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# Operation sequencing in an automated process planning system

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One of the most difficult tasks we face in automated process planning is determination of operation sequencing. In this paper we present an approach to automatic generation of machining sequences in an object-oriented automated process planning system. Sequencing of machining operations is carried out in three phases of planning: initial planning, set-up planning, and final planning. The initial planning generates general plans including the required operations and machine cells. Two types of information are used at this stage, manufacturing process knowledge and component information, including features and associated dimensions, tolerances, surface finish, and material conditions. Based on process requirements decided in the initial planning, the set-up planning selects machines and fixtures, decides the clamping surfaces and feature accessibility, and sequences the set-ups. The final planning determines all the detailed sequences of operations based on the set-ups using the built-in manufacturing logic and heuristics. We introduce the set-up planning, the core of the planning system, to link the part model, initial planning and final detailed planning. The strategy has been implemented in an object-oriented process planning system. An example is provided to demonstrate the approach.

*Keywords:* Operation sequencing, automated process planning, object-oriented paradigm

## 1. Introduction

Automated process planning is one of the major obstacles to achieving CAD/CAM integration and automation in a CIM environment. In the last two decades, numerous research efforts have been made in this area, and a number of process planning systems have been developed; however, most of the systems that have been introduced to industry required much human assistance during planning. To automate process planning, several outstanding issues have to be addressed, including direct interfaces between process planning and CAD systems, automatic generation of machining operation sequence, alternative process plans, plan evaluation and modification, and replanning. This paper addresses the automatic generation of machining sequences in generative process planning. Sequencing of machining operation is affected by several factors including machines, tools, fixtures, part geometry, surface finish, tolerances, heat treatment, and the like. Each of these factors imposes a set of specific constraints on the sequencing of machining operations and some of the constraints may conflict with the others. This further complicates automatic determination of machining sequences.

Two main approaches have been used in process planning: the variant approach and the generative approach. Most of the early developed computer-aided process planning systems are considered as variant systems. They plan machining processes for newly designed parts by retrieving standard process plans from databases based on group technology coding systems, and then human users modify the retrieved plans for the new parts. Although these systems can assist human planners in process planning, they have no power to achieve automatic generation of machining operation sequences.

Systems that could automatically generate machining operations and sequences are called generative process planning systems. Instead of retrieving standard plans, generative process planning systems create process plans for new parts based on built-in manufacturing knowledge

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and algorithms. In theory, generative process planning systems can plan any components as long as they can be described using design elements provided by the planning systems. In order to do so, a low-level geometric description of parts, such as primitives or features, must be used. These form elements, and associated machines, tools, and fixtures are defined and included in the databases. In combination with other knowledge and algorithms, generative systems can generate required process plans including operation sequences. Several such systems can be found in the references: AUTAP (Eversheim and Fuchs, 1980), AUTOPLAN (Vogel and Adlard, 1981), TIPPS (Chang and Wysk, 1983). However, due to complexity of the part design and planning decision-making procedures, the generative approach is still in its early stages of development.

More recently, artificial intelligence has been introduced into the field of process planning to improve planning efficiency and effectiveness. TOM is a rule-based system for machining process planning of holes (Matsushima *et al.*, 1982). Iwata (1987) reported knowledge-based process planning issues in an intelligent manufacturing system. GARI is also an AI-based process planning system. It generates process plans based on part features (Descotte and Latombe, 1984). Van't Erve and Kals (1986a and 1986b) reported development of a knowledge-based generative process planning system named XPLANE. The XPLANE possesses functions including selection of fixtures and jigs, NC programming, tool management and capacity planning. EXCAP is an expert system for planning rotational parts (Wright *et al.*, 1987). TURBO-CAPP is a PC-based expert system, and consists of several modules for manufacturing features identification, knowledge base, machine selection and sequencing, NC program generation, knowledge acquisition and database management (Wang and Wysk, 1987). Core-CAPP is a semi-generative system for a particular company specializing in the manufacture of large forged metal products. Kusiak (1990) developed models of generative process planning using the knowledge-based approach and optimization techniques.

Process planning has long been recognized as a direct link between CAD and CAM. To achieve this link, direct interfacing of process planning and commercial CAD systems is a crucial issue. Joshi and Chang (1987) have developed an interface for the integration of a B-rep-based solid modeller and automated process planning system. The product modelling approach proposed by Kimura *et al.* (1984) and Inui *et al.* (1987) is used to integrate design and various manufacturing activities. To integrate CAD/CAPP/CAM, a part spectrum database has been developed (Peklenik *et al.*, 1985; Peklenik and Sekolonik, 1990). Very comprehensive surveys of process planning can be found in Ham and Lu (1988) and Alting and Zhang (1989).

Although many approaches have been developed and adopted in generative process planning to achieve different degrees of process planning automation, we still need an adequate strategy for automatically sequencing machining operations. A common approach to the sequencing problem is to use features: therefore, planning is conducted for individual geometric entities. The generated operation plans for individual features or surfaces are then sequenced by some systems based on simple heuristics. Obviously, for parts with very few features and simple geometry such an approach may be feasible. When part structure and geometry are complex, process plans generated in this way are neither efficient nor practical. This paper presents a new approach to the automatic generation of the machining operation sequence for a generative process planning system in a cellular manufacturing environment. This approach as part of an automated process planning system has been implemented in Smalltalk, an object-oriented programming language. The paper is organized as follows: first we briefly discuss the approach and the entire object-oriented process planning system, and then concentrate on detailed planning and sequencing. Finally, we use an example for further explanation of the approach and the process planning system.

## 2. Description of the approach

To generate machining operation sequences automatically in a cellular manufacturing system, the following planning activities are needed: selection of operations based on part design, selection of machines, determination of machine cells, selection of fixtures, determination of part set-ups on the chosen fixtures and machines, selection of cutting tools, calculation of detailed machining parameters. Two criteria are used for the determination of detailed machining operations and their sequences: the minimal transportation of parts between and within cells and the minimal set-ups and tool changes. Based on these criteria, process planning activities are divided into three phases: the initial planning phase, the set-up planning phase, and the final planning phase. In the initial planning phase, machining operations are selected for machining a given part and the part is assigned to a specific cell that can provide all the needed machining operations. If no single cell can satisfy the requirement, the part will be assigned to two or more cells. In the set-up planning phase, the minimal set-ups on the machines in the chosen cell(s) are selected and sequenced. These set-ups should allow all the required machining operations to be carried out. In the final planning phase, details of each machining operation that should be carried out at each set-up are determined and these machining operations are carefully sequenced.

