

Machining precedence of 2¹/₂D interacting features in a feature-based data model

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Received: 11 October 2008 / Accepted: 30 April 2009 / Published online: 20 May 2009
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Abstract In process planning, determining feature's machining precedence is an essential step. The task becomes more difficult if features interact with each other, in which case the feature precedence information may suggest multiple machining sequences of the features. This paper considers interacting features in a feature-based model for process planning tasks. For each feature, precedence information is generated considering both roughing and finishing operations. A rule-based system is developed and implemented based on the information about machining precedence of the interacting features. The STEP-NC data model is used as the underlying data model. This model is object-oriented and compliant with the existing STEP standards. The output of the system is also in the STEP format through an information model developed using the EXPRESS language.

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

Nomenclature

P	Final part
B	Raw material (i.e., blank)
F^i	Feature i
F_{AD}^i	Feature absolute depth
F_r^i	Radius of feature i (when it is a hole)

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\cap	Interaction between two features
\cap^v	Interacting volume
CF_{F^i, F^j}	Common face between features i and j
$\vec{C}\bar{F}_{F^i, F^j}$	Normal vector for CF_{F^i, F^j}
CV_{F^i, F^j}	Common volume of features i and j
WS_R^i	Machining workingstep for roughing feature i
WS_F^i	Machining workingstep for finishing feature i
\rightarrow	Precedence
$\&$	AND operand
F_{TAF}^i	Top approach face for feature i
\vec{F}_{TAF}^i	Normal vector for top approach face for feature i
SAF	Side approach face
\vec{T}_{AD}	Tool access direction
ϕ	Null set
$\sigma_P(F^i)$	Common boundary of feature i and the final part

Introduction

Process planning, as a momentous task in product development life cycle, entails interpretation and conversion of design specifications to the required information for manufacturing the product. It may consist of generic data as well as machine-specific data. The former includes for example general machining method(s), suggested machining sequence and cutting strategy whereas the latter may include cutting tool data, machining conditions and tool paths. Some researchers further classified process planning as macro and micro planning (Kannan and Wright 2004), generative and variant approaches (Alting and Zhang 1989; Zhao et al. 2000) or off-line and on-line process planning (Lee et al. 1995; Joo et al. 2001). Nonetheless, machining operation sequencing has always been a challenging issue in Computer-Aided

Process Planning (CAPP) due to its complexity as a so-called nondeterministic polynomial-time problem (Nieble 1965; Garey and Johnson 1979; Tan and Khoshnevis 2000; Gambardella and Dorigo 2000). Its direct influence on machining economy has also been widely recognized (Taiber 1996; Ding et al. 2005). For a CAPP system to generate an effective sequence of machining operations, acquisition of precedence information between machining features becomes a fundamental task that has to be resolved up-front. Furthermore, machining precedence becomes more difficult when features being considered interact with each other. This is due to the fact that feature–feature interactions often lead to alternative sets of machining sequences.

When a CAPP system needs to communicate with other systems as it often does in today's collaborative environment, data exchange and sharing adds further complexity to the problem. One way to overcome this problem is to use neutral data formats (Bhandarkar and Nagi 2000). For this reason, PDES, DXF, IGES, and STEP have been developed since the 1980s to represent and exchange product data. STEP (ISO 1994): Standard for the Exchange of the Product data was developed with the objective of integrating different phases of a product development lifecycle. STEP-NC, as an extension of STEP to NC, uses the feature-based concept, and it has the potential to lead to the way to a new generation of CNC controllers (Xu et al. 2006). In this paper, we use STEP-NC data structure as the feature-based product model to generate the precedence information for interacting machining features. It is also possible to use this data model for maintaining, exchanging and integrating the process planning information with other activities in the product development lifecycle. In the remaining part of this paper, some related works are discussed. The STEP-NC data model will be briefly introduced. A rule-based methodology to generate the precedence information for interacting features will also be presented.

Issues at hand

The problem of operation precedence and sequence in process planning has been dealt with by many researchers and also from different perspectives. However, the issues are rarely addressed alongside feature interactions and multi-pass operations (e.g., roughing and finishing). In the following sub-sections, these issues are briefly discussed and the advantages of using a STEP-NC data model to tackle these problems are presented.

Sequencing machining operations

In feature-based process planning, machining features are recognized, from a CAD model for instance, and the processes as well as their sequences are ascertained based on

the characteristics of the features (Shunmugam et al. 2000). Based on a survey published in 1999 (Reddy et al. 1999), optimization of machining sequence was rarely addressed in more than 150 CAPP-related publications. Among those who did address, Miao defined operation sequencing as a process of ordering the operations in a setup resulting in the lowest machining time (Miao et al. 2002). Others tried to minimize the number of tool changeovers (Tolouei-Rad 2003; Gologlu 2004), tool cost (Taiber 1996) and machining setups (Chu and Gadh 1996; Kannan and Wright 2004). To meet the economic objectives of a manufacturing firm, production cost of machining operations has been the main factor to consider (Yeo et al. 1998; Lee et al. 2001; Wong et al. 2003). Some researchers have dealt with combinational objectives to arrive at a desirable sequence of operations, e.g., minimization of total cost, machine setup, and tool change cost (Lee et al. 2004), non-machining time minimization (Kim and Suh 1998), minimization of production cost and time (Nurre and Vedati 1998; Wang et al. 2006a). A number of techniques have been used, e.g., Petri net (Lee and Jung 1995), fuzzy logic (Gu et al. 1997; Wong et al. 2003), genetic algorithm (Reddy et al. 1999; Singh and Jebaraj 2005), and neural network (Qiao et al. 2000; Joo et al. 2001).

It should be pointed out that feature precedence and operation sequence are problems at two different levels. Feature precedence, which can be portrayed using a tree, graph, matrix, network or other methods (Irani et al. 1995), is the prerequisite for sequencing machining operations in a feature-based process planning system (Sormaz et al. 2004). This is why numerous attempts were made to develop an operation sequence based on the feature precedence information. The proper precedence of machining features may be obtained considering setup, tool changes, tool access directions (Maropoulos et al. 2000; Kim et al. 2001), operation time (Hwang and Miller 1997), cost of tolerance (Yeo et al. 1998) and manufacturing and geometric constraints (Sormaz and Khoshnevis 2000; Liu and Wang 2007). The type of constraints based on which machining operations are sequenced can be classified into two levels, operation constraint and precedence constraint. Take operation constraint as an example. Rough-milling should always precede finish-milling for a feature. The precedence constraint may also dictate the operation sequence based on the location of the features (Miao et al. 2002) as well as other factors such as tool access directions (Chu and Gadh 1996; Kim et al. 2001). Such a feature-based process planning system can be illustrated by Fig. 1 and is considered as an “interfaced” approach. Features that are recognized from a design model are first validated and re-interpreted as necessary. There has been no effective method to validate a machining feature (Shah 1991) although some rules and methodologies have been developed (Gindy et al. 1998; Sormaz and Khoshnevis 2000; Miao et al. 2002). Next, machining precedence between features is established and

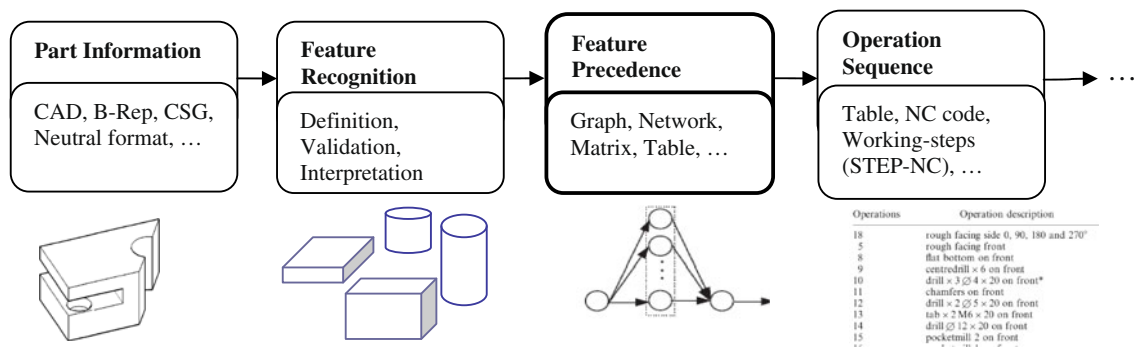
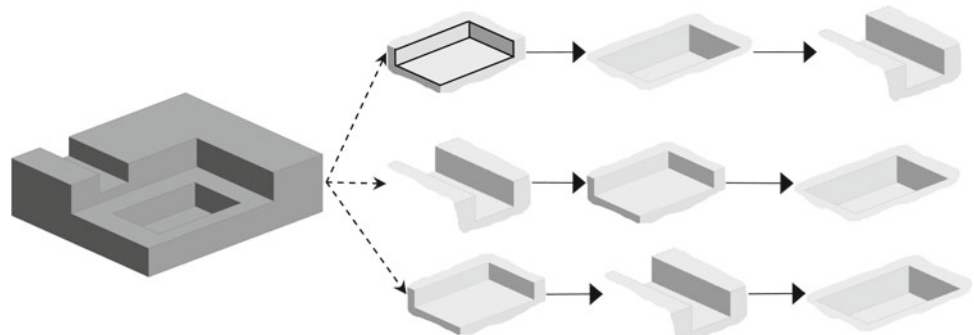


Fig. 1 An interfaced approach in feature-based process planning

Fig. 2 Possible sequences of machining the interacting features



machining operations are sequenced. Operation sequencing is then continued by some downstream activities to accomplish the remaining tasks of process planning.

