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Dealing with feature interactions for prismatic parts in STEP-NC

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Abstract Determining the precedence of machining features is a critical issue in feature-based process planning. It becomes more complex when geometric interaction occurs between machining features. STEP-NC, the extension of STEP (ISO 10303) standard developed for CNC controllers, is a feature-based data model. It represents all the geometric and topological product data minus feature interactions. In this paper, machining precedence of interactive and non-interactive STEP-NC features is discussed. Local and global precedence of machining features are defined on the basis of geometric constraints, such as geometric interaction of features and feature approach face and technological constraint such as access direction of the cutting tool. A software tool has been developed to visualize the STEP-NC part model and to generate the graphs of feature interaction and feature precedence. The output can be then used to augment the STEP-NC data in order to generate the optimal sequence of operations.

Keywords Feature interaction · Feature precedence · Process planning · STEP-NC

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Nomenclature

P	The final part
B	The starting workpiece, blank
F^i	Feature i
$\cap$	Interaction between two features
f_{F^i,F^j}	Common face of feature i, j
F^i_{TAF}	Top approach face for feature i
$\vec{F}^i_{TAF}$	Normal vector for top approach face for feature i
$\vec{T}_{AD}$	Normal vector for tool access direction
ϕ	Null set
$\omega_{i,j}$	The interacting entity of feature i, j
$\sigma_P(F^i)$	The common boundary of feature i and the final part

Introduction

Feature based Computer-Aided Process Planning (CAPP) has been researched for more than three decades. Macro process planning is responsible for selection of machine tools, fixtures and setup order, whereas at the micro level, validation of features, sequence of machining operations, and information of cutting technology are specified (Wang and Shen 2003; Kannan and Wright 2004). STEP-NC is considered as an advanced data model for CNC controllers. STEP-NC in its both versions-Application Interpreted Model (AIM) and Application Reference Model (ARM)—mainly represents the information required for micro process planning. Data for macro process plan is supposed to be provided by ISO 10303-AP 240 (STEP application protocol for process plans of machine parts; ISO 2005). In a STEP-NC file, a feature-based structure is used to capture manufacturing information. In feature-based process planning, a possible order of machining features is often determined before sequencing the machining operations. Therefore, to generate an efficient sequence of operations, precedence relationship of the machining features is essential information. This precedence becomes more complex if the part has interactive features. These interactive machining features with or without other manufacturing constraints, often result in an alternative set of machining sequences (Xu 2005; Wang et al. 2006).

Despite obvious advantages of STEP-NC over the existing standard for part programming such as ISO 6983 (also known as G-Code) (Xu 2006; Xu and Newman 2006), interactive machining features are not considered in the current standard (ISO 2003b). Moreover, no research has been done in using STEP-NC data model to represent feature interactions and the machining precedence of these features. This paper presents a framework for process planning of prismatic parts with interactive features based on the STEP-NC data model.

Literature survey

STEP-NC promises a future breed of intelligent CNC machines. Its object-oriented structure provides a comprehensive data model for feature-based part programming and manufacturing. Because of this, STEP AP224 (ISO 2001) and STEP-NC features have been used for part process planning by some researchers (Amaitik and Kilic 2007; Gao and Sharma 2002; Hou and Faddis 2006; Suh et al. 2003; Nassehi et al. 2007; Medani and Ratchev 2006; Lau et al. 2005; Suh and Cheon 2002). Design information in STEP-NC is represented in terms of machining feature's attributes such as a closed profile, depth and feature placement for introducing a closed pocket. This information will be later used in *workingsteps* (machining operation blocks in STEP-NC). Although this standard has been used to generate process plans, feature interactions are not addressed. In their STEP-NC based process planning (MASCAPP) system, Nassehi et al. (2007) represented some simple types of interactions, but in its final process plan, precedence of interactive features is not considered.

Feature interaction is a determining factor in micro process planning especially in working out the right order of machining operations. Feature interaction can be considered in two different categories: technological interaction and geometric interaction. Technological interactions are pertaining to technological constraints related to machining a part, such as fixture interaction, tolerance interaction and tool interaction (Liu and Wang 2007; Chu and Gadh 1996; Sormaz and Khoshnevis 2000; Xu and Hinduja 1997, 1998). For example, fixture interaction occurs when machining one feature may destroy the clamping face(s) of the other. Tool interaction often occurs in hole-making when the top face of the round hole is partially destroyed by cutting another feature. Geometric interaction takes place when two or more machining features have common geometric entities, i.e. surface or volume (Xu 2001). This type of interaction has been studied by many researchers when recognizing machining features from a part geometric model (Gadh and Prinz 1995; Marefat and Kashyap 1990; Trika and Kashyap 1993; Joshi and Chang 1988). Different kinds of geometric interactions are reported by Xu (2005), Nasr and Kamrani (2007) and Li et al. (2002). Detection and interpretation of these features have been active research topics in automatic feature recognition area for many years and by no means, a satisfied approach has been developed (Ibrahim and McCormack 2005; Sormaz et al. 2004; Woo et al. 2005; Gao and Shah 1998; Wong et al. 2001). Some of the studied approaches include graph-based algorithms, volumetric decomposition techniques and hint-based geometric reasoning. Feature recognition aims to convert design features to machining features for the purpose of downstream process planning (Liu 2000). This mapping process becomes a complex problem when feature interaction occurs (Tsing and Joshi 1994) and therefore, few systems considering feature interaction have been reported (Gao et al. 2004; Li et al. 2002; Gao et al. 2005). Because of alterations in some topological elements of interactive features, the original shape may be changed or become a different feature type (Gao et al. 2005). Therefore, not much work has been done in the field of automatic recognition of interacting features. Although, to achieve a fully feasible precedence of features, both types of interaction (geometric and technological) must be considered, this paper mainly focuses on geometric interaction between the machining features regarding tool access direction as one of the manufacturing constraints.

For non-interactive features, the sequence of machining is not a major concern. In the case of feature interaction, different machining priorities may exist for the interactive features. In Fig. 1a, the notch and hole are machined independently while the two interactive pockets may be machined in two possible sequences. On the other hand, the two interactive closed pockets as shown in Fig. 1b may only have one preferred machining order, the large pocket first and then the small one.

Feature precedence can be represented in different forms such as graph, network, tree and matrix (Irani et al. 1995). It is

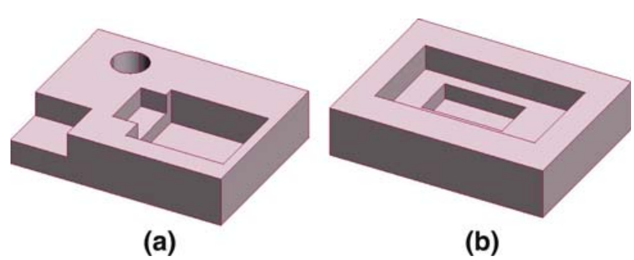


Fig. 1 Feature interactions in two prismatic parts

obvious that determination of feature precedence is always coupled with representation of feature interactions. Hayes (1990) acquired practical rules and identified possible feature interactions and consecutive machining sequences using a graph. Sormaz and Khoshnevis (2000) considered machining time and surface quality to build a feasible and optimal feature precedence graph for prismatic parts with feature interactions. Their contribution did not include interactions between more than two features. Wang et al. (2006) developed the rule-based feature precedence for machining the interactive features, considering intermediate machining volume, tool access direction and machining time. They applied a rule that implies the feature with bigger volume should be cut first when two features interact. However this reasoning is not applicable if the tool approach face for this feature is not accessible. A rule-based approach has also been introduced toward feasible and optimal feature precedence in multi-setup machining cases. The interaction in this study confines to some simple primitive feature interactions (Liu and Wang 2007).

STEP-NC machining features

STEP-NC machining features sit in an object-oriented data structure (Fig. 2). The *workplan* entity includes *executables* which include *workingsteps*. *Machining_workingsteps* are essential entities in a STEP-NC file. They specify the association between a distinct manufacturing feature and a machining operation to be performed on that feature. This entity contains design information (in terms of *manufacturing_ features*) and manufacturing information (in terms of *machining_operation*).

Machining features

The STEP-NC 2.5D manufacturing features are defined in close resemblance to ISO 10303-224 (ISO 2003b; ISO 2001). *Machining_ feature* as a subtype of *two5D_manufacturing_ feature* is meanwhile the abstract supertype of all 2.5D machining features. Figure 3 represents all the STEP-NC features defined as well as their attributes.

In STEP-NC, features may be defined implicitly or explicitly in a part model. With implicit description which is used by STEP-NC (ARM or ISO 14649), a feature is defined by a set of parameters. For example, information of feature's depth, placement, wall and open boundary is used to define a *step*. In the other version of STEP-NC (AIM or ISO 10303-AP238), advanced B-Rep data can be used to explicitly represent a feature, e.g. a *region*. Counterbore or countersunk holes can be considered as interactive features (intersection of two holes) and are described by the compound feature entity. Out of the 2.5D features (*two5D_manufacturing_ features* as in STEP-NC), *pocket, slot, planar face, round hole* and *step* are considered in this research.

Regardless of any feature interaction, all the machining features are currently expressed as independent features in STEP-NC with their own geometry and placement. One of the main advantages in defining a 2.5D STEP-NC feature with an arbitrary profile is that one can always use an open or closed boundary with a single depth (ISO 2003b) and therefore consider it as a single feature.

