IPPS: AN INTEGRATED PROCESS PLANNING PROJECT

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ABSTRACT: The past two decades have witnessed the development of many CAPP (Computer-Aided Process Planning) systems. From variant process planning to generative process planning, great progress has been made. However, due to the complexity of the problems involved, there is still not a truly generative process planning solution. Further, to make a generative system truly useful in production, the issue of integration must be addressed. In this paper, we introduce an integrated process planning project (IPPS), which is currently underway in the Department of Industrial Engineering, Texas Tech University. Besides the general description of IPPS, we focus our discussion on using tolerance analysis for setup selection and process plan representation using ALPS (A Language for Process Specification).

1. INTRODUCTION

Process planning has been recognized as an interface between computer-aided design and computer-aided manufacturing. Automated process planning in a manufacturing environment is vital to achieving the ultimate goal of unmanned and integrated factories in the future [1]. In the past two decades, many research and development efforts have been devoted to analyzing, modeling, and automating process planning activities. From variant process planning to generative process planning, great progress has been made. However, due to the complexity of the problems involved, a truly generative process planning solution still does not exist [2]. According to our survey [3] [4], there are some obvious shortcomings in the research leading to the development of CAPP (Computer-Aided Process Planning) systems:

1. While much research has been done on the integration of CAD (Computer-Aided Design) and process planning, few research efforts have been devoted to the integration of process planning and scheduling. Almost all of the CAPP systems assume that the shop floor is idle and there are unlimited resources on the shop floor. Therefore the process plans generated are somewhat unrealistic (cannot be readily executed on the shop floor).

2. Due to the lack of manufacturing experience, or lack of information about the manufacturing facility, the product design engineer may propose awkward designs in terms of production cost and manufacturing lead time. An ideal process planning system should be able to provide feedback to the design engineer and suggest specific changes of design that would reduce production cost and manufacturing lead time.

3. Tolerance analysis has been recognized as playing a key role in precision manufacturing. However, few process planning systems use tolerance analysis; the analysis used is limited to checking the dimensional tolerance stack-ups rather than generating optimal setups/process plans.

4. Among the CAPP systems developed, there exists considerable data overlap. However, different systems store their data using different formats. Due to the lack of a standard, the data cannot be exchanged. An integrated process planning system should adopt a standard approach (for input and output) in order to facilitate communication and data sharing.

A truly integrated process planning system should be able to deal with the problems mentioned above. This paper discusses an integrated process planning project (IPPS), which is currently being carried out in the Department of Industrial Engineering, Texas Tech University. The IPPS project aims to solve the four problems mentioned above as well as to develop a prototype system. This project is performed in collaboration with the National Institute of Standards and Technology (NIST). It is an integral part of the Process Planning Test Bed (PPTB) project currently underway in the Factory Automation Systems Division (FASD) of NIST. Section 2 of this paper gives a general description of IPPS. Section 3 discusses the use of tolerance analysis for setup selection. Section 4 introduces the use of ALPS (A Language for Process Specification) for process plan representation via a standard approach (ISO 10303-21). This is followed by a conclusion section.

2. INTEGRATED PROCESS PLANNING

An integrated process planning model is shown in Figure 1. The model consists of two modules: (1) a process planning module, and (2) a scheduling module. The process planning module is responsible for generating process plans according to the part design specifications. The scheduling module is responsible for overall management of the flow of production orders and for resource allocation on the shop floor. The process planning activities and scheduling activities are integrated in order to generate realistic (can be readily executed on the shop floor) process plans.

Figure 1 goes here

The need for the integration of process planning and scheduling comes from the very fact that immense problems are encountered when process planning and scheduling are performed separately [5]. The research on the integration of process planning and scheduling has been addressed by Chrysolouris et al. [6] [7], Khoshnevis and Chen [8] [9] [10] [11], Tönshoff et al. [12], Iwata and Fukuda [13], ElMaraghy and ElMaraghy [14], and others. Besides these research efforts, Larsen and Alting [15] discussed three candidate approaches for the integration of process planning and scheduling: (1) NonLinear Process Planning (NLPP), (2) Closed-Loop Process Planning (CLPP), and Distributed Process Planning (DPP). They indicated that the DPP approach is the only one which integrates the technical and capacity related planning tasks into a dynamic fabrication planning. The architecture of IPPS facilitates the implementation of the DPP approach. In IPPS, the process planning and scheduling activities are divided into three phases, i.e., preplanning, pairing planning, and final planning.

2.1 Preplanning

The preplanning phase is a technical manufacturing analysis of the product (both design and customer requirements) in order to identify the processing requirements; it is also an analysis of the processing potentials of the shop floor in regard to operation capabilities.