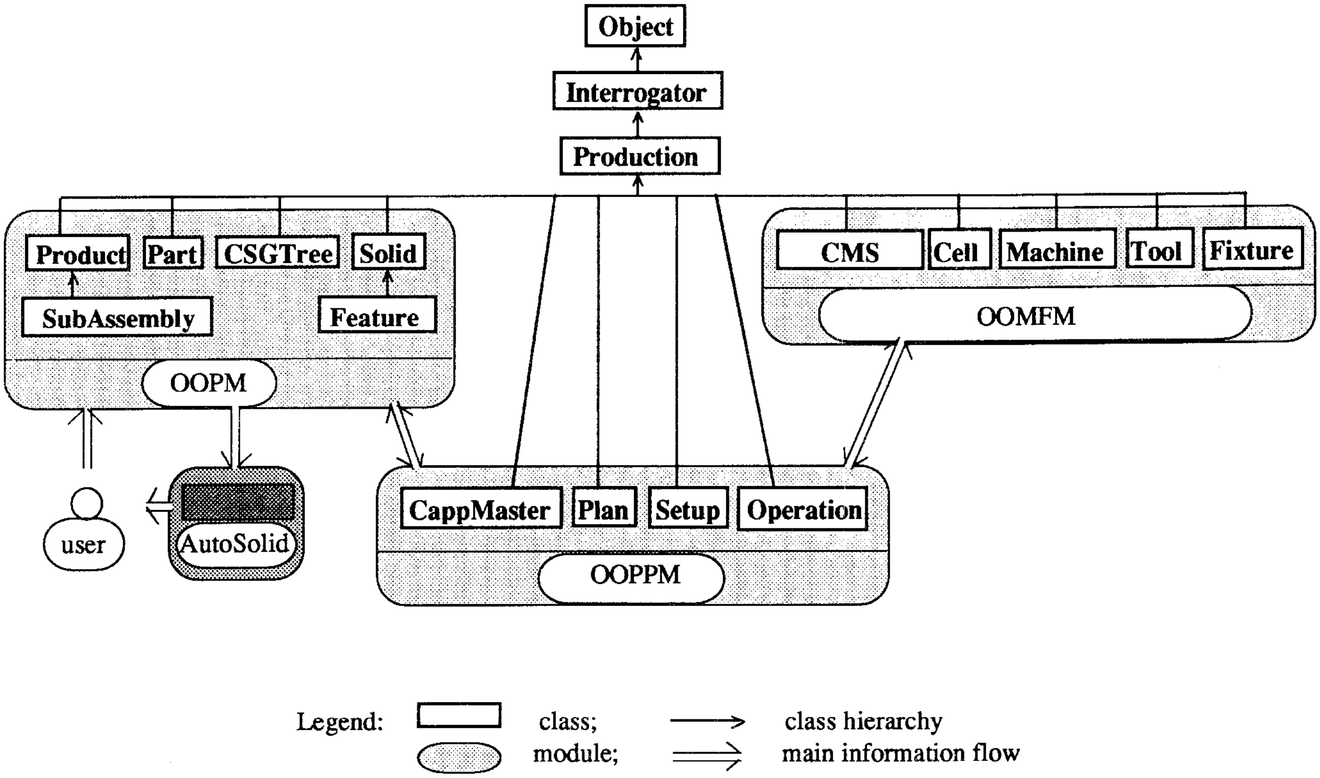

**Fig. 1.** Architecture of object-oriented process planning system (OOPPS).

Compared with most other approaches to the sequencing problem, this approach introduces set-up planning as the core of operation sequencing because each machining operation is associated with a set-up. In turn, the set-ups are linked to fixtures and machines. Once a part's set-up on a fixture is known, the part's feature accessibility can be determined. When the accessible features are identified, detailed operations and their sequencing can be planned. This approach has been implemented in an object-oriented process planning system (OOPPS). In order to explain how the approach works, the entire process planning system is briefly discussed in the following section.

## 3. Object-oriented process planning system (OOPPS)

An object-oriented process planning system (OOPPS) is designed as a pure object-oriented system for achieving process planning automation in a cellular manufacturing environment. In this system, all entities involved in process planning, such as parts, machines, tools, fixtures and process plans, are represented by objects. The OOPPS captures complete information about parts design and the existing cellular manufacturing facilities, and distributes the information into the corresponding object models. It also distributes well-organized knowledge on various process planning tasks to related object models. By appropriately arranging message-sending sequences among these object models, which follow process planning logic, all workable process plans for a given part can be generated by the OOPPS without human assistance.

### 3.1. *Architecture of the OOPPS*

The system architecture of the OOPPS is shown in Fig. 1 and the system consists of three modellers, an object-oriented product modeller (OOPM), an object-oriented manufacturing facility modeller (OOMFM) and an object-oriented process plan modeller (OOPPM). Their functions are to generate models that represent respectively three kinds of entities involved in process planning: parts, manufacturing facilities and process plans. Initially, a user models products and/or parts using the OOPM through a user interface, and analyses the design using Autosolid (a solid modeller). Once the design is satisfactory, the OOPPM creates process plans for the part. In order to generate valid and feasible process plans, the dynamic changes of facilities in workshops need to be modelled. The OOMFM can keep the cellular manufacturing environment updated by indicating the machine status. For example, tools unavailable or machine breakdown can be reflected in the model immediately. Thus, the OOPPM always generates workable process plans. This paper deals with automatic generation of machining sequences; therefore, only the process planning modeller is discussed. Detailed discussion on the other two modellers can be found in Zhang *et al.* (1992).

## 4. The object-oriented process plan modeller

### 4.1. *Process plan model*

Generally, a part is manufactured by sequenced machining operations such as drilling, boring or milling. These operations are usually associated with set-ups on one or more machines. A new process plan format has been developed which has a two-level hierarchy. At the first level, a process plan contains one or a series of sequenced set-ups on one or several machines. At the second level, corresponding to each of these sequenced set-ups, sequenced machining operations with detailed tool requirements and cutting parameters are provided. The process plan representation in the OOPPS is an object-oriented process plan model with two kinds of object: the set-up object and the operation object. The set-up object captures information about a part's set-up on a machine, including machines and fixtures used, part set-up direction, clamping surfaces, features to be machined in this set-up, and machining operations that are required by these features and can be carried out by the machine. The operation object, on the other hand, provides detailed information about a machining operation such as operation type, tool, cutting parameters, and feature(s) to which this operation is applied. Using this structure, an object-oriented process plan model can completely represent complex yet detailed process plans.