Because of the object-oriented data structure, attributes are expressed at a level/stage where it fits, and each machining feature inherits all the attributes of its preceding entities, e.g. *two5D_manufacturing_ feature* and *manufacturing_ feature* (Fig. 4). All features should have *ID, workpiece* and related *machining_operations*. Therefore these attributes are defined in the *two5D_machining_ feature* class.

A machining feature must have its placement which is previously defined at the *two5D_machining_ feature*. The further down the hierarchy goes, the more specific attributes appear. For instance, at the planar face level (Fig. 5a), two attributes are defined: *course of travel* and *removal boundary*, while at the step level, only one attribute is defined,

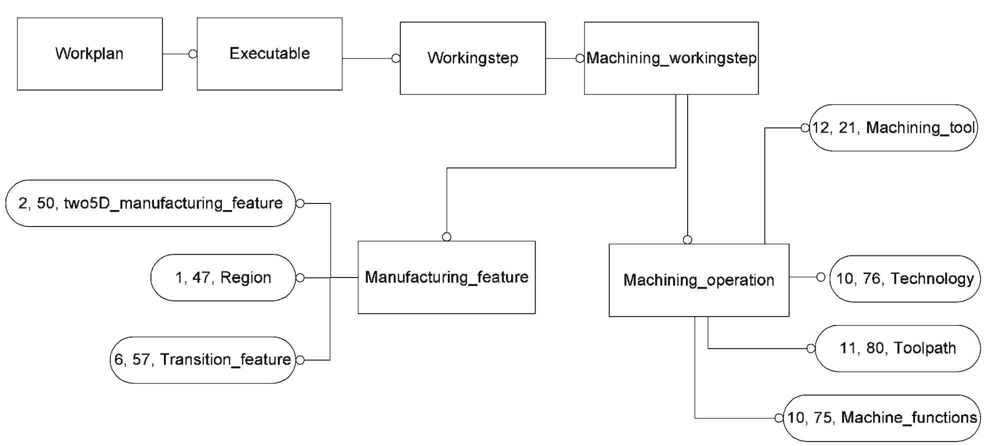


Fig. 2 EXPRESS-G diagram of a part of STEP-NC data (ISO 2003a)

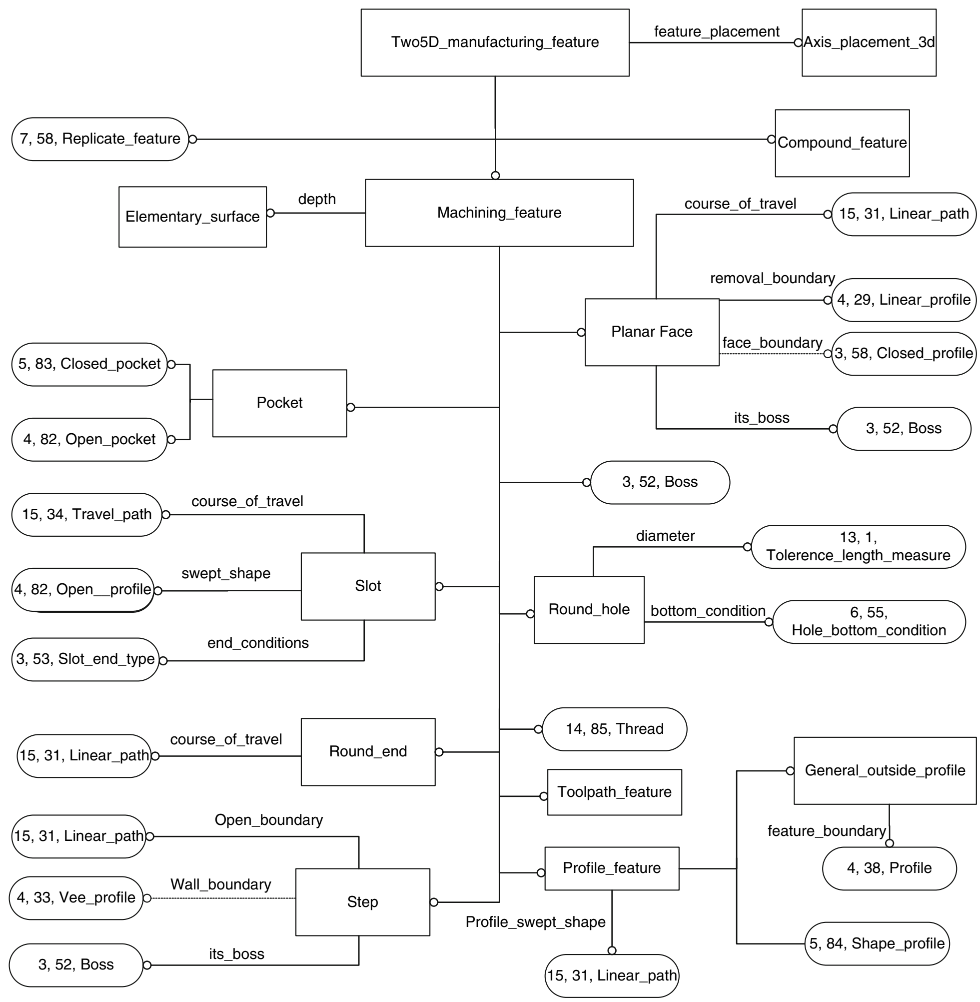


Fig. 3 EXPRESS-G schema of STEP-NC 2.5D manufacturing features (ISO 2003b)

i.e. *open boundary* (a *linear path*; Fig. 5b). However, both planar face and step inherit depth (as an *elementary surface*) as well as feature placement (a 3D Cartesian point) from the *machining_feature* and *two5D_manufacturing_feature* entities, respectively.

One advantage of using STEP-NC implicit data is that the topological and geometric information of the features maintains even if interactions occur.

Setup representation

The other entity of the *workplan* is *workpiece* and its corresponding information such as *workpiece_setup* and *clamping_ positions*. Most of information for setup is defined under *workpiece_setup* entity (Fig. 6). Reference positions are defined relatively. As shown in Fig. 6, each feature coordinate system is stated based on the workpiece coordinate system which is a Cartesian point defined in the setup coordinate system. Likewise, the setup coordinate system is defined relative to the machine's origin.

Tool Access Direction (TAD) is defined by a vector. Vector (0, 0, 1) implies that the cutting tool (e.g. an end mill) approaches the workpiece perpendicular to the XY plane. The setup information will be used later for tool access directions.

Feature interactions defined

There are two main pieces of data in determining the precedence of interactive features: geometric interaction and tool access direction.

Geometric feature interactions

As mentioned before, feature interaction may occur through a common surface or volume. Xu (2005) classified surface and volumetric feature interactions into different types based on the nature of the interacting entity. Interacting entity is introduced as the common geometrical element(s) between two interactive features. It can also be defined as two boundaries that are the contributions of interactive features to the final part (Vandenbrande 1990; Gao and Shah 1998). Volumetric features are also differentiated based on the interacting patch (the common surface of two faces). In surface interaction, the

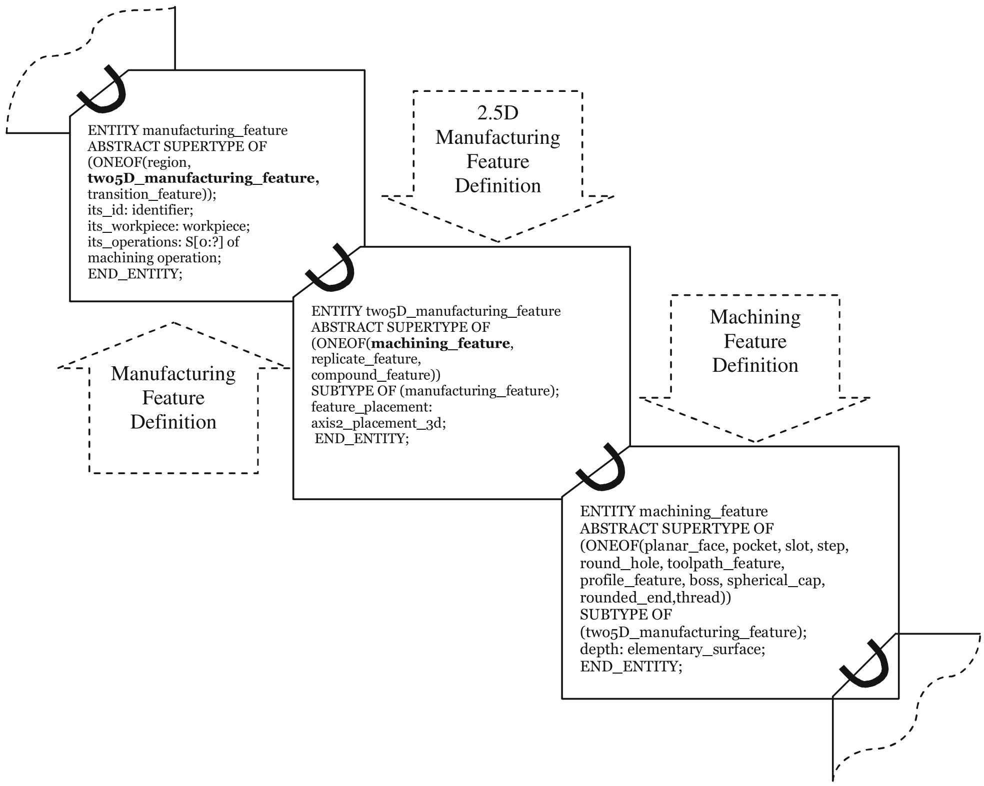


Fig. 4 Definition of typical entities in STEP-NC

interacting entity can be of either wire or face type while in the other type of interaction, the interacting entity is always a face type (Xu 2005). Figure 7 exhibits two types of interacting entity; open wire (Fig. 7a) and closed wire (Fig. 7b) in surface interaction.