The process planning module interprets the part design data and analyzes the job requirements of the part. It is assumed that the part design data is represented using ISO 10303, which is an International Standard for the computer-interpretable representation and exchange of product data [16]. Features within the part are recognized by the process planning module through a feature reasoning mechanism. All the features within the part will be arranged into setups based on tolerance analysis (to be discussed in Section 3). After the features have been arranged into setups, machining processes for each setup will be recommended.

The scheduling module is responsible for providing information about the resources on the shop floor. Shop floor resources include raw materials, machine tools, cutting tools, and fixtures, etc. The information about these resources is maintained in MRP II (Manufacturing Resource Planning) databases. When the process planning module recommends a machining process for a setup, it will check with the scheduling module to make sure that the machining process is expected to be available on the shop floor. In the preplanning stage, availability is roughly estimated and is not constrained by any short time dynamic. For example, suppose there is a shop floor that has milling machines, but does not have shaping machines. We will say that milling processes can be performed on the shop floor even if all the milling machines are currently occupied. We can also say that shaping process cannot be performed on the shop floor at all. At this stage, the scheduling module does not perform any scheduling activities. Instead, it only provides information about the capacity on the shop floor.

In the preplanning phase, the interaction between process planning and scheduling is at a global level, i.e., shop floor level. The processing potential of the shop floor serves as a constraint to the process planning module. Therefore, all the process plans generated can be executed on the shop floor. In other words, the infeasible process plans (from the scheduling point of view) are eliminated in this early stage. By doing this, the number of alternative process plans is reduced and thus the computational complexity will be reduced when a process plan needs to be selected.

2.2 Pairing Planning

The interaction between process planning and scheduling in the pairing planning phase is at a less global level, i.e., machine group level [17]. The alternative process plans generated in the preplanning phase are sent to the scheduling module. The process plans are represented by ALPS using ISO 10303-21 (to be discussed in Section 4). The scheduling module is responsible for scheduling the setups within the process plans for the machine groups. Based on the schedule, the work load for each machine group is then projected via simulation. The work load projection for the machine group can be shown graphically in Figure 2. From the work load projection, we can easily find out whether the capacity of a machine group is violated or not. If the capacity of any machine group is violated by using a process plan, the process plan used is not a feasible plan and should be eliminated. In this way, all the infeasible process plans can be eliminated. If no feasible process plan can be found for a part, the scheduling module is responsible for informing both the design function (for alternative design) and the MRP II function (for new resources).

Figure 2 goes here

If there are more than one feasible process plans, the most desirable one will be selected. The criterion used for process plan selection is the shortest manufacturing lead time. The process plan selection problem is formulated as an optimization problem and an algorithm is given in [17].

2.3 Final Planning

In the final planning phase, the interaction between process planning and scheduling is at a detailed level, i.e., machine level. Each setup within the selected process plan will be assigned to a specific machine. Please notice that at this phase the problem scope is reduced to within a machine group. The scheduling module is responsible for maintaining a schedule database for the machines within each machine group. The schedule database contains information such as which machine will be available at a certain time, the fixture currently used in the machine, etc. It is the responsibility of the process planning module to specify the kind of fixture required. If a new fixture is required, then the previous fixture used in the machine must be removed. The required fixture must be brought from the store room or another machine. Hence the setup time will be longer and the waiting time for a setup also will be longer. According to this information, each setup can be assigned to a specific machine. The details about setup/machine assignment are discussed in [17].

According to the setup/machine assignment, the details of how the setup can be performed using the machine is determined. The details include cutting tool specification, fixture specification, and NC-program generation. After the detailed process plan has been generated by the process planning module, the machining time for each setup can be calculated. According to the calculated machining time, a schedule is made and the schedule database is updated for future use [18].

3. TOLERANCE ANALYSIS FOR SETUP SELECTION

An innovative approach is introduced here to select datums and setups for rotational parts by means of tolerance analysis. The approach uses both dimensional and geometric tolerance specifications from the design to generate a process plan with specified datums and setups, rather than just using the dimensional tolerances to verify an otherwise arbitrarily generated process plan. Because the manufacturing processes are carefully studied and the manufacturing error sources are considered, the datum and setup selection can minimize the requirements for machine accuracy and thus improve the quality and reduce the cost of manufacturing.

3.1 Fundamental Description

Tolerance specifications can be categorized into local tolerances and global tolerances. A local tolerance is only related to a single feature and is mainly determined by machine/process capabilities. However, a global tolerance is related to more than one feature and is influenced also by the datum and setup selection in process planning. If datums and setups in manufacturing are selected properly, manufacture of a part within the design specifications can be easier but requires less accurate machine tools, which will reduce the cost. Or, with the same machine accuracy, parts can be made to tighter tolerances, which will improve the quality and, consequently, the performance of the products. Therefore, the economy of manufacture of many products can be greatly improved by the use of specified datums for positioning purposes.