Multi-pass machining in process planning

Most of the research work carried out in feature-based process planning assumes that machining of a feature be accomplished in a single pass. In other words, roughing and finishing operations on a feature are carried out in tandem. In reality, this may not be true. Take hole-making as an example. Drilling is often followed by reaming or boring operations that are common finishing operations for meeting the desired tolerance and surface finish requirements. Wang et al. (2006a) demonstrated the superiority of multi-pass (using roughing and finishing) over the single-pass throughout several simulation trials. Although the benefits of considering multi-pass strategy have been recognized (Onwubolu 2006), only a handful of researchers have worked on optimizing multi-pass milling operations (Wang et al. 2004). Xu and Hinduja (1997) used a fuzzy decision system to identify and classify the machining operations into finishing, semi-finishing, and roughing features. Chen (2004) introduced a machining model for multi-pass turning operations. Using the object-oriented expert system technology, Kim and Suh (1998) developed a CAPP system considering roughing and finishing operations. To optimize the depth of cut at each stage of an operation for pocket-milling, simulated annealing approach has been used (Wang et al. 2006b). The genetic

algorithm has been used to study and generate optimum number of passes in face-milling operations (Shunmugam et al. 2000). Lee et al. (2001) introduced an iterative approach to generate an operation precedence graph considering rough-facing and side-milling. The same researchers have also applied heuristic methods to solve the operation sequencing problem for rotational parts with roughing and finishing features (Lee et al. 2004).

Feature interactions in process planning

Feature interaction has been recognized by many researchers as a significant issue in process planning. When features interact, the process of feature recognition and feature precedence becomes problematic (Sormaz and Khoshnevis 2000). As mentioned earlier, feature interactions can be treated from two different view-points giving rise to two different types of interactions, geometric interaction and manufacturing interaction (Chu and Gadh 1996; Sormaz and Khoshnevis 2000). Geometric interaction, as discussed in the literature (Gadh and Prinz 1995; Gao and Shah 1998) arises when two or more machining features share a common surface or volume. This gives rise to volumetric and surface feature interactions, respectively. Volumetric and surface feature interactions can provide some insights into the precedence of machining features (Hwang and Miller 1995; Kamhawi et al. 1996; Xu 2001; Sormaz and Arumugam 2004) and consequently the final machining sequence. Figure 2 gives three possible machining sequences when features interact geometrically.

In some cases (e.g., when two steps interact), the common volume can be machined together with any one of the interacting features. Wang et al. (2006a) studied the machining sequence based on a precedence graph for feature-feature interactions in a prismatic part. Using forward and backward chaining, Miller and Hwang (1997) developed a rule-based model to handle the precedence of feature interactions.

Manufacturing interactions on the other hand relate to technological constraints when a part is machined (Sormaz and Khoshnevis 2000; Liu and Wang 2007). Focusing on manufacturing interactions, Chu and Gadh (1996) generated simple precedence based on tool access directions in each setup. Both types of feature interactions have also been considered for clustering and grouping the features for knowledge-based process planning by Liu and Wang (2007) and in a rule-based FPN (feature precedence network) by Sormaz and Khoshnevis (2000). Surface and product quality (Lin et al. 1998; Pal et al. 2005) and feature accessibility and machinability (Faraj 2003) were also considered by some researchers as contributing factors to determining machining sequence.

Integrating process planning with CNC

In spite of some success in using neutral formats for design data exchange, the dream of integrating design with manufacturing has largely remained immaterialized. The most challenging problem has been the semantic difference between the activities and systems of the current CAx (CAD/CAPP/CAM/CNC) chain (Corney et al. 2005; Mokhtar et al. 2007; Newman and Nassehi 2007). The STEP-NC (ISO 2003a) and ISO 10303-238 (ISO 2003b) data model was introduced to provide a platform for making such integration possible. It encompasses all the required information for machining a part including workpiece geometry, set-up planning, machining technology, tool information, and tool path planning. This standard has attracted some interests from industry, e.g., Daimler-Chrysler, Volvo, General Motors, Airbus, and Boeing companies (Xu et al. 2005). Superior to G-code (known as ISO 6983), STEP-NC provides an object-oriented model for NC machining purposes (Xu and Newman 2006). STEP-NC also has some other advantages over G-code (Xu and He 2004).

The discussion in this section so far suggests that crucial factors such as feature interaction and roughing/finishing operations have been rarely taken into account when dealing with machining precedence and operation sequence. Nevertheless, those who did consider these factors did not use a neutral product format, making it hard to integrate in an entire CAx chain. To overcome these shortages, the research work reported herein detects and maintains the machining precedence information among interacting features. The

STEP-NC data model is used as a feature-based model and support a neutral platform. Upon generating the machining precedence information, both roughing and finishing operations are considered.

STEP-NC machining features and operations

In STEP-NC, manufacturing features are classified into *region* and *two5D_manufacturing_features*. *Region* is equivalent to a free form feature, and *two5D_manufacturing_feature* encompasses the 2.5D machining features as well as their replications (ISO 2003c). Machining features are defined in a close resemblance to ISO 10303-224 (ISO 2001). They include *planar_face*, *pocket*, *slot*, *step*, *round_hole*, *boss*, and etc. *Counterbore_hole* and *countersunk_hole* are interacting features (intersection of two holes) and described as a *compound_feature* entity. This classification is summarized in Fig. 3.

The STEP-NC data model allows machining operations and the cutting tools to be defined for every feature resulting in a new entity called *Workingstep* (ISO 2003d; ISO 2004). *Machining_workingsteps* represent the machining process for a specified area on the workpiece, e.g., a feature. It cannot be defined independent of a feature. Therefore, by connecting an operation (e.g., *plane_rough_milling*) to a feature (e.g., *closed_pocket*), the ambiguity of a 1:n relation between operations and features is eliminated (ISO 2003d). The *Machining_workingstep* entity along with its attributes is demonstrated in Fig. 4.

Dealing with feature interactions in STEP-NC

A machining feature in STEP-NC, whether or not it interacts with another feature, is always expressed as a standalone feature. Little research has been done to deal with feature interactions in a STEP-NC based CAPP system. Gonzales and Rosado introduced a knowledge-based model to represent some limited interaction information related to an ISO 10303 AP 224 feature (González and Rosado 2004). In a STEP-Compliant CNC system, Suh et al. (2003) implemented a shop-floor programming system for feature recognition and process planning with simple feature interactions.

Considering feature accessibility and geometric interactions between STEP-NC features, Mokhtar et al. (2008) developed a system to visualize and resolve interactions in a part model. This work enables generation of simple precedence data among interacting features based on a limited number of precedence rules. Information about feature interactions such as common volume (CV), connection face (CF), bridge face (BF), and entrance face (EF) are calculated. A common volume is formed when the machining volumes of

Fig. 3 2.5D manufacturing features in STEP-NC

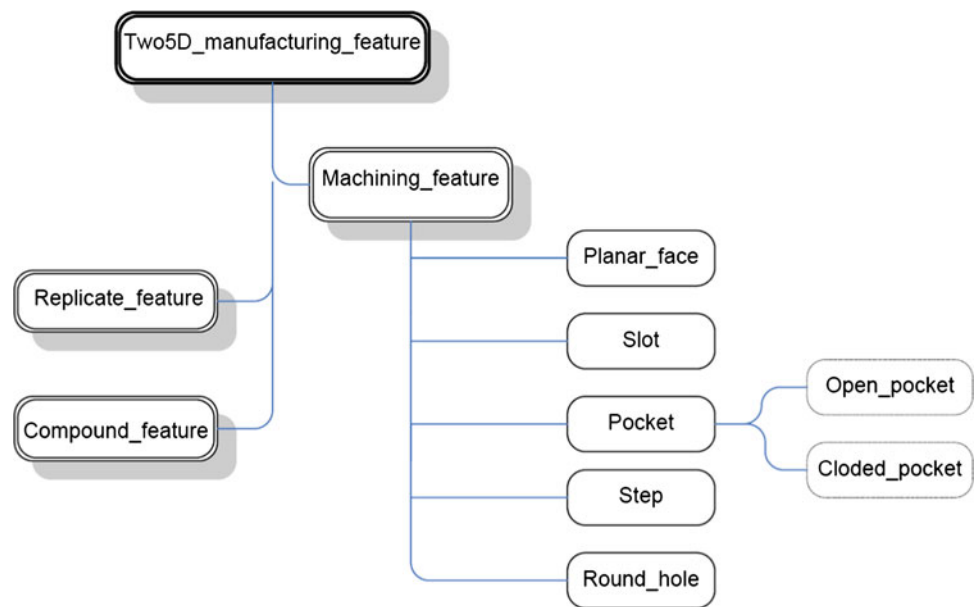
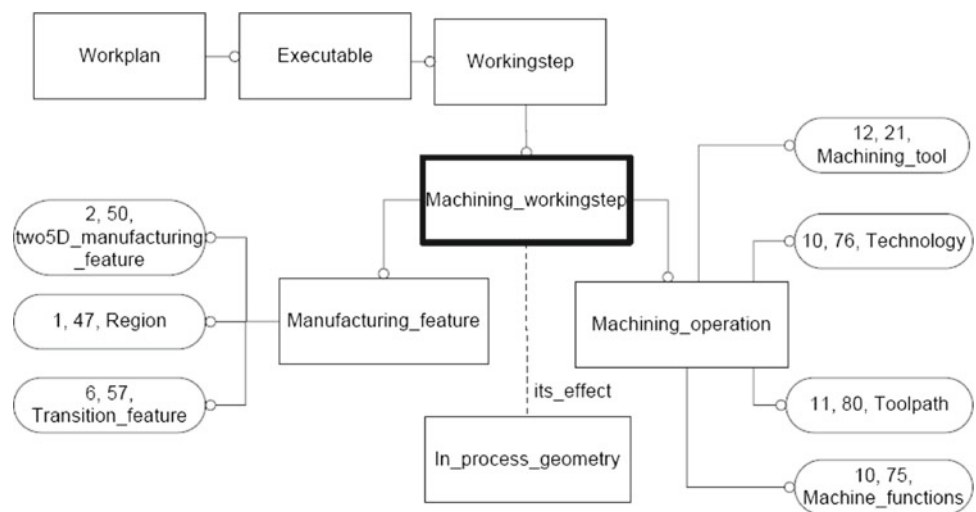