According to this definition, STEP-NC features that are considered as surface features, can be nested, overlapping or intersecting features; the interacting entity is either an open or closed wire. When features are represented as volumes, the entity between two interactive machining features can be defined as a common face or common volume. In Fig. 8a, the slot and pocket have a common face whereas in Fig. 8b, the slot and step interact with each other through a common volume—a cube in this case. Volumetric interaction can be avoided by redefinition of features. In Fig. 8b, if the step is defined as two blind steps, the interaction type is a surface interaction between three features. In some cases, a volumetric interaction may be too complicated to be represented as a surface interaction (Fig. 7b). Both types of interaction may occur throughout the STEP-NC machining features.

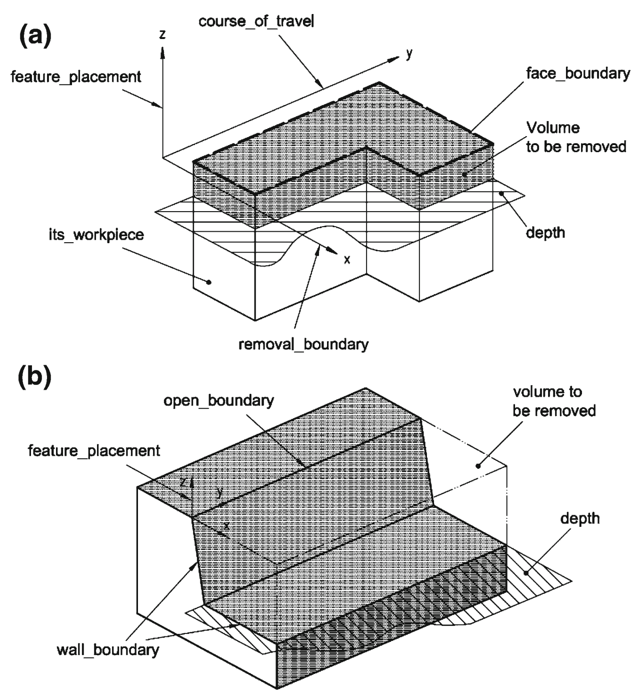


Fig. 5 Planar face (**a**) and step (**b**) representation in STEP-NC (ISO 2003b)

Tool access direction

Cutting tool accessibility is an important constraint for machining a feature in feature-based process planning (Li et al. 2002; Liu and Wang 2007). In every volumetric feature F^i, the top face should be approachable from which, the cutting tool can start machining (assuming a vertical milling

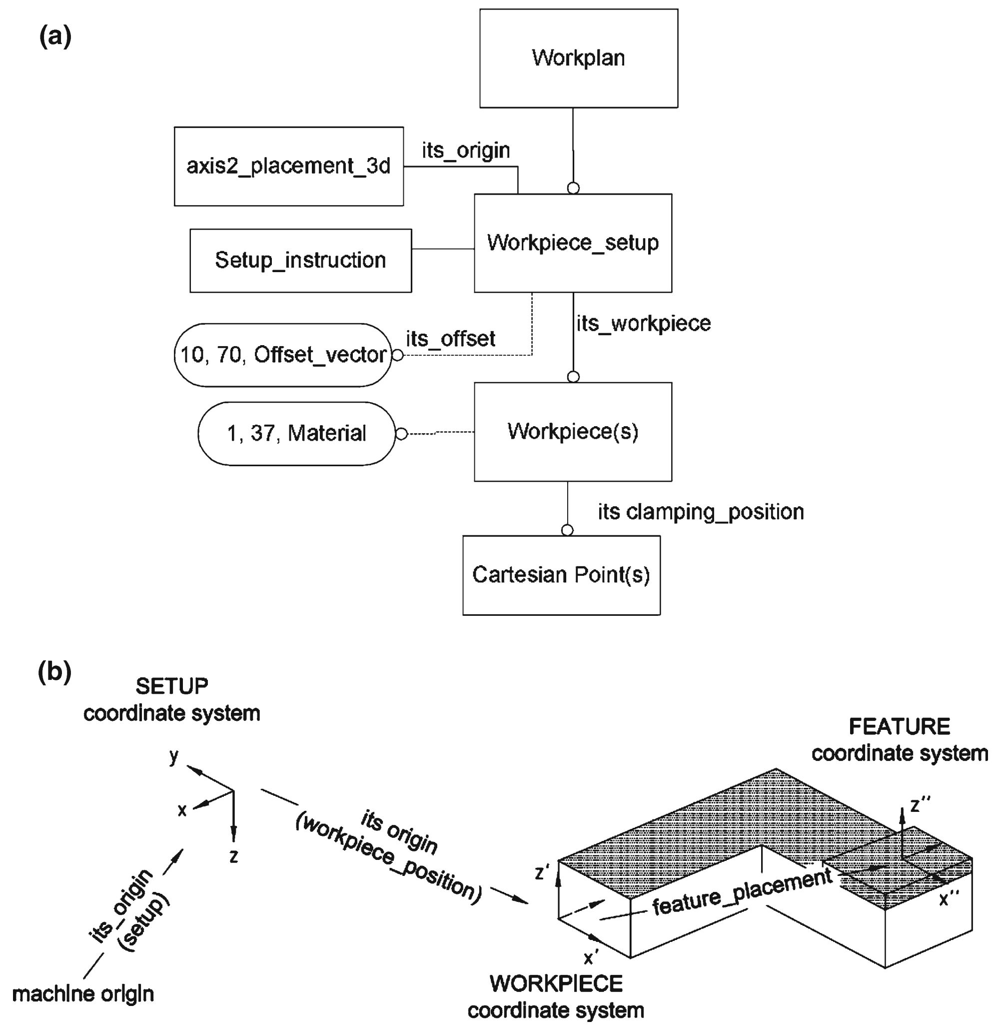
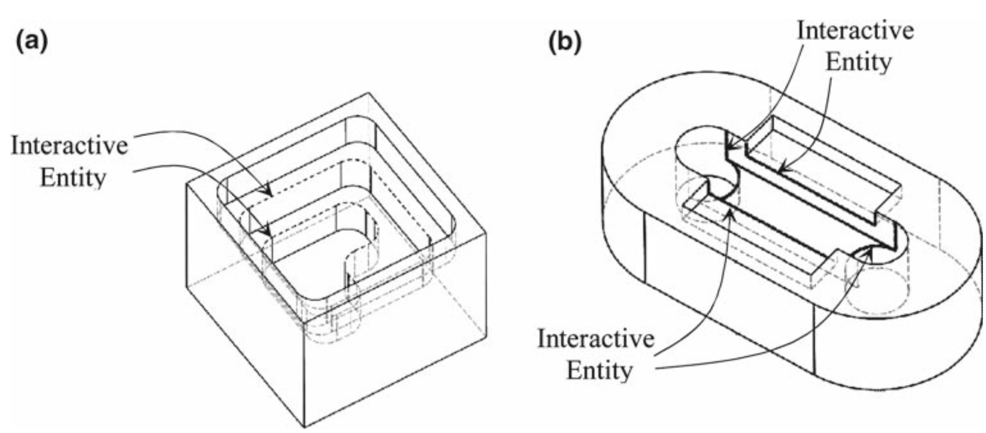


Fig. 6 Workpiece_ setup (**a**) and feature_placement (**b**) representation in STEP-NC

Fig. 7 Interactive entity in two types of feature interaction (Xu 2005)



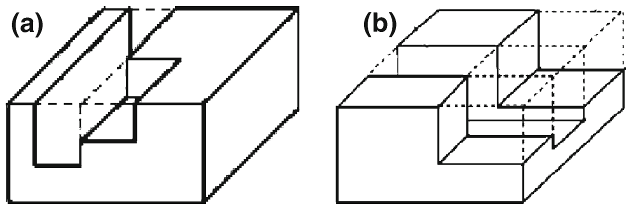


Fig. 8 (**a**) Slot-pocket surface interaction; (**b**) Slot-step volume interaction

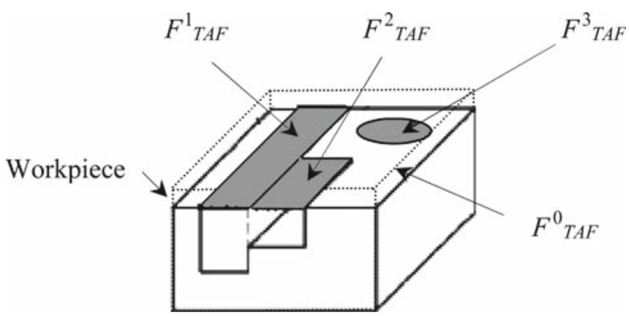


Fig. 9 Interactive entity in surface feature interaction

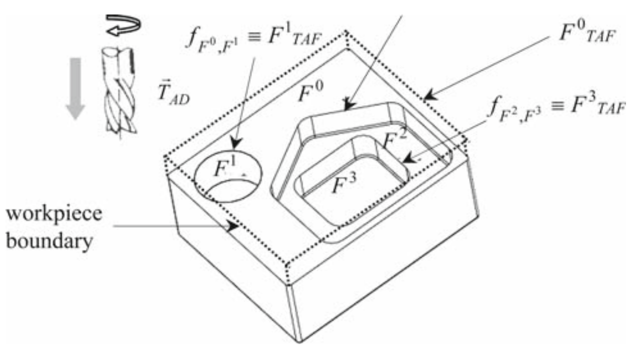


Fig. 10 Tool access direction and feature's top approach faces

machine is used). For the 2.5D features in Fig. 9, these faces are shown and labeled as $F^i_{TAF}(i = 0, \ldots, 3)$, top approach face for feature i. Obviously, the normal vector for this face ($\vec{F}^i_{TAF}$) is parallel to the tool access direction.