### 4.2. *The object-oriented process planning modeller (OOPPM)*

The OOPPM is a generative process planner that directly creates a process plan from an object-oriented part model. Its architecture is shown in Fig. 2. The system consists of several planning stages associated with the three phases of planning: the initial planning, the set-up planning, and the final planning. Planning activities at the initial planning stage include determination of machining operations based on design requirements of a part, and selection of machine cells based on the selected machining operations and part design. The set-up planning selects machines and fixtures for carrying out the operations. Once the fixture and part geometry are known, the clamping surfaces of the part can be decided. When the part is clamped in a fixture, only certain features are accessible at this orientation, and consequently these features can be machined in this set-up. Therefore, feature accessibility is examined to identify all the accessible features for further planning. Then set-ups are selected and sequenced. The result of the set-up planning includes all the necessary set-ups and their sequences. The final planning determines cutting tools and detailed cutting parameters, and synthesizes and sequences the entire plan. Thus, the OOPPM generates process plans based on object-oriented part models created by the OOPM and constraints imposed by the capabilities of the manufacturing facilities represented by an OOMFM model.

## 5. Automatic sequencing in the OOPPS

### 5.1. *Initial planning*

The goal of initial planning is generally to match a part's design requirements with the capabilities of manufacturing facilities. Two tasks need to be accomplished at this stage. The first task is selection of machining operations for a part according to its design requirements. The second is to select machine cells that can provide all the required machining operations.

Selection of machining operations requires two kinds of knowledge: machining process knowledge and operation selection knowledge. There are many kinds of machining process used in manufacturing industry, each of which can produce certain types of surface at a certain performance level. Detailed knowledge about these machining processes has been accumulated by researchers through decades of effort, and is available in handbooks and related literature. Operation selection knowledge that is concerned with generating the required surfaces economically is also available in the literature. To be used effectively, however, this knowledge should be synthesized and integrated with the process planning system in an appropriate way. Previous researches have shown that expert systems are suitable for this task. Therefore, in the OOPPS, these two types of knowledge have been built into an object-oriented expert system that is created using HUMBLE (Piersol, 1987), an object-oriented expert system builder in a Smalltalk-80 environment. This expert system can freely exchange information with an OOPM part model, and can select proper machining operation plans for part features based on the built-in knowledge rules. An example of such rules is partially listed in Fig. 3, which shows that the expert system can generate alternative operation plans for features and how the machining operations involved in each operation plan are initially sequenced. After all the suitable operation plans have been selected for each feature of the part, several alternative general plans can be drawn out for the part's manufacture. Each of these plans contains only one operation plan for each

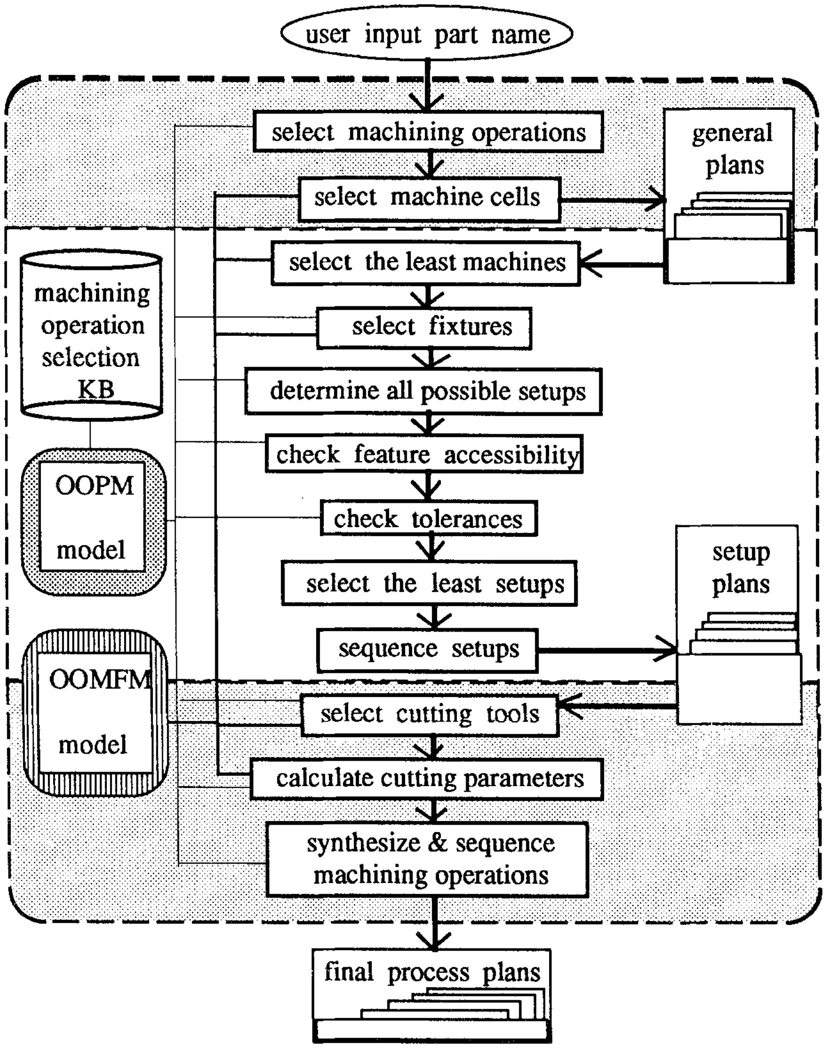

**Fig. 2.** Architecture of object-oriented process plan modeller (OOPPM).

feature. Next, for each general plan, the OOMFM model of manufacturing facilities is searched to find the minimal cells that can provide all the machining operations listed in the general plan. These cells are then included in the general plan. If a general plan contains some machining operations that cannot be provided by any machine in the system, this general plan is abandoned.

### 5.2. *Set-up planning*

Set-up planning is conducted for each general plan. Its task is to find the minimal number of set-ups of the part on the minimal number of machines in the selected cell(s) to reduce the part's in-cell transportation and set-up changes. Set-up planning in the OOPPS involves the following steps.