Fig. 4 Machining_workingstep entity and its attributes

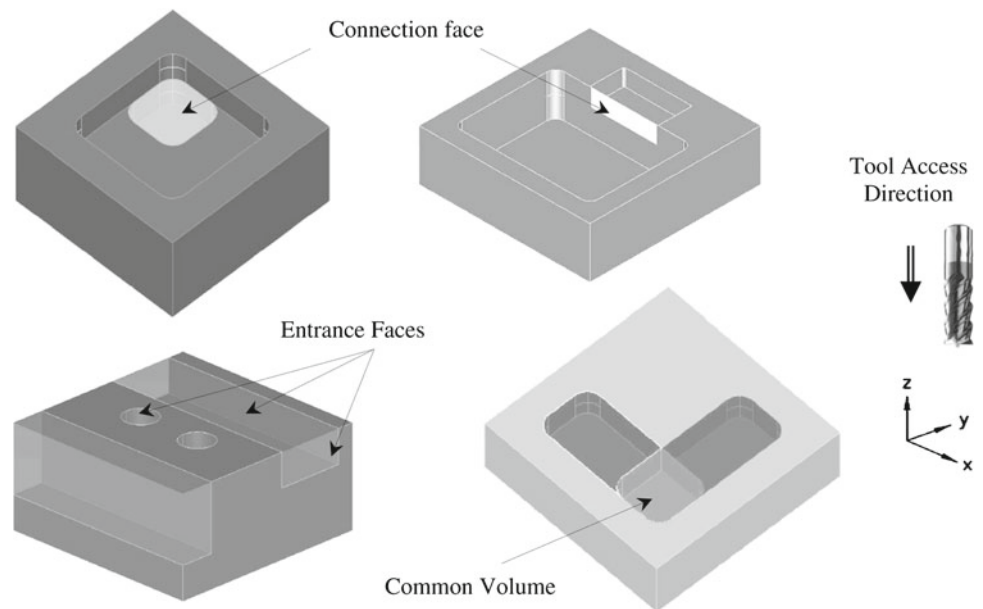


two features intersect each other, i.e., $CV_{F^i, F^j} = F^i \cap^V F^j$. Apparently, this volume can be machined with either of the two contributing features (F^i or F^j). A connection face exists when two features interact with each other through a face, i.e., $CF_{F^i, F^j} = F^i \cap F^j$. In the 2.5D situation, this face may have a normal that is either inline with or at the right angle to the tool access direction (TAD) (\vec{T}_{AD}) that is defined as the direction in which a cutter can commence machining. For instance, for a setup as shown in Fig. 5, the TAD will be (0, 0, -1). For a typical feature i , entrance face (EF_{F^i}) is defined as the common boundary between the feature and the blank ($EF_{F^i} = \sigma(F^i) \cap \sigma(B)$). For a blind hole, its entrance face will be its top face. For a step, its three side faces can be considered as entrance faces.

Precedence constraints in machining interacting features

Machining precedence is established between two interacting features considering geometric, technological, and economic factors. This research studies the precedence of machining operations (roughing and finishing) for features with interactions. As mentioned in a previous section, *Machining_workingstep* in a STEP-NC data model can represent roughing and finishing operations for a particular feature. Therefore, the precedence rules in this research are concerned with roughing and finishing workingsteps (WS_R , WS_F), rather than the machining features. For a specific pair of interacting features, roughing operations may follow precedence rules that are different from those of finishing operations. In this

Fig. 5 Different types of interacting entities



research, we have divided precedence constraints into two categories, hard precedence constraints (HPC) and soft precedence constraints (SPC). These constraints are discussed in details in the following sections.

Hard precedence constraints

Hard precedence constraints, which may also be called predominant constraints, mainly consider feasibility and machinability. Only under extreme situations can this kind of precedence be violated. In this paper, HPC has three categories, Top Face Accessibility (TFA), Hole Integrity Requirement (HIR), and Transition Feature Existence (TFE).

Top face accessibility

This constraint implies the accessibility of a machining feature. For each feature to be machined, at least one face should be accessible to a cutter. Figure 6 shows this face when two pockets interact. In this figure, the lower pocket is nested in the upper pocket; the top (nesting) feature should be machined before the bottom (nested) feature. The rationale behind this rule is to avoid air-cutting and use of a longer cutter, hence

TFA rule:

$$\begin{aligned}
 & \text{If} [(F^i \cap F^j = CF_{F^i, F^j}) \ \&\& \ (CF_{F^i, F^j} \times \vec{T}_{AD} = 0) \\
 & \quad \&\& (F_{AD}^i > F_{AD}^j)]; \\
 & \text{then} (WS_R^j \rightarrow WS_R^i)
 \end{aligned}$$

where, F_{AD}^i is the absolute depth of feature F^i . It is defined as the distance from its bottom face to the workpiece top

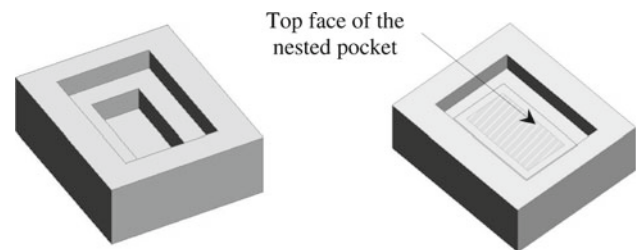
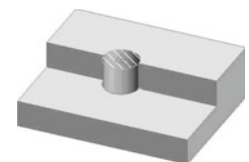


Fig. 6 Top face accessibility

Fig. 7 Hole integrity requirement



face. It can be calculated based on its feature *depth* and the *elementary_surface* in the STEP-NC data model.

Hole integrity requirement

To make a round hole, its top face should be fully exposed. Figure 7 shows a hole interacting with a step; the step removes part of the top entrance face for the hole. In this case, the hole is to be cut first. Otherwise, the drilling bit may be damaged or deflected and it becomes hard to achieve the desired quality for the hole. For the same reason, any finishing operations for the hole (e.g., boring or reaming) should immediately follow the roughing (drilling) operation(s). Consequently, the step should always be machined last. Therefore, we have,

HIR rule: “If a hole interacts with another non-hole feature which causes part of the opening end of the hole missing,

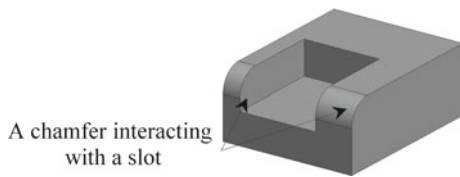


Fig. 8 Transition feature existence

the hole must be cut and finished before the other feature”,

$$\begin{aligned} & \text{If}[(F^i \cap F^j = CV_{F^i, F^j}) \&\& (F^i \neq \text{hole}) \\ & \&\& (F^j == \text{hole})]; \\ & \text{then}[(WS_R^j \rightarrow WS_R^i) \wedge (WS_F^j \rightarrow WS_F^i)] \end{aligned}$$

Transition feature existence

Machining of a transition feature (e.g., a chamfer or fillet as defined in STEP-NC) should be performed after the features that interact with it are machined. Such an example is shown in Fig. 8 where two fillet features interact with a slot. Operation for machining a transition feature is usually one finishing cut. Therefore, we have

Rule TFE: “If a transition feature interacts with another feature, the transition feature is machined last”,

$$\begin{aligned} & \text{If}[(F^i \cap F^j \neq \phi) \&\& (F^j == \text{transition_feature})]; \\ & \text{then}[(WS_R^i \rightarrow WS^j) \&\& (WS_F^i \rightarrow WS^j)] \end{aligned}$$

Soft precedence constraints

Compared with the hard precedence, soft (or preferred) constraints suggest preference of machining one feature before the other. Violating these constraints may result in inefficient operations in terms of machining quality, cost, and time. We classify the SPCs into the following five categories: Side Approach Cutting (SAC), Interaction with Connection Face (ICF), Hole-Hole Interaction (HHI), Interaction with Connection Face (ICF), Hole Deburring (HDB), and Unnecessary Finishing Cut (UFC). These SPCs are discussed in the following paragraphs.