When two features F^i, F^j interact ($F^i \cap F^j \neq \phi$), they share at least one common face (f_{F^i,F^j}) (Kim et al. 2001). If the normal vector for this common face is parallel to the tool access direction ($\vec{F}^i_{TAF} \times \vec{T}_{AD} = 0$) and this common face is the top face for feature $i (f_{F^i,F^j} \equiv F^j_{TAF})$, feature F^i can not be machined until its interacting feature (F^j) is machined first. Upon machining F^j, the top face of F^i becomes available. In the part shown in Fig. 10, planar face F^0, is a surface interacting with both F^1 and F^2, i.e. ($F^0 \cap F^1 \neq \phi$), ($F^0 \cap F^2 \neq \phi$). F^0 is milled first and then F^1_{TAF}, F^2_{TAF} become available. Likewise, since ($F^0 \cap F^3 \neq \phi$), F^3_{TAF} will appear (accessible by the cutter) after removing F^0.

Methodology of detecting and representing feature interactions

To detect machining precedence of the interacting features in a STEP-NC data model, both geometric constraint (the existence of feature top approach face) and technological constraint (tool access direction) are studied. In this section, we explain how these two constraints are considered to establish the machining precedence for STEP-NC features.

Detecting feature interaction

In the STEP-NC ARM, attributes of each machining feature (Fig. 3) can be used to construct both volume and surface features. For instance, to generate a volume for a step, the cross-section defined by the *wall-boundary* attribute, is swept along a path defined by the *open-boundary* attribute (Fig. 5b).

To detect feature interactions, feature volumes are first obtained for all the machining features defined in a STEP-NC data model. Geometric reasoning can then commence to detect and define feature interactions.

For detecting volume or surface interactions between machining features, the following theorems and definitions apply:

Assuming the final Part model (P) is defined as the result of subtracting all the volumetric features ($i = 0, 1, \ldots, n$) from the Blank (B), i.e.

$$P = B - \bigcup_{i=0}^{n} F^i \tag{1}$$

and the surface(s) on the part model formed as a result of removing machining feature F^i is expressed as,

$$\sigma_P(F^i) = F^i \cap P \tag{2}$$

then, for a machining feature to be valid,

$$\sigma_P(F^i) \neq \phi \tag{3}$$

for two features (F^i, F^j) to be interactive,

$$F^i \cap F^j \neq \phi \tag{4}$$

to determine the interacting entity between two features that also lies on the final part, the following can be used,

$$\omega_{i,j} = \sigma_P(F^i) \cap \sigma_P(F^j), \quad \omega_{i,j} \neq \phi \tag{5}$$

note that $\omega_{i,j}$ can only be edges, but not surfaces (Fig. 11). Another important observation is that $\omega_{i,j}$ will always be convex (Suh et al. 1991), be it closed (Fig. 11a) or open

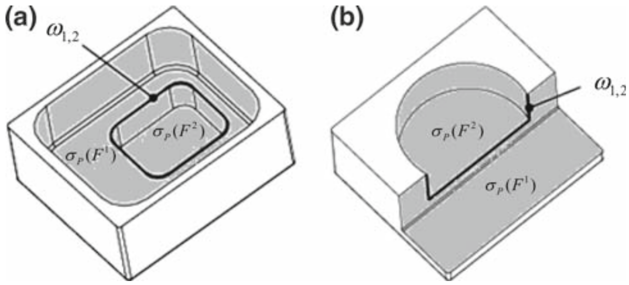


Fig. 11 Interactive entities

(Fig. 11b). $\omega_{i,j}$ is also a piece of critical information for identifying the top approach face, F^i_{TAF}.

Feature precedence

To determine a possible sequence of machining features, two different criteria are taken into account: feasibility and optimality. A feasible sequence is a sequence in which features are technically machinable. An optimal sequence is a feasible sequence that is also economically favorable considering factors such as machining time and part quality. It is obvious that feasibility is a prerequisite for optimality. For the part shown in Fig. 12, three sequences are feasible but not all are optimal. Feature precedence graph in this figure shows one possible way of the representing the sequences. This directed graph, called Feature Precedence Graph, belongs to a class of the Directed Acyclic Graphs. As the graph shows, either the big pocket or the hole should be machined after the planar face. Clearly, when node F^j follows F^i, it denotes that F^i has precedence over F^j. However, F^j may not have to be machined immediately after F^i; other features could be machined between F^i and F^j in an optimal machining sequence.

As mentioned before, geometric interactions between features play a significant role in determining the machining order of features and consequently sequence of operations. There are two different types of precedence: local precedence and global precedence. Local precedence represents the priority between the interacting features, whereas global precedence considers all the features. Usually, the local feature precedence is determined before global feature precedence. In this paper, the availability of F^i_{TAF} is discussed for interactive features to establish a local precedence. For non-interactive features, F^i_{TAF} is available and they will appear in the global precedence. For this purpose, in both cases of interactive and non-interactive features, the cutting tool should have access to machine the corresponding feature. We assume at this stage a single cutter (end mill and/or drilling bit) be used (Fig. 12).

In this research, local and global precedence is dealt with separately, i.e. the local precedence is analysed and a preferred sequence is decided first before the global sequences are sought.

In Fig. 12, the features are ordered in accordance with the availability of their approach faces. Figure 12 shows three feasible sequences resulted from the precedence graph. It is assumed that while one feature is being machined, other features are not to be violated. In practice, one may drill F^1 before milling F^0. In this case, part of the other feature (F^0), is cut unnecessarily. In this research, cutting tools are assumed to only remove the corresponding machining feature but not part of any others.

System development

This section describes a prototype system that has been developed based on the aforementioned methodology.

Framework

Machining features are delineated from a STEP-NC data model. Part information along with the manufacturing data such as cutting tools and their parameters, and tool access directions are also retrieved from the same STEP-NC model. Other input includes the raw workpiece data. In order to detect the common boundary of a feature with the final part, volumes of the machining features are first constructed. The main output of the system is a feature precedence graph. Figure 13 shows the proposed framework.

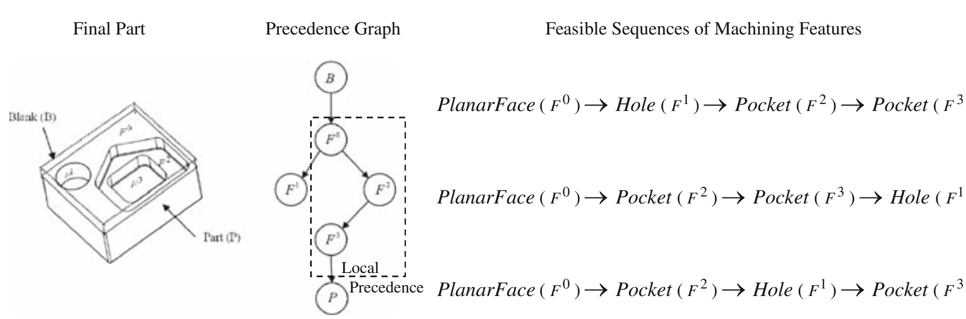


Fig. 12 Different sequences for machining a part

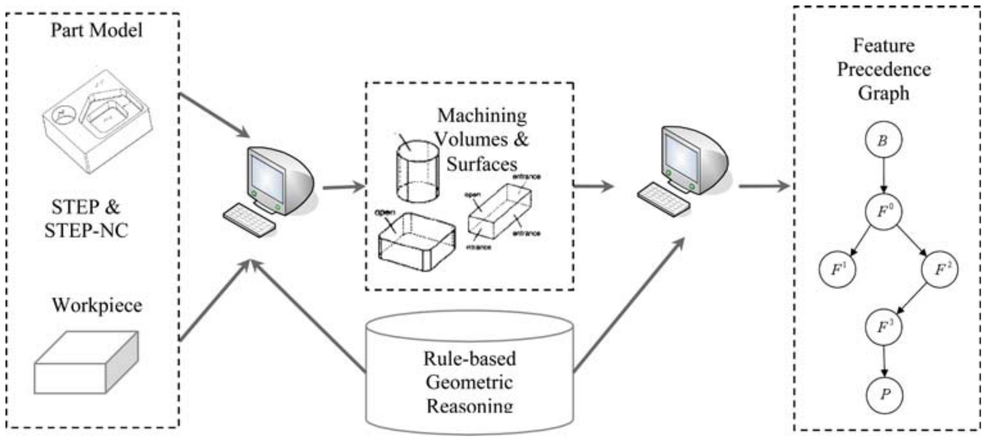


Fig. 13 Schematic inputs and outputs of the proposed framework

The flowchart in Fig. 14 illustrates the working procedure of the system. After extraction of the machining surfaces and volumes, and the information about tool access direction, the common boundary of each feature is calculated and for the valid features, their machinability in the current setup is checked. In the case of interaction (existence of a convex edge that belongs to two given surface features), the position of the common face's normal vector is considered. The availability of this face in consideration with the defined tool access direction denotes if local or global precedence is applied. Only single-setup parts having a box-shaped blank are considered at this stage. The features are assumed to be machined on a 3-axis CNC.