#### 5.2.1. *Step 1: machine selection*

All machines in a selected cell(s) are examined to find the machine that can provide the most machining operations required by the part. If the selected machine cannot cover all the required machining operations, the remainder of the machines are checked again to find another one that can provide most of the remaining operations. This machine is queued after the previously selected machine. This procedure is repeated until a minimal number of machines are selected to provide all the required machining operations. Now each of the selected machines is associated with a specific set of machining operations required by a group of features of the part.

#### 5.2.2. *Step 2: selection of fixtures*

For each of the selected machines, the most suitable fixture for the part is selected according to the part's

```
operationsOfBore

if: ( feature = 'bore' )
then: [if: ( diameter > 2.0 )
        then:
        [if: ( partCode = 'S1' )
         then:[...].
         if: ( partCode = 'B2' )
         then:
          [if: isThroughBore
           then:
              [if: (diaTolerance >= 0.008 & ( surfaceFinish > 125))
              then: [if: (diameter <= 4.0)
                  then: [operation nowIncludes: 'drill-spadeDrill-'
                                          withCertainty: 0.9].
                  operation nowIncludes: 'drill-roughMill-'
                                         withCertainty: 0.9.
                  ].
              if: (diaTolerance < 0.008 & (diaTolerance >= 0.004)) &
                      (surfaceFinish <= 125 & (surfaceFinish > 63))
              then:
               [if: (diameter <= 4.0)
               then:
               [operation nowIncludes: 'drill-spadeDrill-roughReam-
                                   finishReam-' withCertainty: 0.9.
                operation nowIncludes: 'drill-roughMill-roughReam-

            ......

             [if: (diameter <= 4.0)
             then: [operation nowIncludes: 'drill-spadeDrill-
                           roughGrind-grind-' withCertainty: 0.9].
              operation nowIncludes: 'drill-roughMill-
                           semiFinishMill-finishMill-grind-'
                                      withCertainty: 0.9.
             operation nowIncludes: 'drill-roughMill-roughGrind-
                                grind-' withCertainty: 0.8
             ].
             ]
      else: [...].
      if: ( diameter <= 2.0 )
      then:[...].
      ]
```

**Fig. 3.** Sample rules for generating operations (in Smalltalk).

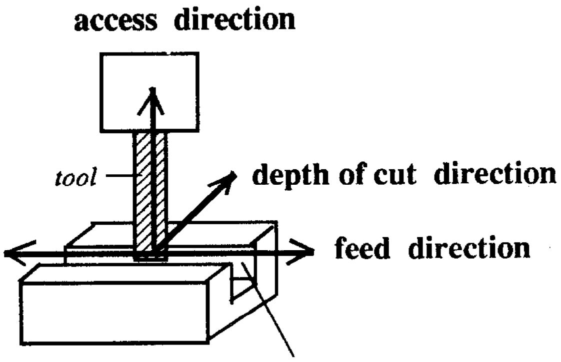

**Fig. 4.** Three auxiliary directions.

type, geometry, dimensions, and required machining operation, and the capabilities of available fixtures on the machine. Normally, a machine has several fixtures each of which is defined in terms of classes of parts. Fixture selection is a pattern-matching process. Each part in the product model is assigned a classification code that indicates part class including overall geometry and dimensions. Knowledge regarding fixture selection is coded in the planning system. In this implementation, only a vice is considered available on a CNC milling machine for block-type components. If the dimensions of a component exceed the holding range of the vice, it is clamped directly on the machine table.

### 5.2.3. *Step 3: determination of clamping surfaces*

Once a fixture is chosen, all possible set-ups of the part on the selected fixture are generated. For a block-type part to be held in a wrench, each set-up is defined by a set-up direction, a pair of clamping surfaces and clamping locations. When determining the clamping surfaces, the concerns are that the part will be held securely by the fixture (i.e. enough clamping force against the cutting force and vibrations), and that most of the features will be accessible by the cutting tools.

### 5.2.4. *Step 4: determination of feature accessibility*

For each possible set-up, the part's features that can be machined in this set-up are determined based on two criteria: (1) that the feature is accessible by the cutting tool in the set-up; (2) that the feature does not have geometric tolerances relating to datum features that are inaccessible in this set-up. The first criterion calls for a feature accessibility check. In the OOPPS, each feature is automatically assigned three auxiliary directions by the OOPM. These directions are called access direction, depth-of-cut direction and feed direction, respectively (see Fig. 4). Access direction is the direction along which a cutter can reach this feature. Depth-of-cut direction is the direction along which depth of cut is defined. Feed direction represents required cutter feeding direction during the machining process. These directions are defined. by the OOPM for each feature based on its orientation and related manufacturing knowledge. With the help of the auxiliary directions, the accessibility of each feature can be determined according to the feature's type and orientation in the current set-up. To satisfy the second criterion, both feature accessibility and tolerances need to be examined. The feature accessibility check has been discussed. Once the feature accessibility is decided, the tolerance check is straightforward for the involved features because each feature object in an OOPM part model contains complete information about its tolerance requirements. There is an exceptional case: if features have geometric tolerances relating to unaccessible datum features, but can be accessible only at this set-up, then the features are considered as accessible and data are changed to satisfy the original tolerance requirements.

### 5.2.5. *Step 5: set-up selection*

On each selected machine, the set-up is selected based on the criterion that it is the one in which the most features can be machined. If there are still features remaining after this set-up, a search is conducted again in the remaining set-ups. This recursive process is repeated until all the features can be machined on the chosen set-ups. These selected set-ups constitute the lowest number of set-ups required on the machine.

### 5.2.6. *Step 6: sequencing of set-ups*

In this step, sequencing of the set-ups on each selected machine is carried out. The first set-up is chosen as the one on which the most features can be machined. If there are more than two set-ups remaining, the second should be the set-up whose clamping surfaces have been machined in the first set-up. The rest, if any, are sequenced according to the number of features to be machined, from the maximum to the minimum.

After going through these six steps, the lowest number of set-ups on the minimal number of machines are generated and sequenced.

### 5.3. *Final planning*

In the generated set-up plans, each set-up is associated with a set of features to be machined; each of these features is related to an initial operation plan generated by the operation selection expert system. The tasks of the final planning include selecting cutting tools and cutting parameters for each machining operation required in each set-up, and synthesizing and sequencing all the machining operations from the set-up's perspective. Cutting tool selection knowledge is built into the OOPPS as object methods (Goldberg and Robson, 1983). Selection of cutting parameters is based on empirical expanded Taylor tool-life equations.