Side approach cutting

For each machining feature, the side approach face (SAF) is an entrance face and is defined as the face that coincides with the side faces of the workpiece. SAF(s) are shown for two interacting features in Fig. 9. The pocket and slot have two and one side faces respectively, from which the cutting tool can approach. Removing the pocket first results in the connection face to become a SAF for the slot. Common practice tells us that it is always more desirable for a cutter to enter

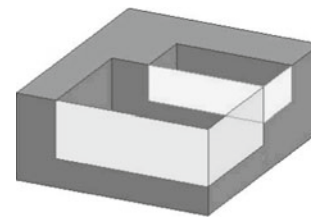


Fig. 9 Side approach cutting

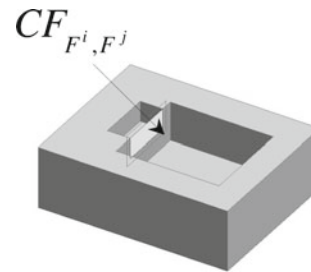


Fig. 10 Interaction with a connection

the material side-ways as compared to plunging from the top. However, in the cases where a feature has no SAF (see the feature in Fig. 6), plunging becomes inevitable. Therefore, we have

SAC rule: “For two interacting features that are not holes and their interaction is not of a nesting/nested type, the feature with more number of entrance faces is machined first. It should be noted that if one of the features is a hole, rule HIR or HHI should prevail”. That is,

$$\begin{aligned} & \text{If}[(F^i \cap F^j = CF_{F^i, F^j}) \&\& (C\vec{F}_{F^i, F^j} \times \vec{T}_{AD} \neq 0) \\ & \&\& ((SAF_{F^i})_s > (SAF_{F^j})_s)]; \\ & \text{then}(WS_R^i \rightarrow WS_R^j) \end{aligned}$$

Interaction with connection face

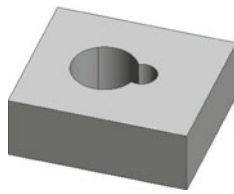
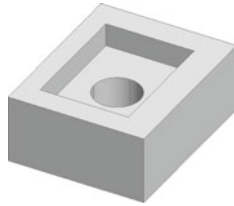
If two features are not of a nesting or nested type and they interact via a connection face, the shallower feature is machined through the connection face if the other feature is machined first (Fig. 10). Therefore, we have

Rule ICF: “If two features that are not holes interact with each other through a connection face and are adjacent to each other, the feature with a greater depth is machined first”,

$$\begin{aligned} & \text{If}[(F^i \cap F^j = CF_{F^i, F^j}) \&\& (F^i \cap F^j \neq CV_{F^i, F^j}) \\ & \&\& (C\vec{F}_{F^i, F^j} \times \vec{T}_{AD} \neq 0) \&\& (F_{AD}^i > F_{AD}^j)]; \\ & \text{then}(WS_R^i \rightarrow WS_R^j) \end{aligned}$$

Hole–hole interaction

To prevent tool breakage or tool deflection, when two parallel holes interact (Fig. 11), the smaller hole is drilled first. It is obvious that removing a part of entrance face of the

Fig. 11 Hole–hole interaction**Fig. 12** Hole-deburring

bigger hole when machining the smaller hole first presents a less serious problem than otherwise. Even if their top faces are not co-planar, this rule still applies. Finishing operation for the smaller hole should also precede that of the bigger hole. In STEP-NC, nested holes may be considered as a compound feature such as a *counterbore_hole* which can also be machined with the *counter_sinking* operation. Therefore, we have,

Rule HHI: “If two holes interact, the smaller hole is cut first”,

$$\begin{aligned} & \text{If}[(F^i \cap F^j = \phi) \ \&\& \ (F^i == \text{hole}) \\ & \ \&\& \ (F^j == \text{hole}) \ \&\& \ (F_r^i > F_r^j)]; \\ & \text{then}[(WS_R^j \rightarrow WS_R^i) \ \&\& \ (WS_F^j \rightarrow WS_F^i)] \end{aligned}$$

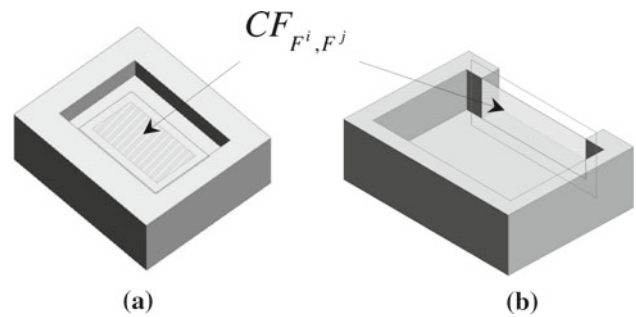
where, F_r^i — radius of hole i .

Hole deburring

This constraint deals with the quality of the machined surface of a hole. After drilling and other subsequent operations (e.g., reaming or boring), burrs may remain around the edges of the hole. If this surface is part of another feature (e.g., a pocket as shown in Fig. 12), machining the pocket after drilling the hole can remove these burrs. However in this particular case, rule HPC as discussed earlier suggests that the pocket should be machined before the hole is drilled. Therefore, the hole-deburring constraint should be applied to finishing operations.

Rule HDB: “If a hole is nested in a non-hole feature, the finishing operation of the non-hole feature would be postponed after the finishing operation of the hole”,

$$\begin{aligned} & \text{If}[(F^i \cap F^j = CF_{F^i, F^j}) \ \&\& \ (F^i == \text{hole}) \\ & \ \&\& \ (F^j \neq \text{hole}) \ \&\& \ (C\vec{F}_{F^i, F^j} \times \vec{T}_{AD} = 0)]; \\ & \text{then}(WS_F^i \rightarrow WS_F^j) \end{aligned}$$

**Fig. 13** Unnecessary finishing cut

Unnecessary finishing cut

Finishing operations often have a lower material removal rate in comparison with roughing operations due to the fact that a smaller feed rate and depth of cut are usually opted. It is not uncommon that an expensive finishing cutter may also be used. So finishing operations are normally less economic, and should be kept to a minimum. In Fig. 13a, the connection face of the nesting and nested pocket is highlighted. Due to the TFA rule (a hard constraint), the nested pocket should be cut after the nesting pocket. If roughing and finishing of the nesting pocket are accomplished in two successive steps, the connection face that is already finished will be removed in the roughing operation of the nested pocket. In this case, the finishing operation of the bigger pocket should be postponed after roughing or finishing the smaller one. If a connection face exists between two features (Fig. 13b), this precedence is applied to both features. In this case, finishing operations for the slot and pocket should be performed after the roughing operations for the pocket and slot are done. We therefore have,

Rule UFC1: “If one feature is nested in another, the roughing operation for the lower feature is carried out before the finishing operation of the upper feature”,

$$\begin{aligned} & \text{If}[(F^i \cap F^j \neq \phi) \ \&\& \ (C\vec{F}_{F^i, F^j} \times \vec{T}_{AD} = 0) \\ & \ \&\& \ (F_{AD}^i > F_{AD}^j)]; \\ & \text{then}(WS_R^j \rightarrow WS_F^i) \end{aligned}$$

Rule UFC2: “If two features interact via a connection face and they are side-by-side, both features are roughed first before finishing operations”,

$$\begin{aligned} & \text{If}[(F^i \cap F^j \neq \phi) \ \&\& \ (C\vec{F}_{F^i, F^j} \times \vec{T}_{AD} \neq 0)]; \\ & \text{then}[(WS_R^j \rightarrow WS_F^i) \ \&\& \ (WS_R^i \rightarrow WS_F^j)] \end{aligned}$$

Note that the UFC rules do not apply when a hole exists.