System prototype

A schematic architecture of system implementation is shown in Fig. 15. A combined EXPRESS schema, based on ISO 14649-11, 10, 111, is used for data modeling (ISO 2003c, 2004). OCC (Open Cascade) library (Open Cascade Technology 2000) is used for 3D data presentation and manipulation. ROSE library (developed by STEP-Tools Inc. 2008) uses the functions provided by C++ classes to create and manipulate the EXPRESS schema. The input is a STEP-NC ARM file containing explicit features as well as information about workpiece, workplan, workingsteps, tools and etc. Geometric models in the form of volumes are then constructed. These volumes are later used to identify machining surfaces, tool access direction and finally possible feature interactions. To build and handle feature precedence and interaction graphs, BOOST library is used. For graph visualization, the graphs are restored with DOT graph description language. Graphviz (short for Graph visualization) library is then called to read the DOT file and generate the graph layouts. Finally, display of the graphs is realized through MFGraph library in the Microsoft Foundation Classes.

The main menus items and function buttons of the interface are shown in Fig. 16. The program enables 3D viewing of different forms. STEP-NC data file is also presented in a tree-structure. The graphic area can display 3D views of the component and its features, the feature precedence diagram and the interaction graph.

The interface also provides the options of defining a workpiece. A simple box-like shape blank can be defined with a set of X, Y and Z values. The values can be either retrieved from the STEP-NC file, or entered (and modified) by a user. The interface can also load a workpiece defined by ISO10303 AP203. This way, a complete description of the workpiece can be given and the workpiece may take any shape. As a third option, the user can define a workpiece by its enclosing box with the two specified offsets.

Case studies

The first case study is based on a component named "Fishhead", designed by Airbus for research into STEP-NC applications. The part contains common features found in a typical aerospace part (Fig. 17a). The part undergoes roughing and finishing operations, assuming the minimum box of the part is the blank. The roughing operations can be done on a 3-axis mill, whereas the finishing requires at least 4-axis machining. Figure 17b shows the intermediate workpiece after rough-machining. This intermediate workpiece has four closed pockets ($F^0 \sim F^3$), a square open pocket (F^5) with a cut-off (F^6) at the base, and a round hole (F^4) inside one of the closed pockets. A STEP-NC ARM file is developed to represent the features as well as other necessary data (see Appendix).

Upon loading the STEP-NC file, the user interface (Fig. 18) displays the 3D part model and a tree-like structure showing the STEP-NC data model. The user can browse

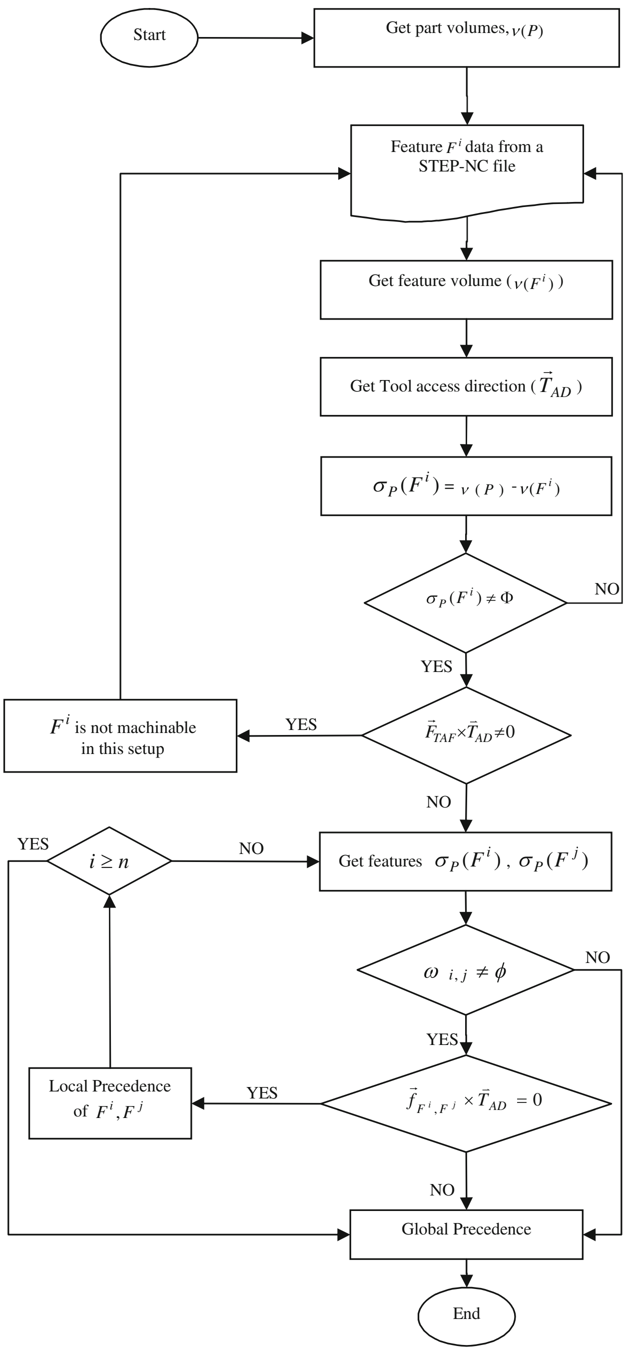


Fig. 14 Algorithm for detecting local and global feature precedence

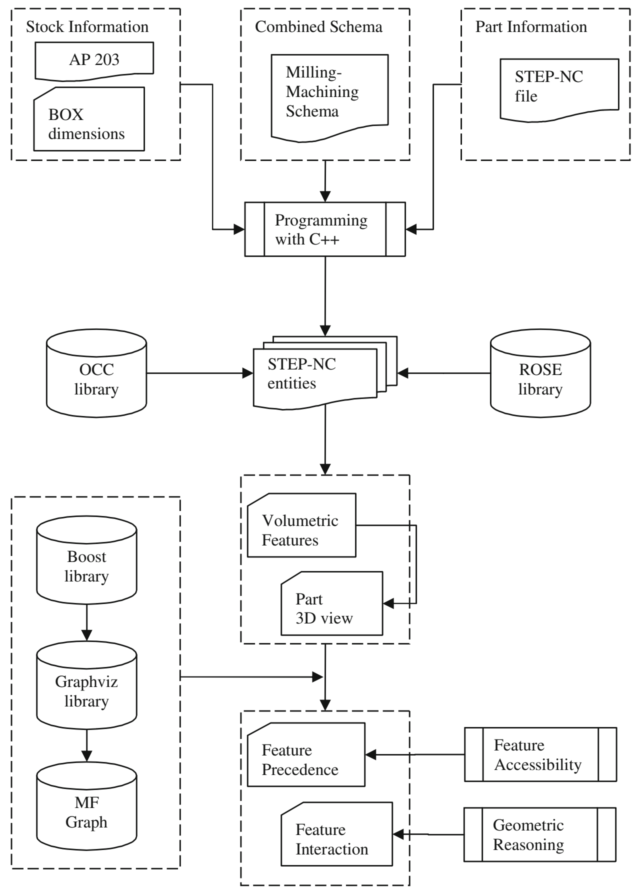


Fig. 15 System implementation architecture

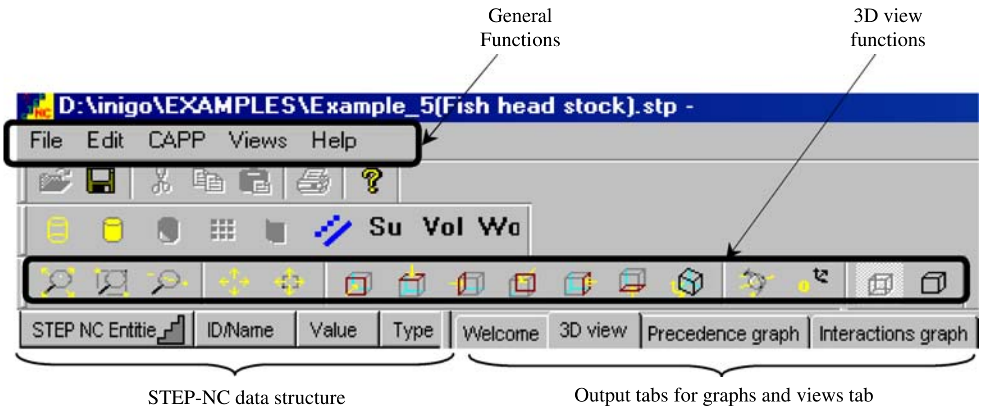
the entities in the model by clicking on the elements in the tree. Modifications are also possible with most of the other entities.