When all the machining operations are fully defined, their synthesis and final sequencing is carried out, based on related manufacturing logic and minimal tool changes. Two general types of manufacturing logic are given below:

(1) External surface machining first, internal surface machining second;

(2) Rough machining first, semi-finish second and finish machining last.

For prismatic components, sequencing of machining operations is carried out according to the following priority order:

(i) rough machining of external surfaces from top to bottom along the set-up direction;

(ii) semi-finish machining of external surfaces from top to bottom along the set-up direction;

(iii) rough machining of internal surfaces from top to bottom along the set-up direction with following sub-priority order:

  (a) drilling;
  (b) rough milling (boring);

(iv) semi-finish machining of internal surfaces from top to bottom along the set-up direction in the following sub-priority order:

  (a) spade drilling;
  (b) semi-finish milling;
  (c) semi-finish reaming;
  (d) counter-boring;

(v) finish machining of internal surfaces from top to bottom along the set-up direction in the following sub-priority order:

  (a) finish milling;
  (b) finish reaming;

(vi) chamfering;

(vii) tapping.

## 6. An example

A prismatic part example is shown in Fig. 5. A partial object-oriented design model of the part is given in Fig. 6. The part consists of 31 features. The blank material for making the part is a block with dimensions $4.8 \times 6.8 \times 2.55$ in. The manufacturing system consists of two cells, one for rotational parts, and the other for non-rotational parts. The initial planning, by sending a message to the model, identifies all features of the part, and generates all possible manufacturing operations for the features. These operations include rough, semi-finish and finish operations, and alternative processes that will be used to generate alternative process plans. For this example, the required operations include milling, drilling, reaming, chamfering and taping. Based on these required operations and the part's general dimensions, the most appropriate machine cell is chosen for manufacturing the part. The criterion for selecting machine cells is to find the least cells that can provide all the required operations. Since the planned operations can be done on a CNC milling machine and a grinding machine, the non-rotational parts cell containing the milling machine and the grinding machine was chosen for this example (Fig. 7). Two general plans were created at this stage because of the presence of alternative operation plans for each feature.

At the set-up planning stages, several planning tasks need to be accomplished. For each generated general plan, machines available in the chosen cell are selected