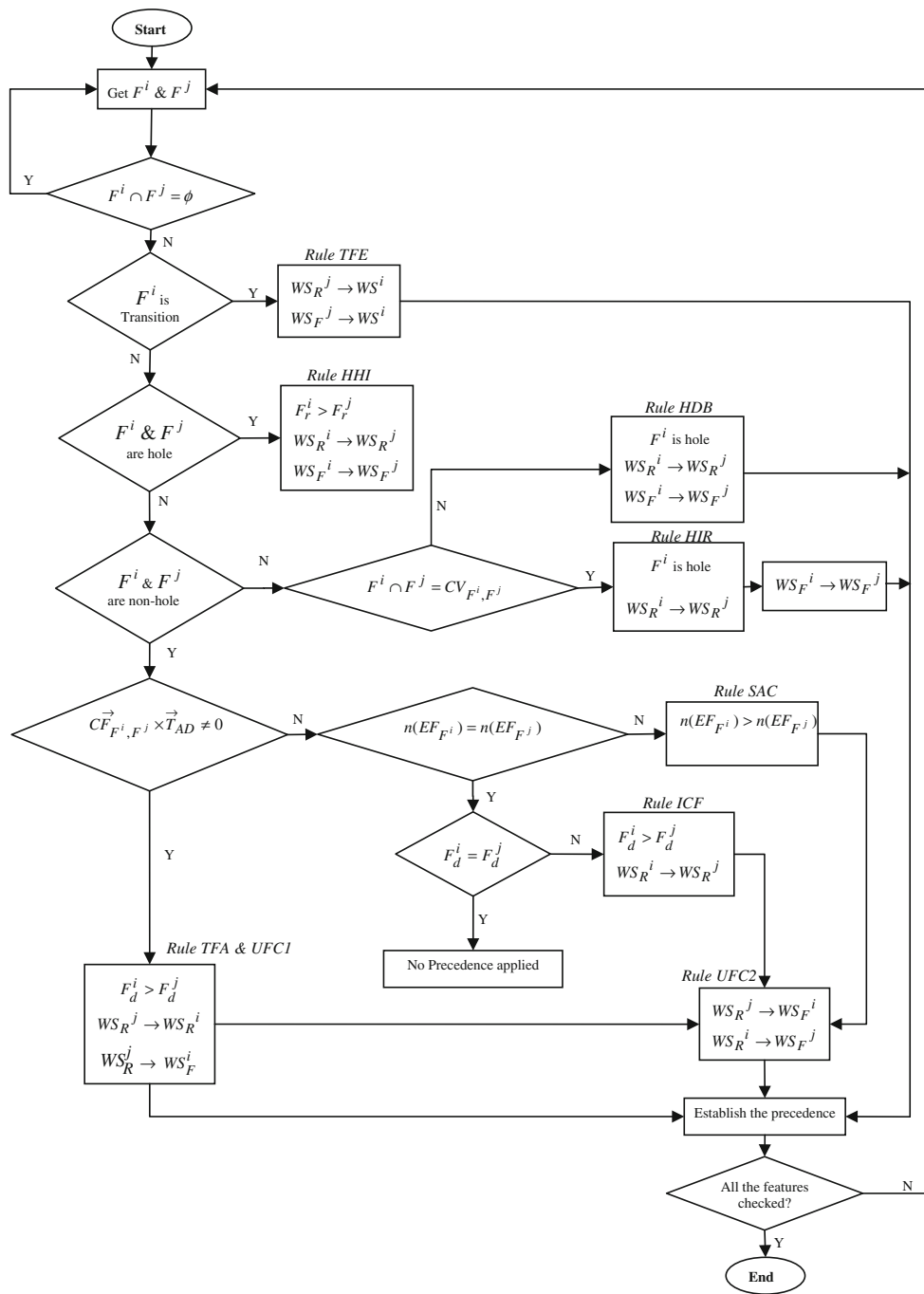


Fig. 14 Algorithm for precedence generation

Algorithms

When applying the precedence rules, interacting features are examined one set (of two or more features) at a time from the list of interacting features. These interacting features have already been generated and saved in a STEP-NC file. For each pair of features that are interacting, the precedence rules are checked and their corresponding working-

steps are sequenced. Hard precedence rules have priority over soft precedence rules. Figure 14 shows the algorithm that has been developed to detect feature precedence information. This information is then stored in an object-oriented structure in the STEP physical file format.

Some assumptions have been made in the algorithm. Except for the transition features, all features will have maximum two machining passes, roughing and finishing. Pockets,

Fig. 15 “STEP-in STEP-out” architecture of the prototype system

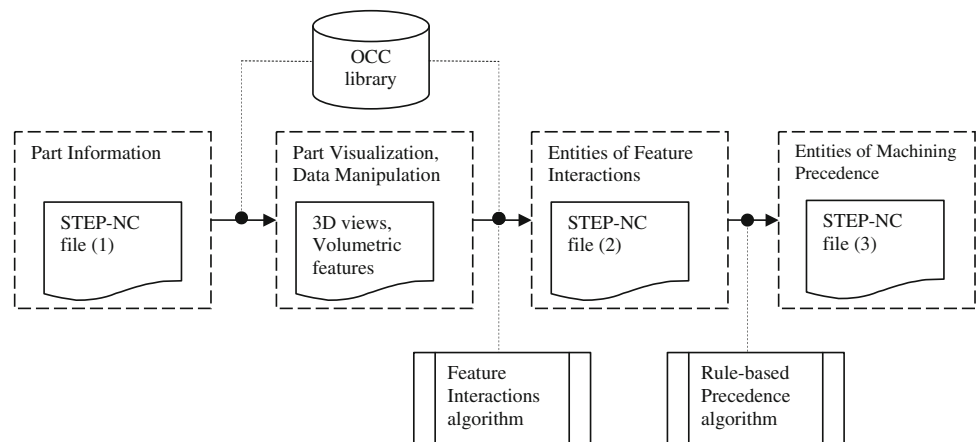
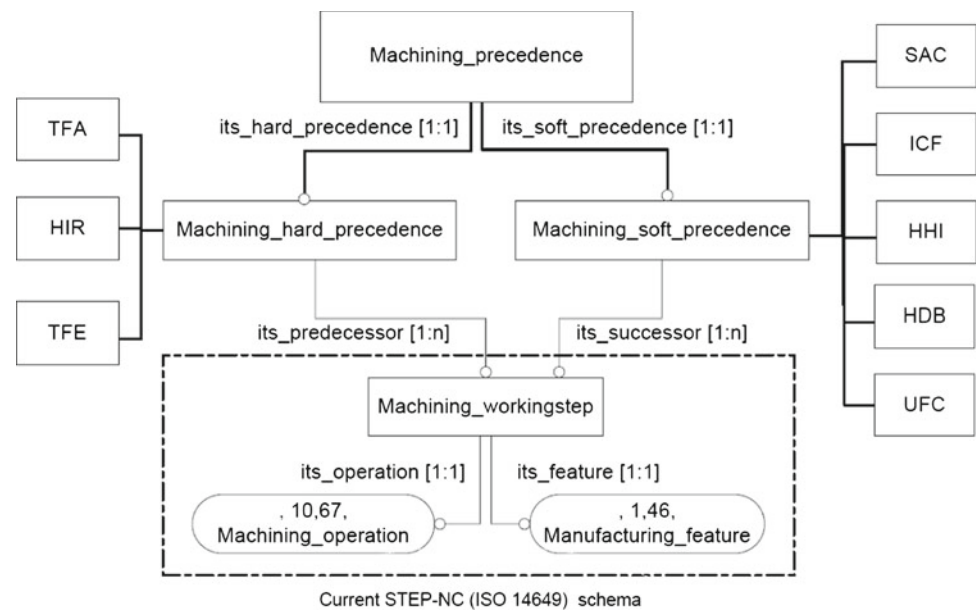


Fig. 16 Machining precedence schema



slots, and steps typically need roughing and finishing while outside profile features may be cut in one pass (Miao et al. 2002). The starting workpiece is assumed to be a box-shaped billet; its dimensions are retrieved from a STEP file. Since only 2.5D features are dealt with, all the operations are to be performed on a 3-axis CNC machine. If two interacting pockets have the same depth, they are considered as a single pocket as defined as a *general_closed_profile* in STEP-NC. *General_open_profile* can also be used to describe a pocket and a step having the same depth.

Implementation

A prototype system has been developed based on the above-mentioned algorithm. Microsoft Visual C++ is the main programming language. Open CASCADE (OCC) has been used as the underlying solid modelling kernel (Open Cascade Technology 2000). This is considered indispensable as the geometric reasoning tasks to be carried out rely heavily on

Boolean operations and other common functions in a 3D modelling kernel. Open CASCADE follows the B-rep scheme, and has a hierarchical and robust data model. Alongside a set of powerful geometric and topologic operations, it also offers a complete suite of visualisation tools for displaying all types of geometric entities in a graphic user interface (GUI).

The rule-based system is adopted. Figure 15 depicts this “STEP-in, STEP-out” architecture. To include the machining precedence information in a *machining_workingstep*, a precedence schema is developed using the EXPRESS language (Fig. 16). In doing so, the precedence information is made fully compatible with the STEP-NC standard.

Case studies

To validate the rules and algorithms, two examples are presented. These examples have incorporated all the cases where

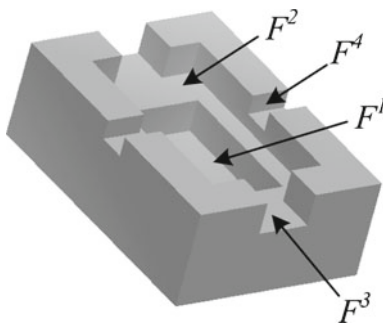


Fig. 17 Example 1

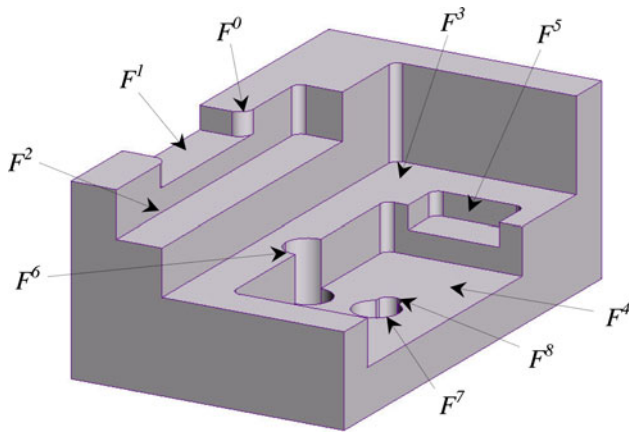


Fig. 18 Example 2

interactions occur and proper machining sequences are sought. The first example is shown in Fig. 17. It is a prismatic component including four interacting features: two pockets (F^1 and F^2) and two slots (F^3 and F^4). The interacting entity between the closed pockets is a connection face while the two through slots and the upper pocket intersect through a volume.