The program proceeds with recognizing and representing feature interactions. The first step is to determine and construct feature volumes as well as machining surfaces. As shown by the feature interactions graph in Fig. 19a, the closed pocket (F^3) interacts with the hole (F^4). Similarly, the square open pocket (F^5) interacts with the cut-off feature (F^6). Due to the availability of their top approach faces, all the features can be machined at the first approach of the cutting tool (the end-mill) with the only exception of F^4 and F^6 since their top faces are not accessible. The graph suggests that F^4 and F^6 are machined after their corresponding interacting features (F^3 and F^5), respectively. Therefore, according to the precedence diagram shown in Fig. 19b, some of the possible machining sequences are:

$$(F^0 F^1 F^2 F^3 F^5 F^4 F^6)$$
$$(F^1 F^2 F^3 F^0 F^4 F^5 F^6)$$
$$(F^2 F^1 F^0 F^3 F^4 F^5 F^6)$$

The second case study contains more interactive features (Fig. 20). There are eight 2.5D STEP-NC manufacturing features and 16 occurrences of interactions (of both surface and volumetric types).

Machining surfaces are shown in Fig. 21. There are 13 surface interactions, $F^0 \cap (F^1 \sim F^6)$, $F^1 \cap F^2$, $F^2 \cap F^3$, $F^5 \cap F^1$, $F^5 \cap F^3$, $F^4 \cap F^2$, $F^6 \cap F^7$, $F^7 \cap F^8$ and 3 volume interactions ($F^4 \cap F^6$, $F^5 \cap F^6$ and $F^4 \cap F^5$). All of these 2.5D features can be machined in one setup and with a single tool access direction (it is assumed that the course of travel in



Su: Surface feature representation; Vol: Volume feature representation; Wo: Final shape of workpiece

Fig. 16 Main menus and function buttons

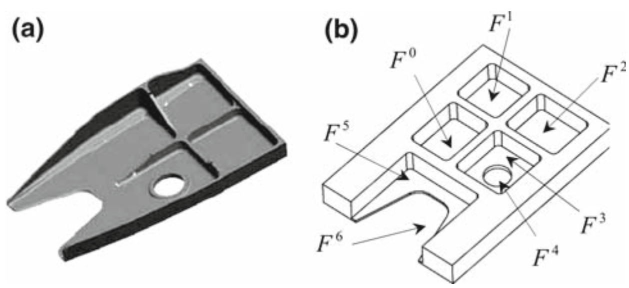


Fig. 17 (**a**) Final fishhead (**b**) semi fishhead (sample part 1)

F5 does not permit to cut it in a different setup with side milling operation). The planar face (F^0) interacts with the steps ($F^1 \sim F^3$), the slots (F^4, F^5) and the closed pocket (F^6). The top approach faces for these features ($F^1_{TAF} \sim F^6_{TAF}$) are hidden underneath F^0. Therefore once F^0 is machined, the other features ($F^1 \sim F^6$) can be machined. On the other hand, the closed pocket (F^7) interacts with two features; the closed pocket (F^6) and the hole (F^8). In this case, the hole and the small pocket can not be machined before their corresponding interactive features (F^7, F^6) are machined. These

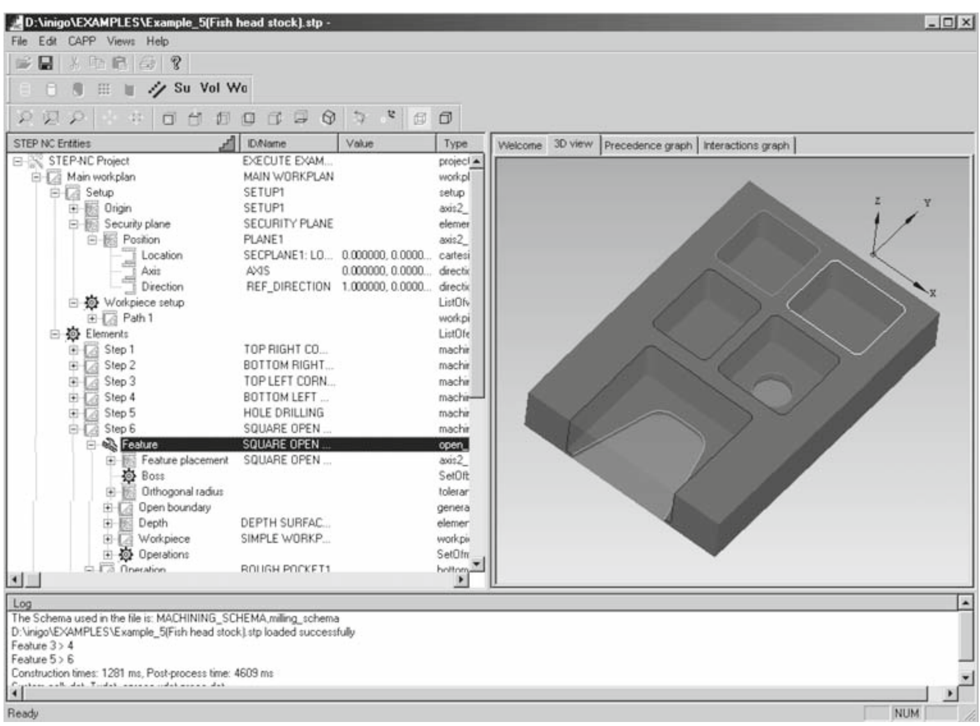


Fig. 18 Prototype main windows (tree structure, 3D view)

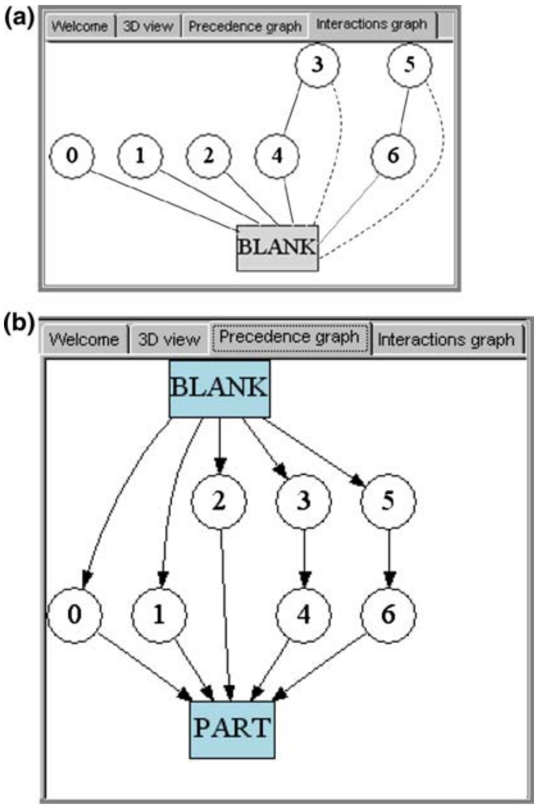


Fig. 19 (**a**) Feature interaction graph, (**b**) Feature precedence diagram

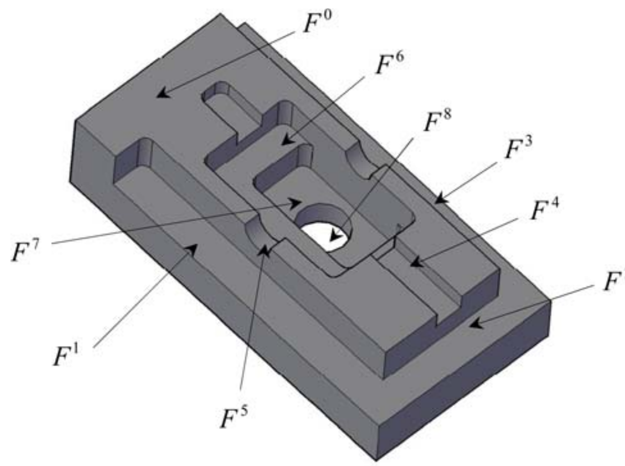


Fig. 20 Sample part 2

interactions are depicted in machining precedence diagram shown in Fig. 22.