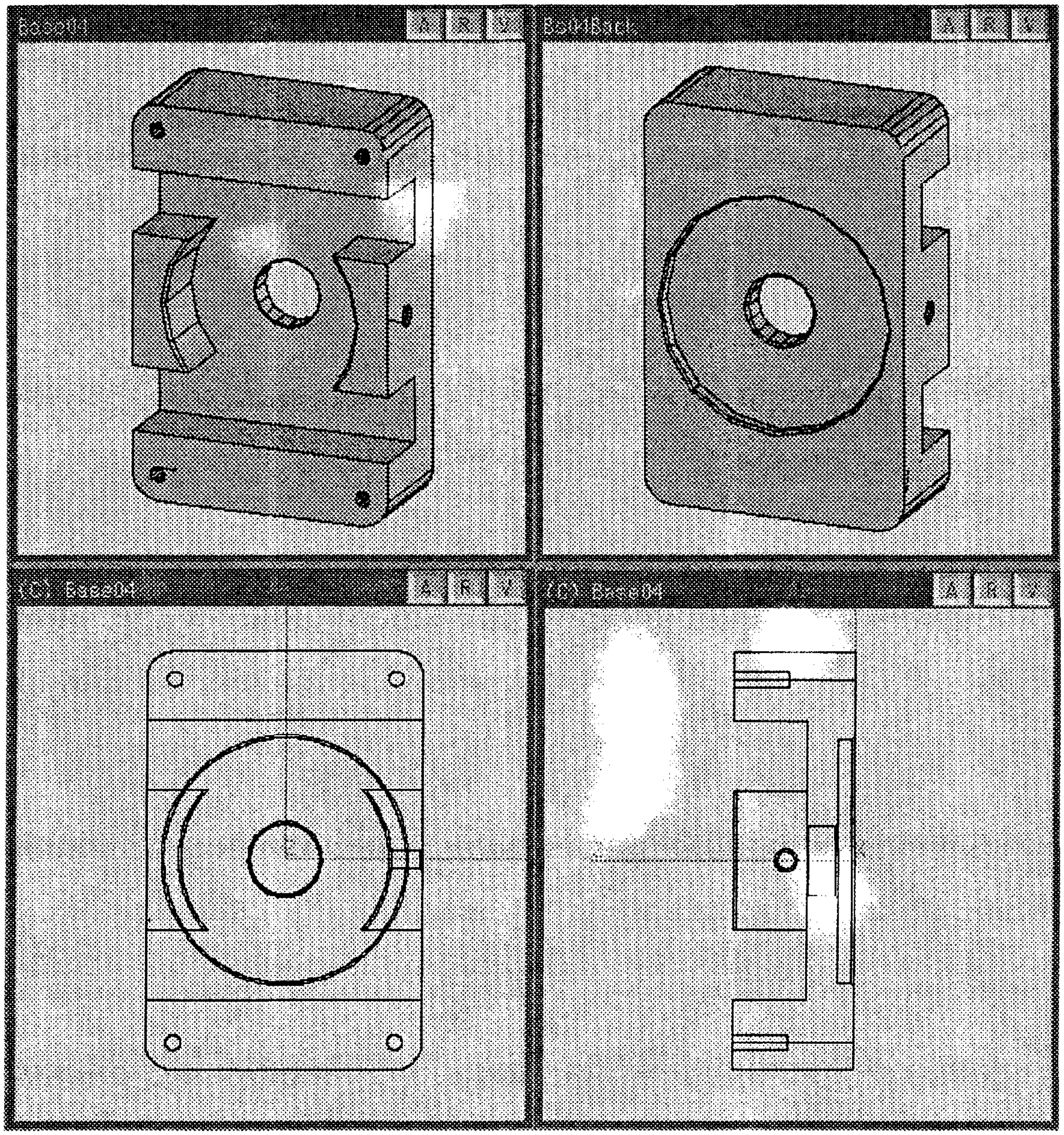

**Fig. 5.** An example part named Base04.

for carrying out the planned operations. The grinding machine was used only to finish the hole grinding finally with tight tolerances and most of the machining operations were done on the milling machine. The fixture selection for the milling machine is a pattern-matching process based on part geometry and dimensions. The part blank material is in a block shape and, therefore, a wrench was selected. In general, a block has three pairs of possible clamping surfaces each of which has four possible set-up directions; therefore, the total 12 possible set-ups were generated (Fig. 8). For this example, the part had 12 possible set-ups. For each possible set-up, the feature accessibility was examined to find the number of features to be machined on this set-up. The first set-up was chosen as that on which the maximal number of features could be machined (Fig. 9, see set-up I). The operations that could be completed on this set-up included face milling, courter milling, drilling, bore milling, slots milling, chamfering and tapping. Since some features were not accessible in this set-up, the second set-up was selected, based on the criteria mentioned earlier, that the clamping surfaces have been machined at the first set-up, and the maximal remaining features could be manufactured (see set-up II). On the second set-up, the face milling, drilling and boring were planned. The third set-up was also selected, based on the above

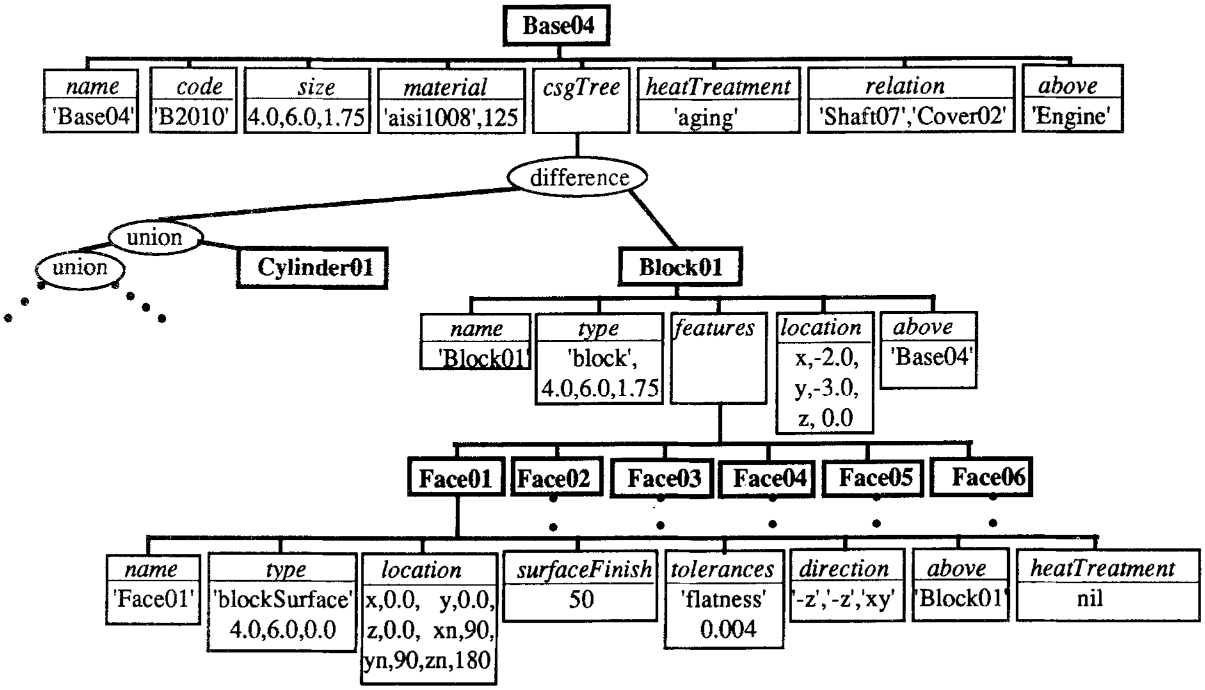

**Fig. 6.** The OOPM model of the part Base04 shown in Fig. 5.

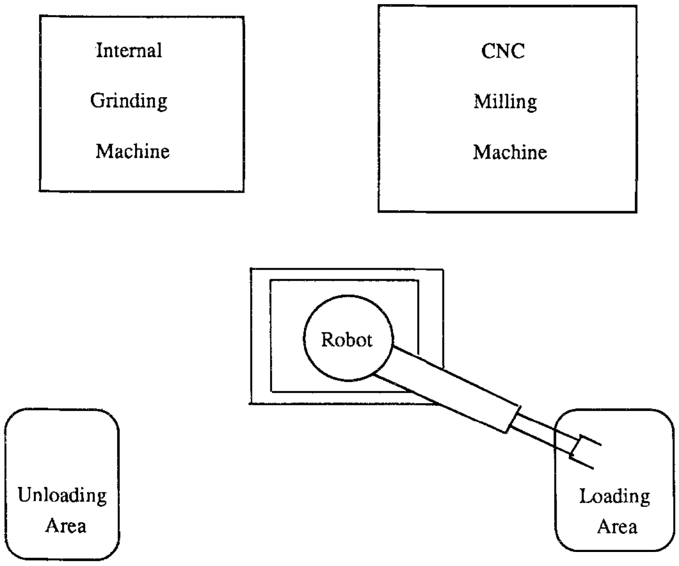

**Fig. 7.** Machine cell for non-rotational parts.

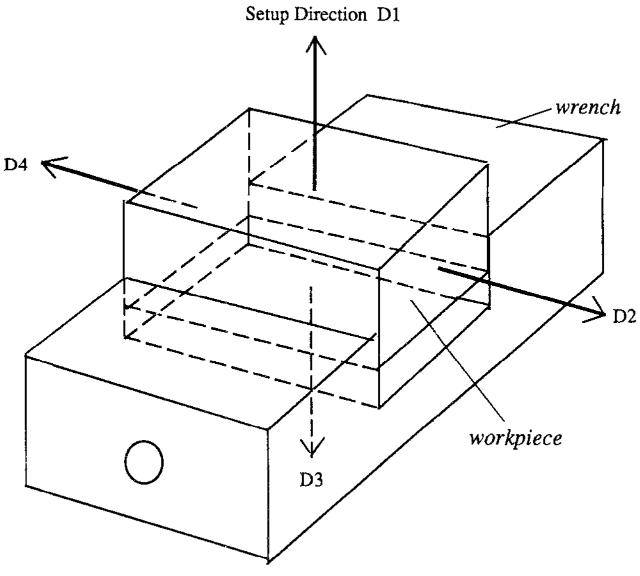

**Fig. 8.** Possible set-up directions.

criteria, for processing the remaining features (see set-up III). The final set-up was on the grinding machine for finishing the bore with the tight tolerance (see set-up IV). This completed the set-up planning. For each set-up the final planning started by selecting cutting tools for each operation on the set-up. The first operation on set-up I was face milling, shown in Fig. 9 (set-up I); the stub end mill was chosen with dimensions of diameter 2 in and length 0.74 in; and operation parameters were then calculated using an expanded Taylor tool-life equation. Finally, all the operations were synthesized and sequenced based on manufacturing logic such as rough–semi-finish–finish, and the minimal tool change criterion. Thus for each type operation, the features using the same