Following the precedence algorithm, feature F^2 should be machined before feature F^1 (TFA rule applied) but its finishing cut should be delayed until feature F^1 finish-milled (UFC rule applied). Machining of the upper pocket has priority over rough-milling of the two slots (SAC rule applied) and meanwhile roughing operation of F^3 is preferred to that of F^4 (ICF rule applied). Their finishing cuts however, may follow the soft precedence rules of UFC. One may consider F^2 and F^3 as a single feature such as an open pocket. The interpretation of the features as shown in this example may result from the fact that the features have different tolerances or surface finishes to be met, which requires different machining operations. Hence, they are two distinct manufacturing features albeit having the same bottom condition.

The second case study is a part with nine machining features (Fig. 18). It is designed to incorporate almost all the interaction types. They are two slots (F^1 , F^2), a step (F^3), two pockets (F^4 , F^5), three holes (F^6 , F^7 , F^8), and a round

edge feature (F^0). The information about these features and their corresponding machining workingsteps is retrieved from the STEP-NC part 21 file as shown in Appendix A. Surface and volume interactions occur in-between 12 pairs of features—(F^0 , F^1), (F^0 , F^2), (F^1 , F^2), (F^2 , F^3), (F^3 , F^4), (F^3 , F^5), (F^3 , F^6), (F^4 , F^5), (F^4 , F^6), (F^4 , F^7), (F^4 , F^8), (F^7 , F^8).

Based on the interaction type between these features, the following machining precedences are established,

Hard Precedence:

- Roughing operations for both pockets and all three holes are to be performed after rough-milling the step (TFA rule);
- Operations for making hole F^6 should precede the machining of the open pocket (HIR rule);
- Rounding-off the edge (F^0) should not be done before roughing and finishing of its two interacting slots (TFC rule);

Soft Precedence:

- Roughing of the open pocket is best carried out before that of the closed pocket (SAC rule);
- The bigger slot is best rough-milled before the smaller one (ICF rule);
- Both drilling and reaming operations for the smaller hole (F^8), precede drilling and reaming of the big one (F^7) (HHI rule);
- The finishing operations for these two holes can be postponed until the open pocket is finished (HDB rule);
- Both pockets are nested in the step. Therefore, they should be rough-machined before the step is finished (UFC1 rule);
- Due to the interactions between adjacent features such as the slots, pockets, and step, each one of these features should have its finishing operation carried out after the roughing operation of its interacting feature (UFC2 rule);

The 3-D model of the sample part (the right column) as well as its STEP-NC data hierarchy (left column) is displayed using the STEP-NC Processor (Fig. 19).

To calculate the machining precedence, a user can select the precedence rules to be applied (Fig. 20). Hard precedences are recommended by default and soft precedences may be applied considering the quality and economical constraints. A help file is embedded in the interface providing a brief guide to the user (Fig. 21). All the precedence information is stored as an extension to the original STEP-NC file (Lines #179 to # 202 in the Appendix A).

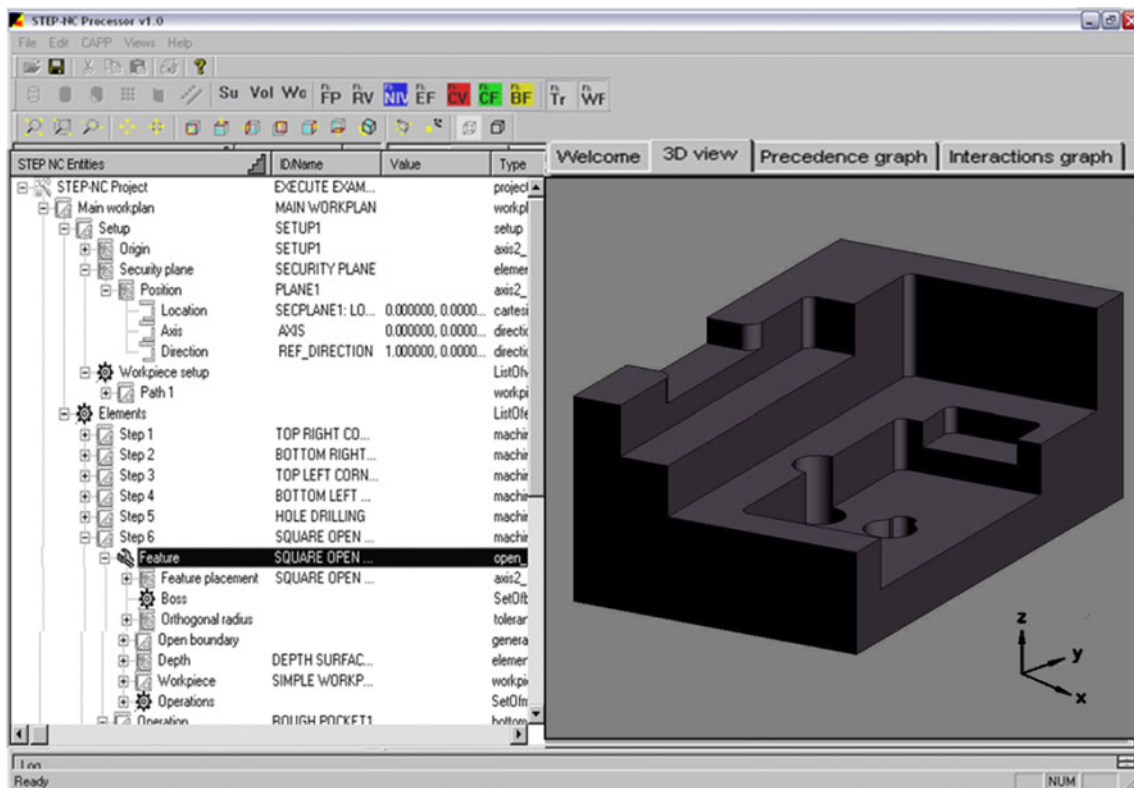
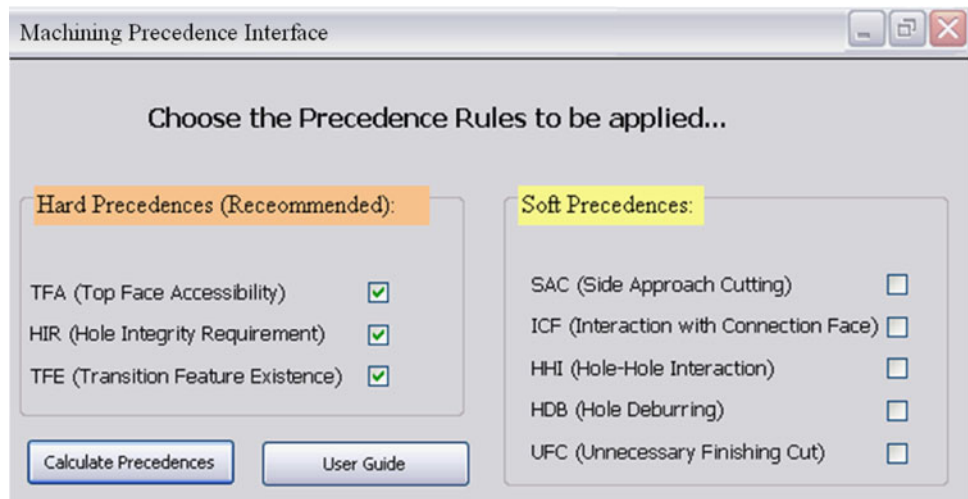