Conclusions

Interactions between machining features are intriguing, but also critical issue in feature-based process planning. In this paper, we used STEP-NC ARM (ISO 14649) geometric data to represent the surface and volumetric feature interactions. In the current standard, feature interaction is not mentioned. Precedence of machining features was also determined for

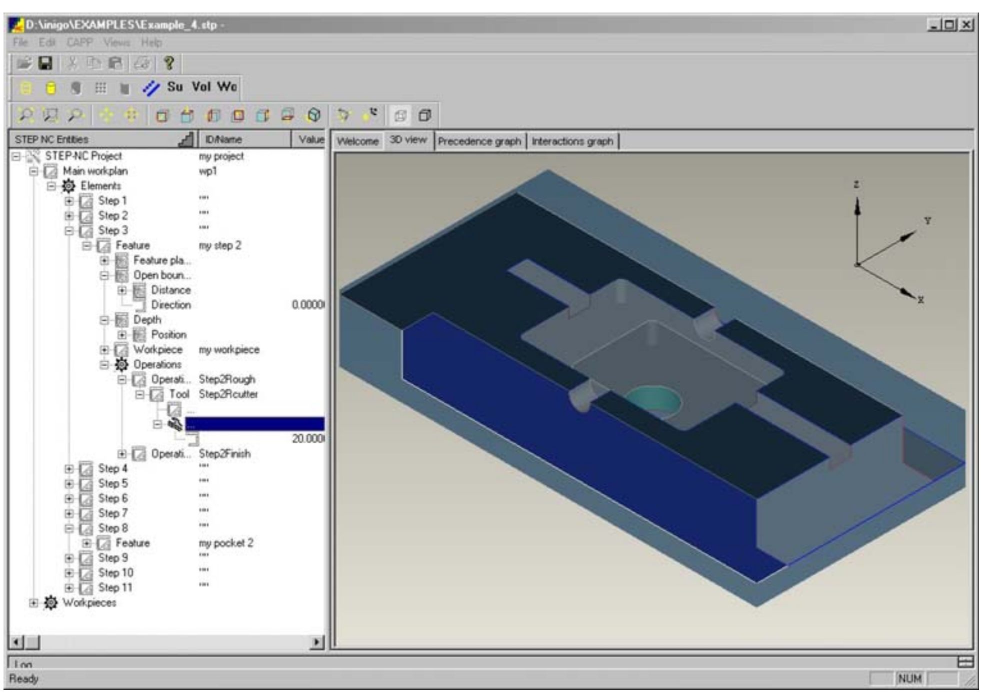


Fig. 21 Sample part 2 (machining surfaces are highlighted)

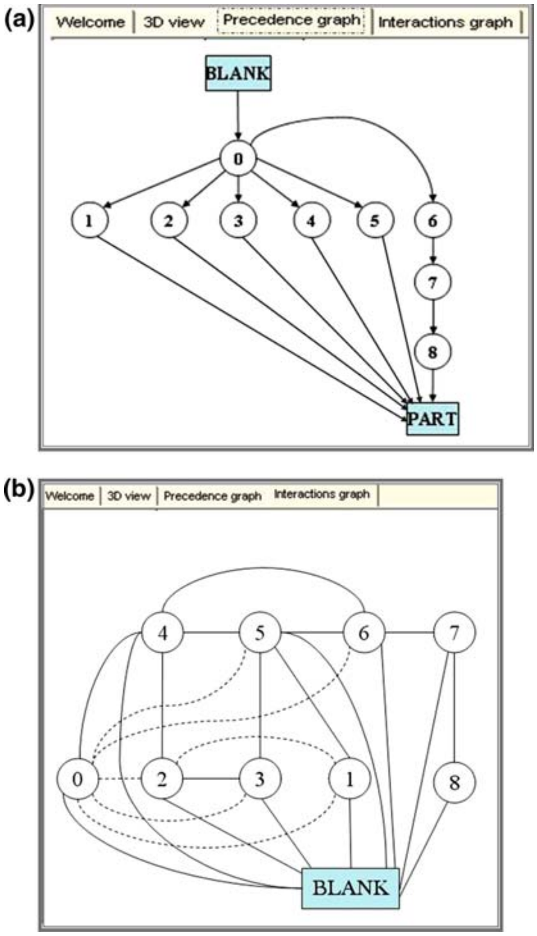


Fig. 22 Feature precedence for sample part 2

interactive and non-interactive features in terms of local and global precedence. The information of tool access direction was also extracted out of technical data in the STEP-NC file. Based on the geometric reasoning and feature accessibility, a prototype software was developed. In this prototype, the interface is user-friendly and can process STEP-NC files and generate the precedence diagram and interaction graph. Part data can be easily manipulated and STEP-NC data file can be updated using the tree-like structure. The outcome, in the form of precedence diagrams, shows the possible sequences for machining a part in one setup. However, to simplify the size of the problem, the only covered features in this research are: open and closed pocket, planar face, step, slot and round hole. For future research, more of the STEP-NC features will be considered. Consideration over other technological constraints or different cutting tools is not yet given. Moreover, to achieve a more feasible feature precedence or sequence, it is apparent that other than tool access directions, other manufacturing constraints must also be considered along with geometric constraints. The methodology can be extended to cater for 4- or 5-axis CNC machining, taking multiple setups into account.

Appendix

STEP-NC (ISO 14649) file for the fishhead part:

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(
/* description */ ('Feature Interaction EX.1',
FILE_NAME(
/* name */ 'FISHHEAD.STP',
/* time_stamp */ '2007-09-11T00:14:22+12:00',
/* author */ ('IIMS'),
/* organization */ ('THE UNIVERSITY OF AUCKLAND'),
/* preprocessor_version */ 'ST-DEVELOPER v11',
/* originating_system */ 'ISO 14649',
/* authorisation */ $);
FILE_SCHEMA (‘COMBINED SCHEMA');
ENDSEC;
DATA;
#10=POLYLINE('CONTOUR OF POCKET1',(#57,#58,#59,#60));
#11=POLYLINE('CONTOUR OF POCKET2',(#61,#62,#63,#64));
#12=GENERAL_PROFILE($,#10);
#13=GENERAL_PROFILE($,#11);
#14=OPEN_POCKET('SQUARE OPEN POCKET',#108,(#122),
  #32,#105,(),$,#141,$,#152,#12,$);
#15=OPEN_POCKET('DIAGONAL OPEN POCKET',#108,(#122),
  #34,#106,(),$,#141,$,#154,#13,$);
#16=PROJECT('EXECUTE EXAMPLE1',#17,(#108),$,$,$);
#17=WORKPLAN('MAIN WORKPLAN',(#111,#112,#113,#114,
  #115,#116,#117),$,#18, $);
#18=SETUP('SETUP1',#19,#99,(#107));
#19=AXIS2_PLACEMENT_3D('SETUP1',#36,#65,#66);
#20=AXIS2_PLACEMENT_3D('PLANE1',#37,#67,#68);
#21=AXIS2_PLACEMENT_3D('WORKPIECE',#42,#69,#70);
#22=AXIS2_PLACEMENT_3D('POCKET1',#43,#71,#72);
#23=AXIS2_PLACEMENT_3D('POCKET1',#44,#73,#74);
#24=AXIS2_PLACEMENT_3D('POCKET2',#45,#75,#76);
#25=AXIS2_PLACEMENT_3D('POCKET2',#46,#77,#78);
#26=AXIS2_PLACEMENT_3D('POCKET3',#47,#79,#80);
#27=AXIS2_PLACEMENT_3D('POCKET3',#48,#81,#82);
#28=AXIS2_PLACEMENT_3D('POCKET4',#49,#83,#84);
#29=AXIS2_PLACEMENT_3D('POCKET4',#50,#85,#86);
#30=AXIS2_PLACEMENT_3D('HOLE1',#51,#87,#88);
#31=AXIS2_PLACEMENT_3D('HOLE1',#52,#89,#90);
#32=AXIS2_PLACEMENT_3D('SQUARE OPEN POCKET',#53,#91,#92);
#33=AXIS2_PLACEMENT_3D('SQUARE OPEN POCKET',#54,#93,#94);
#34=AXIS2_PLACEMENT_3D('DIAGONAL OPEN POCKET',#55,#95,#96);
#35=AXIS2_PLACEMENT_3D('DIAGONAL OPEN POCKET',#56,#97,#98);
#36=CARTESIAN_POINT('SETUP1: LOCATION ',(0.,0.,0.));
#37=CARTESIAN_POINT('SECPLANE1: LOCATION ',(0.,0.,30.));
#38=CARTESIAN_POINT('CLAMPING_POSITION1',(0.,20.,25.));
#39=CARTESIAN_POINT('CLAMPING_POSITION2',(100.,20.,25.));
#40=CARTESIAN_POINT('CLAMPING_POSITION3',(0.,100.,25.));
#41=CARTESIAN_POINT('CLAMPING_POSITION4',(100.,100.,25.));
#42=CARTESIAN_POINT('WORKPIECE1:LOCATION ',(0.,0.,0.));
#43=CARTESIAN_POINT('POCKET1: LOCATION ',(28.32,231.,0.));
#44=CARTESIAN_POINT('POCKET1: DEPTH ',(28.32,231.,-41.5));
#45=CARTESIAN_POINT('POCKET2: LOCATION ',(111.97,231.,0.));
#46=CARTESIAN_POINT('POCKET1: DEPTH ',(111.97,231.,-43.));
#47=CARTESIAN_POINT('POCKET3: LOCATION ',(34.32,133.,0.));
#48=CARTESIAN_POINT('POCKET3: DEPTH ',(34.32,133.,-45.));
#49=CARTESIAN_POINT('POCKET4: LOCATION ',(110.74,133.,0.));
#50=CARTESIAN_POINT('POCKET4: DEPTH ',(110.74,133.,-41.));
#51=CARTESIAN_POINT('HOLE1: LOCATION ',(146.74,176.,0.));
#52=CARTESIAN_POINT('HOLE1: DEPTH ',(146.74,176.,-52.));
#53=CARTESIAN_POINT('SQUARE OPEN POCKET: LOCATION ',
  (48.32,0.,0.));
#54=CARTESIAN_POINT('SQUARE OPEN POCKET: DEPTH ',
  (48.32,0.,-45.));
#55=CARTESIAN_POINT('DIAGONAL OPEN POCKET: LOCATION ',
  (55.44,0.,0.));
#56=CARTESIAN_POINT('DIAGONAL OPEN POCKET: DEPTH ',
  (55.44,0,-50.));
#57=CARTESIAN_POINT('P1',(0.,0.,0.));
#58=CARTESIAN_POINT('P2',(0.,116.,0.));
#59=CARTESIAN_POINT('P3',(122.,116.,0.));
#60=CARTESIAN_POINT('P4',(122.,0.,0.));
#61=CARTESIAN_POINT('P1',(0.,0.,0.));
#62=CARTESIAN_POINT('P2',(25.99,97.,0.));
#63=CARTESIAN_POINT('P3',(81.77,97.,0.));
#64=CARTESIAN_POINT('P4',(107.76,0.,0.));
#65=DIRECTION(' AXIS ',(0.,0.,1.));
#66=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#67=DIRECTION(' AXIS ',(0.,0.,1.));
#68=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#69=DIRECTION(' AXIS ',(0.,0.,1.));
#70=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#71=DIRECTION(' AXIS ',(0.,0.,1.));
#72=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#73=DIRECTION(' AXIS ',(0.,0.,1.));
#74=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#75=DIRECTION(' AXIS ',(0.,0.,1.));
```