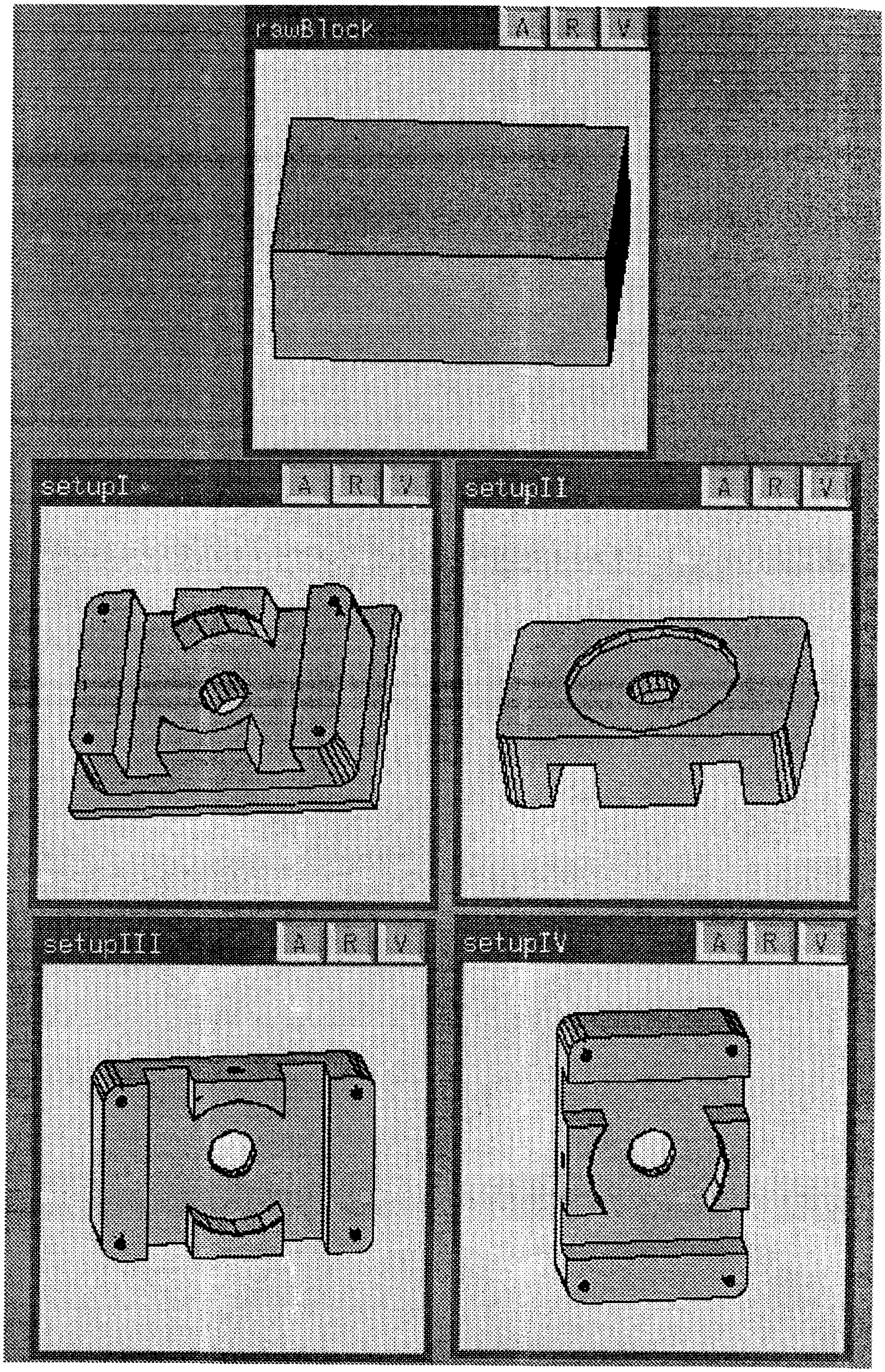

**Fig. 9.** Planned set-ups of the part Base04 shown in Fig. 5.

**Table 1.** Process plan one for part Base04

*Part name: Base04*
*Workpiece material: aisi1008* *Plan Series no: 1*

| *Set-up* | *Operation* | | *Type* | *Feature* | | *Tool* | *Fixture* | *Machine* | *Cell* |
|---|---|---|---|---|---|---|---|---|---|
| *no.* | *no.* | *Type* | | *no.* | *Identifier* | *code* | *code* | *code* | *code* |
| 1*† | | | | | | | Wrch001 | MT001 | Cell02 |
| | 1 | roughMill | blockSurface | 1 | Face202 | T023 | | | |
| | 2 | roughMill | roundedCorner<br>blockSurface | 4<br>4 | Face205<br>Round201<br>Face203<br>Round202<br>Face206<br>Round203<br>Face204<br>Round204 | T016 | | | |
| | 3 | semiFinishMill | blockSurface | 1 | Face202 | T023 | | | |
| | 4 | semiFinishMill | blockSurface | 2 | Face203<br>Face204 | T016 | | | |
| | 5 | drill | bore | 1 | Bore201 | T008 | | | |
| | 6 | drill | bore | 1 | Bore202 | T007 | | | |
| | 7 | roughMill | bore | 1 | Bore201 | T016 | | | |
| | 8 | chamferMill | chamfer | 2 | Chamfer201<br>Chamfer202 | T001 | | | |
| | 9 | roughMill | slotSide<br>slotBottom | 2<br>1 | Face210<br>Face211<br>Face212 | T018 | | | |
| | 10 | roughMill | slotSide<br>slotBottom | 2<br>1 | Face207<br>Face208<br>Face209 | T018 | | | |
| | 11 | semiFinishMill | slotSide | 2 | Face210<br>Face211 | T017 | | | |
| | 12 | semiFinishMill | slotSide | 2 | Face207<br>Face208 | T017 | | | |
| | 13 | drill | femaleScrew | 4 | Screw204<br>Screw202<br>Screw201<br>Screw203 | T006 | | | |
| | 14 | tap | femaleScrew | 4 | Screw204<br>Screw202<br>Screw201<br>Screw203 | T014 | | | |