Fig. 19 Part visualization by STEP-NC Processor

Fig. 20 User interface for setting machining precedences

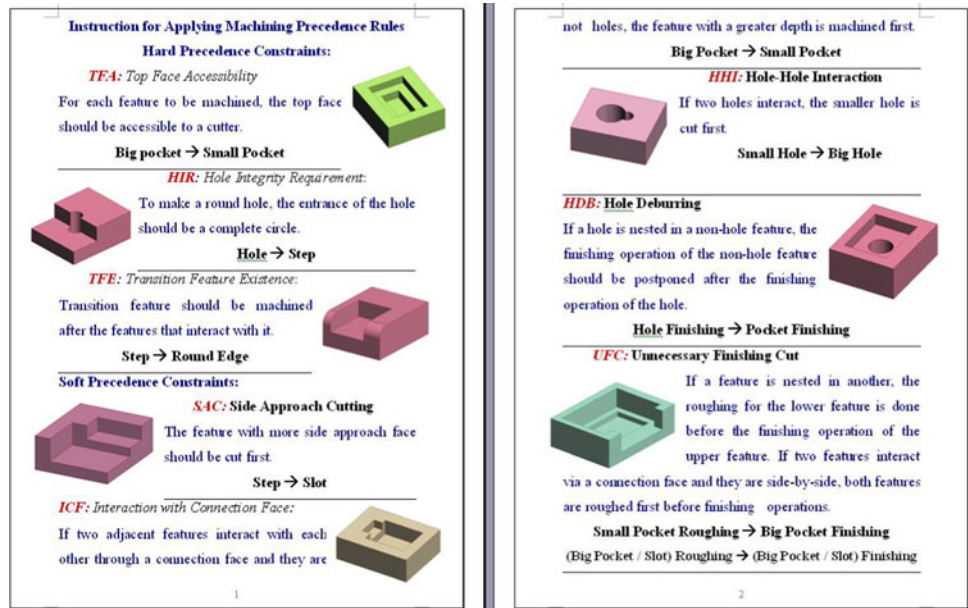


Conclusions

The information about machining constraints for interacting features in a feature-based data model can be considered as hard and soft precedence. These two categories of precedence are further classified into specific types. Unlike most of the systems developed, the machining precedence information in this research is generated considering fea-

ture's roughing and finishing operations. This is materialized by making use of the workingsteps concept in STEP-NC, which can include data about roughing and finishing operations for a single feature. The user interface allows the user to specify appropriate precedence rules depending on the manufacturing requirements. The feature precedence information is connected with the machining_workingstep entity, so that it can be utilised when machining_workingsteps are used at

Fig. 21 User guide to select the precedence rules



the operation sequencing stage. The precedence data are also saved and kept together with the STEP-NC file. In this way, all the information is consolidated in one file.

Although STEP-NC is capable of modelling free form manufacturing features, the current research is confined to 2.5D machining features. Based on the outputs of this research, further research is being carried out to determine an optimal final operation sequence to be kept in the STEP-NC *workplan* entity.

Acknowledgements The authors acknowledge the contributions from Iñigo Lazcanotegui and Tobias Dipper to the development of some of the early stage work.

Appendix A

Sample part STEP-NC (Part 21) file:

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('Machining Precedence for Interactive
Features'), '2;1');
FILE_NAME('Case_study.stp','2008-09-18T16:30:37',
('University of Auckland'),('','GraphicalInstance 1.0 Beta
5 [1.0.5.20]','');
FILE_SCHEMA (('MACHINING_SCHEMA',
'MILLING_SCHEMA', 'FEATURE_INTERACTION
_SCHEMA', 'PRECEDENCE_SCHEMA'));
ENDSEC;
DATA;
..
#1 = PROJECT('Machining Precedence',#2,(#11,#11), #169,#170,);
#2 = WORKPLAN('main workplan',(#102,#117,#119,
#120,#123,#124,#127,#128,#131,#132,#136,#137,#146,
#147,#175,#153,#154),$,#164,);
#3 = SLOT('Small Slot',#11,(#107,#118),#12,#14,#17, #20,(#24));
#4 = SLOT('Big Slot',#11,(#121,#122),#25,#27,#30,#33, (#38));
#7 = CLOSED_POCKET('Closed Pocket',#11,
```

```
(#133,#135),#70,#72,(,)$,#75,$,$,#78);
#8 = ROUND_HOLE('Top Hole',#11,(#138,#139),#81,
#83,#86,$,#87);
#9 = ROUND_HOLE('Bottom Big Hole',#11, (#168,#148),
#88,#90,#93,$,#94);
#10 = ROUND_HOLE('Bottom Small Hole',#11,
(#155,#160),#95,#97,#100,$,#101);
#11 = WORKPIECE('Simple Cubic Wokpiece', $,$,$,$,$,());
#12 = AXIS2_PLACEMENT_3D('Small Slot',#13,$,$);
#13 = CARTESIAN_POINT('Small Slot',(10,35,0));
#14 = PLANE('Small Slot Elementary Surface',#15);
#15 = AXIS2_PLACEMENT_3D('Small Slot',#16,$,$);
#16 = CARTESIAN_POINT('Small Slot Depth',(0, 0, -5));
#17 = LINEAR_PATH($,#18,#19);
#18 = TOLERANCED_LENGTH_MEASURE(10,,$);
#19 = DIRECTION('Small Slot Direction',(-1, 0, 0));
#20 = SQUARE_U_PROFILE($,#23,$,0,$,0.);
#23 = TOLERANCED_LENGTH_MEASURE(30,,$);
#24 = OPEN_SLOT_END_TYPE();
#25 = AXIS2_PLACEMENT_3D('Big Slot',#26,$,$);
#26 = CARTESIAN_POINT('Big Slot',(15,0,0));
#27 = PLANE('Big Slot Elementary Surface',#28);
#28 = AXIS2_PLACEMENT_3D('Big Slot',#29,$,$);
#29 = CARTESIAN_POINT('Big Slot Depth',(0, 0, -10));
#30 = LINEAR_PATH($,#31,#32);
#31 = TOLERANCED_LENGTH_MEASURE(70,,$);
#32 = DIRECTION('Big Slot Direction',(0,1,0));
#33 = SQUARE_U_PROFILE($,#34,#37,0.,#36,0.);
#34 = TOLERANCED_LENGTH_MEASURE(10,,$);
#36 = TOLERANCED_LENGTH_MEASURE(0,,$);
#37 = TOLERANCED_LENGTH_MEASURE(0,,$);
#38 = FLAT_SLOT_END_TYPE();
#48 = STEP('Step',#11,(#125,#126),#49,#51,#54,$,());
#49 = AXIS2_PLACEMENT_3D('Step',#50,$,$);
#50 = CARTESIAN_POINT('Step',(20,0,0));
#51 = PLANE('Step Elementary Surface',#52);
#52 = AXIS2_PLACEMENT_3D('Step',#53,$,$);
#53 = CARTESIAN_POINT('Step',(0, 0, -20));
#54 = LINEAR_PATH($,#55,#56);
#55 = TOLERANCED_LENGTH_MEASURE(90,,$);
```