```
#76=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#77=DIRECTION(' AXIS ',(0.,0.,1.));
#78=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#79=DIRECTION(' AXIS ',(0.,0.,1.));
#80=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#81=DIRECTION(' AXIS ',(0.,0.,1.));
#82=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#83=DIRECTION(' AXIS ',(0.,0.,1.));
#84=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#85=DIRECTION(' AXIS ',(0.,0.,1.));
#86=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#87=DIRECTION(' AXIS ',(0.,0.,1.));
#88=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#89=DIRECTION(' AXIS ',(0.,0.,1.));
#90=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#91=DIRECTION(' AXIS ',(0.,0.,1.));
#92=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#93=DIRECTION(' AXIS ',(0.,0.,1.));
#94=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#95=DIRECTION(' AXIS ',(0.,0.,1.));
#96=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#97=DIRECTION(' AXIS ',(0.,0.,1.));
#98=DIRECTION(' REF_DIRECTION',(1.,0.,0.));
#99=PLANE('SECURITY PLANE',#20);
#100=PLANE('DEPTH SURFACE FOR POCKET1',#23);
#101=PLANE('DEPTH SURFACE FOR POCKET2',#25);
#102=PLANE('DEPTH SURFACE FOR POCKET3',#27);
#103=PLANE('DEPTH SURFACE FOR POCKET4',#29);
#104=PLANE('DEPTH SURFACE FOR ROUND HOLE1',#31);
#105=PLANE('DEPTH SURFACE FOR SQUARE OPEN POCKET',#33);
#106=PLANE('DEPTH SURFACE FOR DIAGONAL OPEN POCKET',#35);
#107=WORKPIECE_SETUP(#108,#21,$,$,());
#108=WORKPIECE('SIMPLE WORKPIECE',#110,0.01,$,$,#1160,
  (#38,#39,#40,#41));
#109=PROPERTY_PARAMETER('E=200000N/M2');
#110=MATERIAL('ST-50','STEEL',(#109));
#111=MACHINING_WORKINGSTEP('TOP RIGHT CORNER POCKET
  ROUGHING',#99,#118,#122, $);
#112=MACHINING_WORKINGSTEP('BOTTOM RIGHT CORNER
  POCKET ROUGHING',#99,#119, #122,$);
#113=MACHINING_WORKINGSTEP('TOP LEFT CORNER POCKET',
  #99,#120,#122,$);
#114=MACHINING_WORKINGSTEP('BOTTOM LEFT CORNER
  POCKET',#99,#121,#122,$);
#115=MACHINING_WORKINGSTEP('HOLE DRILLING',#99,#172,#174,$);
#116=MACHINING_WORKINGSTEP('SQUARE OPEN POCKET ROUGHING',
  #99,#14,#122,$);
#117=MACHINING_WORKINGSTEP('DIAGONAL OPEN POCKET ROUGHING',
  #99,#15,#122, $);
#118=CLOSED_POCKET('POCKET1',#108,(#122),#22,#100,(),$,#141,$,#142,#168);
#119=CLOSED_POCKET('POCKET2',#108,(#122),#24,#101,(),$,#141,$,#142,#169);
#120=CLOSED_POCKET('POCKET3',#108,(#122),#26,#102,(),$,#141,$,#142,#170);
#121=CLOSED_POCKET('POCKET4',#108,(#122),#28,#103,(),$,#141,$,#142,#171);
#122=BOTTOM_AND_SIDE_ROUGH_MILLING($,$,'ROUGH
POCKET1',15.,$,#124,#138,#133,$,$,$,#140,6.5,5.,1.,0.5);
#123=MILLING_CUTTING_TOOL('REAMER_22MM',#126,(#130),100.,$,$);
#124=MILLING_CUTTING_TOOL('MILL 18MM',#137,(#131),80.,$,$);
#125=MILLING_CUTTING_TOOL('SPIRAL_DRILL_20MM',#175,(#132),90.,$,$);
#126=TAPERED_REAMER(#127,6,.RIGHT.,.F.,$,$);
#127=MILLING_TOOL_DIMENSION(22.,$,$,40.,$,$,$);
#128=MILLING_TOOL_DIMENSION(18.,$,$,29.,0.,$,$);
#129=MILLING_TOOL_DIMENSION(20.,31.,0.1,45.,2.,5.,8.);
#130=CUTTING_COMPONENT(50.,$,$,$,$);
#131=CUTTING_COMPONENT(50.,$,$,$,$);
#132=CUTTING_COMPONENT(70.,$,$,$,$);
#133=MILLING_MACHINE_FUNCTIONS(.T.,$,$,.F.,$,(),.T.,$,$,());
#134=MILLING_MACHINE_FUNCTIONS(.T.,$,$,.F.,$,(),.T.,$,$,());
#135=DRILLING_TYPE_STRATEGY($,$,$,$,$,$);
#136=DRILLING_TYPE_STRATEGY(0.75,0.5,2.,0.5,0.75,8.);
#137=TAPERED_ENDMILL(#128,4,.RIGHT.,.F.,$,$);
#138=MILLING_TECHNOLOGY(0.04,.TCP.,$,-20.,$,.F.,.F.,.F.,$);
#139=MILLING_TECHNOLOGY(0.03,.TCP.,$,-16.,$,.F.,.F.,.F.,$);
#140=CONTOUR_PARALLEL($,$,.CW.,.CONVENTIONAL.);
#141=PLANAR_POCKET_BOTTOM_CONDITION();
#142=TOLERANCED_LENGTH_MEASURE(7.,#155);
#143=TOLERANCED_LENGTH_MEASURE(72.,#156);
#144=TOLERANCED_LENGTH_MEASURE(70.,#157);
#145=TOLERANCED_LENGTH_MEASURE(86.,#158);
#146=TOLERANCED_LENGTH_MEASURE(72.,#159);
#147=TOLERANCED_LENGTH_MEASURE(64.,#160);
#148=TOLERANCED_LENGTH_MEASURE(86.,#161);
#149=TOLERANCED_LENGTH_MEASURE(79.,#162);
#150=TOLERANCED_LENGTH_MEASURE(86.,#163);
#151=TOLERANCED_LENGTH_MEASURE(37.44,#164);
#152=TOLERANCED_LENGTH_MEASURE(6.,#165);
#153=TOLERANCED_LENGTH_MEASURE(6.,#166);
#154=TOLERANCED_LENGTH_MEASURE(20.,#167);
#155=PLUS_MINUS_VALUE(0.1,0.1,3);
#156=PLUS_MINUS_VALUE(0.1,0.1,3);
#157=PLUS_MINUS_VALUE(0.1,0.1,3);
#158=PLUS_MINUS_VALUE(0.1,0.1,3);
#159=PLUS_MINUS_VALUE(0.1,0.1,3);
#160=PLUS_MINUS_VALUE(0.1,0.1,3);
#161=PLUS_MINUS_VALUE(0.1,0.1,3);
#162=PLUS_MINUS_VALUE(0.1,0.1,3);
#163=PLUS_MINUS_VALUE(0.1,0.1,3);
#164=PLUS_MINUS_VALUE(0.3,0.3,3);
#165=PLUS_MINUS_VALUE(0.1,0.1,3);
#166=PLUS_MINUS_VALUE(0.1,0.1,3);
#167=PLUS_MINUS_VALUE(0.1,0.1,3);
#168=RECTANGULAR_CLOSED_PROFILE($,#144,#143);
#169=RECTANGULAR_CLOSED_PROFILE($,#145,#146);
#170=RECTANGULAR_CLOSED_PROFILE($,#147,#148);
#171=RECTANGULAR_CLOSED_PROFILE($,#149,#150);
#172=ROUND_HOLE('HOLE1 D=22MM',#108,(#174),#30,#104,#151,$,#173);
#173=THROUGH_BOTTOM_CONDITION();
#174=DRILLING($,$,'DRILL HOLE1',10.,$,#125,#139,#134,$,$,$,$,$,#136);
#175=TWIST_DRILL(#129,2,.RIGHT.,.F.,0.84);
#1160=BLOCK('my block',#1290,222.,319.,50.);
#1290=AXIS2_PLACEMENT_3D('my placement',#820,$,$);
#820=CARTESIAN_POINT('block position',(0.,0.,-50.));
ENDSEC;
END-ISO-10303-21;
```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