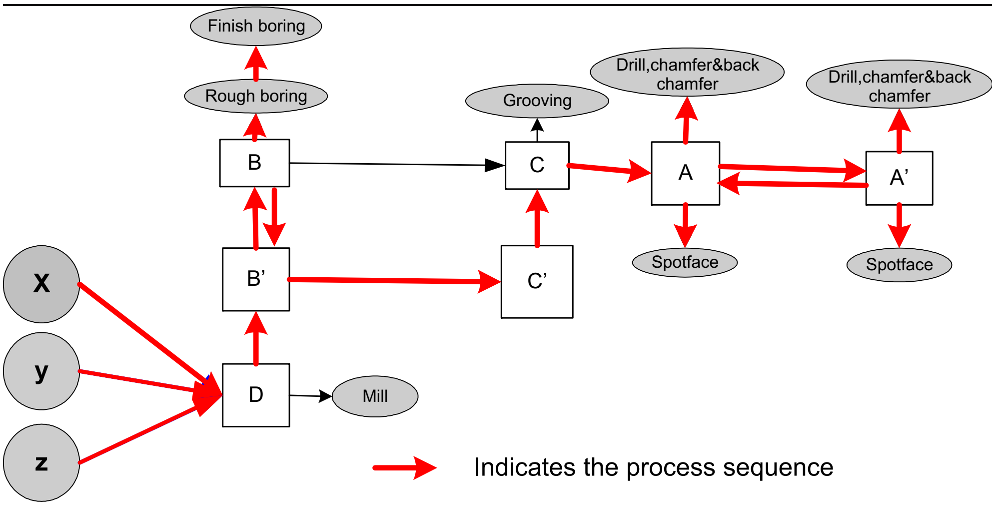
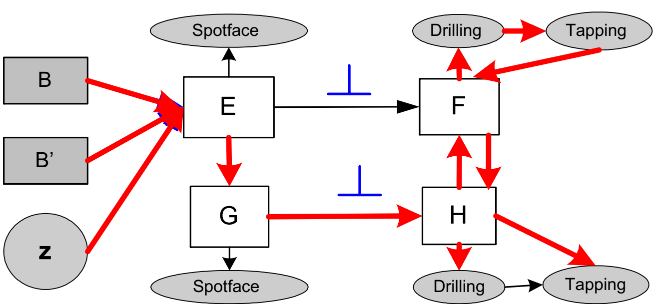


Fig. 11 DMG2 of the example part (second solution)

Table 6 Setup plan of the example caliper

	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′*
	Setup 2 1 Spotfacing *E*,*G* 2 Drilling *F* 3 Drilling *H* 4 Tapping *F* 5 Tapping *H*

which group 3 can be carried out with group 2 through the use of the precedence constraint to maintain feature manufacturing sequence. Figure 10 shows the corresponding DMG2. Compared with part FTG, it can be seen that there is a perpendicular tolerance requirement between feature *B* and *D*. In this solution, *B* and *D* are machined in different setups, and a tolerance stack-up between *B* and *D* is generated.

However, if 3-1/2-axis machining centers with table index function are available, the setup planning will generate another solution. It is assumed that the machine tool coordinate and part coordinate overlap, that groups 1, 2 and 3 can be finished in one setup by indexing machine table 180° and that groups 3 and 4 are finished in another setup by indexing machine table 106°. The corresponding DMG2 is shown in Fig. 11. In this solution, the number of setups has been reduced to two and features *B* and *D* are machined in the same setup so that there is no tolerance stack-up generated between setups.

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 degrees, the in-degree of X,Y,Z is $d^-(v)=0$, while $d^-(B)>0, d^-(B')>0, d^-(z)>0$; therefore, the setup sequence is from (X,Y,Z) to (B,B',Z).

4.3 Process sequence

Table 6 shows one solution of process sequencing where 3-1/2 axis machining centers are used in the production of the example part.

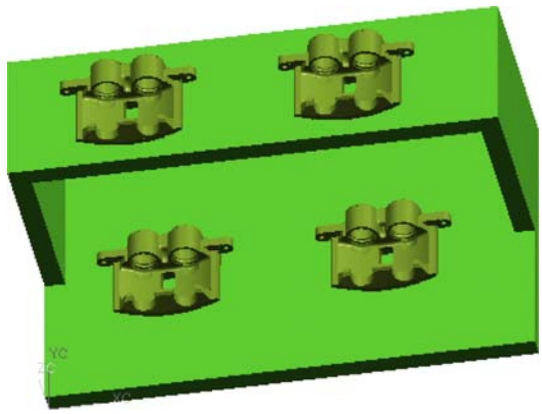
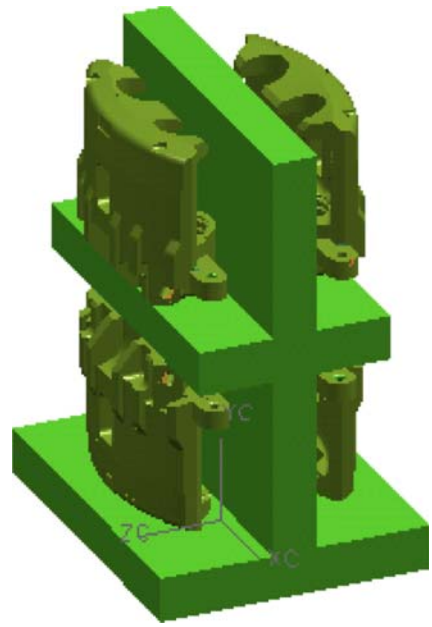
4.4 Station level setup planning

Pre-defined fixture bases are used in the station level setup planning. Corresponding machine tool requirements are generated and evaluated. Table 7 shows different fixture bases used in the two setups.

5 Summary

Nowadays, consumers are demanding better and cheaper products to be delivered faster. To satisfy customer needs, manufacturing companies are striving to reduce the product development cycle time, including the production planning time. The research focuses on the strategies of automated setup planning for non-rotational parts, which is a critical step in CAPP to transform design into production. Graph

Table 7 Station level setup planning

Fixture base type			Setup 1	Setup 2
			Bridge	Tombstone
Part layout on fixture base				
Machine tool requirements	No. of axes		3-1/2	2-1/2
	Moving range	*X*	800 mm	500 mm
		Y	363 mm	500 mm
		Z	765 mm	700 mm

theory is used to represent the part information by FTG and setup information by DMG. Also, the problem of automated setup planning is transferred to converting FTG to DMG based on tolerance analysis and manufacturing resource capability analysis. In addition to the analyses, best practice knowledge of precedence constraints and fixture planning are utilized in determining setup plans. A case study is carried out to reveal the effectiveness of the utilization of different flexible manufacturing resources. Better setup plans can be generated by the use of proper machine tools and fixture bases.

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