```

#56 = DIRECTION('Step',(0,1,0));
#57 = OPEN_POCKET('Open Pocket',#11,(#129,#130),
#58,#60,0,$,#63,$,#64,#65,$);
#58 = AXIS2_PLACEMENT_3D('Open Pocket',#59,$,$);
#59 = CARTESIAN_POINT('Open Pocket',(45,40,-20));
#60 = PLANE('Open Pocket Elementary Surface',#61);
#61 = AXIS2_PLACEMENT_3D('Open Pocket',#62,$,$);
#62 = CARTESIAN_POINT('Open pocket',(0,0,-10));
#63 = PLANAR_POCKET_BOTTOM_CONDITION();
#64 = TOLERANCED_LENGTH_MEASURE(5,$);
#65 = SQUARE_U_PROFILE($,#66,#69,0,#68,0.);
#66 = TOLERANCED_LENGTH_MEASURE(60.,$);
#67 = TOLERANCED_LENGTH_MEASURE($,$);
#68 = TOLERANCED_LENGTH_MEASURE(5.,$);
#69 = TOLERANCED_LENGTH_MEASURE(5.,$);
#70 = AXIS2_PLACEMENT_3D('Closed Pocket',#71,$,$);
#71 = CARTESIAN_POINT('Closed Pocket',(45,75,-20));
#72 = PLANE('Closed Pocket Elementary Surface',#73);
#73 = AXIS2_PLACEMENT_3D('Closed Pocket',#74,$,$);
#74 = CARTESIAN_POINT('Closed Pocket',(0,0,-5));
#75 = PLANAR_POCKET_BOTTOM_CONDITION();
#77 = RECTANGULAR_CLOSED_PROFILE($,$,$);
#78 = RECTANGULAR_CLOSED_PROFILE($,#79,#80);
#79 = TOLERANCED_LENGTH_MEASURE(10.,$);
#80 = TOLERANCED_LENGTH_MEASURE(20.,$);
#81 = AXIS2_PLACEMENT_3D('Top Hole',#82,$,$);
#82 = CARTESIAN_POINT('Top Hole',(30,40,-20));
#83 = PLANE('Top Hole Elementary Surface',#84);
#84 = AXIS2_PLACEMENT_3D('Top Hole',#85,$,$);
#85 = CARTESIAN_POINT('Top Hole',(0,0,-20));
#86 = TOLERANCED_LENGTH_MEASURE(10.,$);
#87 = THROUGH_BOTTOM_CONDITION();
#88 = AXIS2_PLACEMENT_3D('Bottom Big Hole',#89,$,$);
#89 = CARTESIAN_POINT('Bottom Big Hole',(45,40,-30));
#90 = PLANE('Bottom Big Hole Elementary Surface',#91);
#91 = AXIS2_PLACEMENT_3D('Bottom Big Hole',#92,$,$);
#92 = CARTESIAN_POINT('Bottom Big Hole',(0,0,-10));
#93 = TOLERANCED_LENGTH_MEASURE(10.,$);
#94 = THROUGH_BOTTOM_CONDITION();
#95 = AXIS2_PLACEMENT_3D('Bottom Small Hole',#96,$,$);
#96 = CARTESIAN_POINT('Bottom Small Hole',(45,45,-30));
#97 = PLANE('Bottom Small Hole Elementary Surface',#98);
#98 = AXIS2_PLACEMENT_3D('Bottom Small Hole',#99,$,$);
#99 = CARTESIAN_POINT('Bottom Small Hole',(0,0,-10));
#100 = TOLERANCED_LENGTH_MEASURE(5.,$);
#101 = THROUGH_BOTTOM_CONDITION();
#102 = MACHINING_WORKINGSTEP('Roughing Small Slot',
#103,#3,#107,$);
#103 = PLANE('Main Sec Plane',#104);
#104 = AXIS2_PLACEMENT_3D('sec plane',#105,$,$);
#105 = CARTESIAN_POINT('Sec Plane',(0,0,20));
#107 = BOTTOM_AND_SIDE_ROUGH_MILLING
($,$,'Roughing Small Slot',$,$,#108,#113,#114,$,$,$,$,$,$);
#108 = MILLING_CUTTING_TOOL('Main Cutter',#109,(),$,$,$);
#109 = BULLNOSE_ENDMILL(#110,$,$,$,$);
#110 = MILLING_TOOL_DIMENSION(10.,$,$,$,$,$);
#113 = MILLING_TECHNOLOGY($,CCP,$,$,$,F.,F.,F.,F.);
#114 = MILLING_MACHINE_FUNCTIONS(F.,$,$,$,$,(),F.,$,$,());
#117 = MACHINING_WORKINGSTEP
('Finishing Small Slot',#103,#3,#118,$);
#118 = BOTTOM_AND_SIDE_FINISH_MILLING($,$,
'Finishing Small Slot',$,$,#108,#113,#114,$,$,$,$,$,$);
#119 = MACHINING_WORKINGSTEP('Roughing Big
Slot',#103,#4,#121,$);
#120 = MACHINING_WORKINGSTEP('Finishing Big
Slot',#103,#4,#122,$);
#121 = BOTTOM_AND_SIDE_ROUGH_MILLING
($,$,'Roughing Big Slot',$,$,#108,#113,#114,$,$,$,$,$,$);
#122 = BOTTOM_AND_SIDE_FINISH_MILLING
($,$,'Finishing Big Slot',$,$,#108,#113,#114,$,$,$,$,$,$);
#123 = MACHINING_WORKINGSTEP('Roughing Step',
#103,#48,#125,$);
#124 = MACHINING_WORKINGSTEP('Finishing Step',
#103,#48,#126,$);
#125 = BOTTOM_AND_SIDE_ROUGH_MILLING
($,$,'Roughing Step',$,$,#108,#113,#114,$,$,$,$,$,$);
#126 = BOTTOM_AND_SIDE_FINISH_MILLING
($,$,'Finishing Step',$,$,$,$,$,$,$,$,$,$);
#127 = MACHINING_WORKINGSTEP('Roughing Open Pocket',
#103,#57,#129,$);
#128 = MACHINING_WORKINGSTEP('Finishing Open Pocket',
#103,#57,#130,$);
#129 = BOTTOM_AND_SIDE_ROUGH_MILLING($,$,'Roughing
Open Pocket',$,$,#108,#113,#114,$,$,$,$,$,$);
#130 = BOTTOM_AND_SIDE_FINISH_MILLING($,$,'Finishing
Open Pocket',$,$,#108,#113,#114,$,$,$,$,$,$);
#131 = MACHINING_WORKINGSTEP('Roughing Closed Pocket',
#103,#7,#133,$);
#132 = MACHINING_WORKINGSTEP('Finishing Closed Pocket',
#103,$,#135,$);
#133 = BOTTOM_AND_SIDE_ROUGH_MILLING($,$,'Roughing
Closed Pocket',$,$,#108,#113,#114,$,$,$,$,$,$);
#135 = BOTTOM_AND_SIDE_FINISH_MILLING($,$,'Finishing
Closed Pocket',$,$,#108,#113,#114,$,$,$,$,$,$);
#136 = MACHINING_WORKINGSTEP('Roughing Top
Hole',#103,#8,#138,$);
#137 = MACHINING_WORKINGSTEP('Finishing Top Hole',
#103,#8,#139,$);
#138 = DRILLING($,$,'Drilling Top Hole',$,$,#140,#113,#114,
$,$,$,$,$);
#139 = BORING($,$,'Boring Top Hole',$,$,#143,#113,#114,
$,$,$,$,$,$);
#140 = MILLING_CUTTING_TOOL('Big Drilling Bit',
#141,(),$,$,$);
#141 = CENTER_DRILL(#142,$,$,$);
#142 = MILLING_TOOL_DIMENSION(10.,$,$,$,$,$);
#143 = MILLING_CUTTING_TOOL('Boring Tool',#144,(),$,$,$);
#144 = BORING_TOOL(#145,$,$,$,$);
#145 = MILLING_TOOL_DIMENSION(10.,$,$,$,$,$);
#146 = MACHINING_WORKINGSTEP('Roughing Bottom Big
Hole',#103,#9,#168,$);
#147 = MACHINING_WORKINGSTEP('Finishing Bottom Big
Hole',#103,#9,#148,$);
#148 = REAMING($,$,'Reaming Bottom Big Hole',$,$,#150,#113,
#114,$,$,$,$,$,$);
#150 = MILLING_CUTTING_TOOL('Big Reamer',#151,(),$,$,$);
#151 = REAMER(#152,$,$,$,$);
#152 = MILLING_TOOL_DIMENSION(10.,$,$,$,$,$);
#153 = MACHINING_WORKINGSTEP('Roughing Bottom Small
Hole',#103,#10,#155,$);
#154 = MACHINING_WORKINGSTEP('Finishing Bottom Small
Hole',#103,#10,#160,$);
#155 = DRILLING($,$,'Drilling Bottom Small Hole',
$,$,#157,#113,#114,$,$,$,$,$);
#157 = MILLING_CUTTING_TOOL('Small Drilling bit',
#158,(),$,$,$);
#158 = TWIST_DRILL(#159,$,$,$,$);
#159 = MILLING_TOOL_DIMENSION(5.,$,$,$,$,$);
#174 = ADDRESS('The University of Auckland',
$,$,$,$,$,$,$,$,$);
#173 = PERSON('amok007','Mokhtar','Alireza',$,$,$);
#172 = LOCAL_TIME(4,$,$,$);

```

```

#171 = CALENDAR_DATE(2008,20,7);
#170 = DATE_AND_TIME(#171,#172);
#169 = PERSON_AND_ADDRESS(#173,#174);
#168 = DRILLING($,$,'Drilling Bottom Big Hole',
  $,$,#140,#113,#114,$,$,$,$,$);
#167 = CARTESIAN_POINT('setup',(0,0,0));
#166 = AXIS2_PLACEMENT_3D ('Setup axisplacement',
  #167,$,$);
#165 = WORKPIECE_SETUP(#11,#166,$,$,());
#164 = SETUP('main setup',$,#103,(#165));
#160 = REAMING($,$,'Reaming Bottom Small Hole',
  $,$,#161,#113,#114,$,$,$,$,$,$,$);
#161 = MILLING_CUTTING_TOOL ('Small Reamer',
  #162,(),$,$,$);
#162 = REAMER(#163,$,$,$,$);
#163 = MILLING_TOOL_DIMENSION(5.,$,$,$,$,$);
#175 = MACHINING_WORKINGSTEP
  ('Round Edge Milling',#14,#176,#177,$);
#178 = TOLERANCED_LENGTH_MEASURE(5.,$);
#177 = SIDE_FINISH_MILLING($,$,'Finishing the
  chamfer',$,$,$,$,$,$,$,$,$,$);
#176 = EDGE_ROUND('Transition Feature',
  #11,(),#3,#4,#178,$,$);
#179=MACHINING_HARD_PRECEDENCE(#180,#123,
  $,#127,#131,#136,#146,#153);
#180 = TFA ();
#181 = MACHINING_HARD_PRECEDENCE
  (#182,#127,#136,#137,$);
#182 = HIR ();
#185 = MACHINING_HARD_PRECEDENCE
  (#186,#175,#117,#120,$); #186 = TFE ();
#188 = MACHINING_SOFT_PRECEDENCE
  (#189,#127,$,#131); #189 = SAC ();
#190 = MACHINING_SOFT_PRECEDENCE
  (#191,#119,$,#116); #191 = ICF ();
#192 = MACHINING_SOFT_PRECEDENCE
  (#193,#146,#153,#154,$); #193 = HHI ();
#195 = MACHINING_SOFT_PRECEDENCE
  (#196,#128,$,#147,#154);
#196 = HDB ();
#197 = MACHINING_SOFT_PRECEDENCE
  (#198,#124,#127,#131,$);
#198 = UFC ();
#199 = MACHINING_SOFT_PRECEDENCE
  (#198,#119,$,#117,#124);
#200 = MACHINING_SOFT_PRECEDENCE
  (#198,#120,#116,#123,$);
#201 = MACHINING_SOFT_PRECEDENCE
  (#198,#127,$,#132);
#202 = MACHINING_SOFT_PRECEDENCE
  (#198,#128,#131,$);
ENDSEC;
END-ISO-10303-21;

```

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