**Table 1.** *contd.*

*Part name: Base04*
*Workpiece material: aisi1008* *Plan Series no: 1*

| *Set-up* | *Operation* | | *Type* | *Feature* | | *Tool* | *Fixture* | *Machine* | *Cell* |
|---|---|---|---|---|---|---|---|---|---|
| *no.* | *no.* | *Type* | | *no.* | *Identifier* | *code* | *code* | *code* | *code* |
| | 15 | finishMill | blockSurface | 1 | | T023 | | | |
| | | | | | Face202 | | | | |
| | 16 | finishMill | blockSurface | 2 | | T016 | | | |
| | | | | | Face203 | | | | |
| | | | | | Face204 | | | | |
| **2** | | | | | | | Wrch001 | MT001 | Cell02 |
| | 1 | roughMill | blockSurface | 1 | | T023 | | | |
| | | | | | Face201 | | | | |
| | 2 | semiFinishMill | blockSurface | 1 | | T023 | | | |
| | | | | | Face201 | | | | |
| | 3 | drill | bore | 1 | | T008 | | | |
| | | | | | Bore203 | | | | |
| | 4 | roughMill | boreEnd | 1 | | T016 | | | |
| | | | bore | 1 | | | | | |
| | | | | | Bore203 | | | | |
| | | | | | Face214 | | | | |
| | 5 | semiFinishMill | boreEnd | 1 | | T018 | | | |
| | | | bore | 1 | | | | | |
| | | | | | Bore203 | | | | |
| | | | | | Face214 | | | | |
| | 6 | finishMill | bore | 1 | | T018 | | | |
| | | | | | Bore203 | | | | |
| | 7 | roughReam | bore | 1 | | T015 | | | |
| | | | | | Bore202 | | | | |
| | 8 | finishReam | bore | 1 | | T012 | | | |
| | | | | | Bore202 | | | | |
| | 9 | chamferMill | chamfer | 2 | | T001 | | | |
| | | | | | Chamfer203 | | | | |
| | | | | | Chamfer204 | | | | |
| | 10 | finishMill | blockSurface | 1 | | T023 | | | |
| | | | | | Face201 | | | | |
| **3** | | | | | | | Wrch001 | MT001 | Cell02 |
| | 1 | drill | bore | 1 | | T004 | | | |
| | | | | | Bore204 | | | | |
| | 2 | spotDrill | chamfer | 1 | | T010 | | | |
| | | | | | Chamfer205 | | | | |
| **4** | | | | | | | Chuck010 | MT003 | Cell02 |
| | 1 | grind | bore | 1 | | T051 | | | |
| | | | | | Bore202 | | | | |

*Details of set-up 1 are shown in Table 2, as an example of set-ups.

†Details of operation 1 on set-up 1 are shown in Table 3, as an example of operations.

**Table 2.** Set-up 1 in process plan 1

*Part name: Base04*
*Workpiece material: aisi1008* *Plan series no: 1*

Set-up No. **1**

*Cell code*: Cell02
*Machine*:
  code: MT001
  name: MATSUURA MC760V
  type: VMC
*Fixture code*: Wrch001
*Clamping surfaces*: Face205 Face206
*Setup direction*: +z
*Required operations*:
Chamfer201->’chamferMill-’
Screw204->’drill-tap-’
Round201->’roughMill-’
Screw201->’drill-tap-’
Screw202->’drill-tap-’
Round203->’roughMill-’
Round202->’roughMill-’
Face210->’roughMill-semiFinishMill-’
Face211->’roughMill-semiFinishMill-’
Face212->’roughMill-’
Round204->’roughMill-’
Face207->’roughMill-semiFinishMill-’
Face202->’roughMill-semiFinishMill-finishMill-’
Face208->’roughMill-semiFinishMill-’
Face203->’roughMill-semiFinishMill-finishMill-’
Screw203->’drill-tap-’
Face209->’roughMill-’
Chamfer202->’chamferMill-’
Bore201->’drill-roughMill-’
Face204->’roughMill-semiFinishMill-finishMill-’
Face205->’roughMill-’
Face213->’roughMill-’
Face206->’roughMill-’
Bore202->’drill-’

**Table 3.** Operation 1 in set-up 1

*Part name: Base04*
*Plan series no: 1* *Set-up no:* **1**

*Operation No. 1*

*Operation type*: roughMill
*Tool*:
  code: T023
  name: stubEndMill
  material: HSS
  size: D2.0 × L0.75 (in)
*Cutting parameters*:
  depth of cut: 0.34 in
  feed rate: 0.0015748 in/tooth
  cutting speed: 92.7638 fpm
*Features to be machined*:
  Face202 (blockSurface)

tools were grouped and their sequences were finally decided. The entire plan is shown in Tables 1–3.

## 7. Discussions and conclusions

Automatic generation of machining sequence is one of the key issues in automated process planning. In some generative process planning systems reported in the literature, the complexity behind the automation of sequencing was avoided by restricting the features and part geometry, or by introducing human assistance. In this research, the automatic generation of the machining sequence is embedded in the process planning activities. The set-up planning is used to link the process and machine selection, feature accessibility examination, and cutting tool selection that have a definite influence on the sequencing of machining operations. In addition, an approach to generative process planning is also presented using an object-oriented system. A prototype of such an object-oriented process planning system for cellular manufacturing systems has been developed. This system integrates complete information and associated knowledge about all three aspects of process planning, the part model, the manufacturing facility model and the process plan model. Such uniform object orientation throughout the system significantly enhances information exchange between involved objects and makes the system highly integrated. Although the methodology reported in this paper seems feasible, however, there are still many technical details to be considered in our future research, some of which are under consideration, including detailed calculations of clamping locations in the set-up planning, low-level tool path generation and optimization, and design representation using PDES/STEP for the process planning.

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