In manufacturing processes, there are three ways to obtain the specified global relationship between the features: (1) arrange them in the same setup, (2) use some of them as locating datum(s) and machine the other(s), and (3) use other feature(s) as locating datum(s) to machine them in different setups. In the first case, the setup errors are not included in the relationship. The geometric relationship of the features machined in the same setup will mainly depend on the geometry built into the machine tool. When CNC machine tools are used, the tool movements are controlled by the control unit through the coordinate measuring system on the machine tool. The dimensional relationship, such as the distance between two parallel features machined in the same setup, will be determined mainly by the accuracy of the control unit, which becomes a built-in capability of the machine tool. Therefore, in this case, the relationships (both dimensional and geometric) between the features, as the local tolerance specifications mentioned above, are mainly determined by the built-in machine/process capabilities. The relationship is the easiest one to be obtained and, therefore, the most economical relationship obtainable.

The second case is recommended by many authors [19] [20] [21]. However, the setup errors will be included in the relationship. To control the tolerance of the relationship, the accuracy of locating the part has to be concerned, which becomes a major part of the tolerance of the relationship. This method used to locate a part on design datum in manufacturing is originally taken from the inspection process. In inspection, a part is usually located on its datum(s), which makes the measurement of the relationship much easier. Since not much clamping force is needed in inspection, the location of a part can be quite accurate. However, it is different in manufacturing. The part has to be clamped tightly against the cutting force. The clamping force may increase the setup error according to the clamping mechanism of the fixture.

In the third case, the specified relationship is obtained indirectly through some other features. The variation of these features will be introduced to the relationship. In this case, and only in this case, tolerance chains are formed. The tolerances will stack up in the specified relationship. It is not desirable when the tolerance for the required relationship is tight. If the datums and setup are not selected based on the tolerance specifications from design, although the widely used tolerance chain method can check the stackup of dimensional tolerances, the arbitrary selection of datums and setups may result in undesirable stack-up of tolerances which may make the manufacturing impossible even with the best machine tools.

To summarize, the following statements can be made. The relationship between features of a part can be obtained (1) synchronously, (2) asynchronously, or (3) through a chain. The accuracy and economy of manufacturing a part will decrease in that order. No tolerance chain is formed for the relationship obtained in the same setup. The features obtained in the same setup are mutually datumed. The machine/process capability and tolerance-cost relationship should be clearly defined for relationships obtained in different ways mentioned above.

3.2 Datum and Setup Selection

A systematic tolerance analysis approach for automated datum and setup selection is used in IPPS. First, both dimensional and geometric tolerance specifications from design are analyzed and ranked according to manufacturing data which contains information about machine tools and locating and clamping mechanism of the fixtures. Since all the features of a rotational part can be machined in two setups, the features to be machined are divided in three groups: those that can only be machined in one of the setups, those that can only be machined in the other setup, and those that can be machined in either setup (e.g., a through hole). Then an algorithm is used to check, from the most critical one, if the features with specified relationship can be machined in the same setup. Those features which physically can be in either setup may be assigned to a specific setup if necessary. If the features cannot be machined in the same setup, some of the features will be used to locate the part for machining of the other(s). The datums and setups can be selected automatically to make the manufacturing more accurate and economical. The purpose is to exclude as many manufacturing error sources from the critical relationships as possible and leave the inevitable manufacturing errors (chain errors) to those unimportant relationships with looser tolerances.

The performance of the algorithm will be illustrated through an example. For a rotational part, starting from one end of the part, a letter or a number can be assigned to each feature to be machined in the actual feature adjacent sequence. The orientation of a feature is defined as the direction in which the tool can access the feature. All features with the same orientation can be machined in the same setup. The orientation of each feature is determined by adjacent diameters. For example, if a feature is an external feature and its diameter is larger than that of both sides, then it has two orientations. Value '+1' or '-1' is assigned for each single orientation and '0' for both orientations. If a part has n features and we denote natural orientations with O', we have

$$O'[i] = \begin{cases} 1 & \text{one single orientation} \\ 0 & \text{both orientations} \\ -1 & \text{the other orientation} \end{cases}$$

where i = 1, 2, ... , n

A priority number is assigned for each specified relationship to the relevant features. If there is no specified relationship, a zero is assigned to that feature. We denote the relationships of the features with R

$$R[i] = \begin{cases} 1, 2. ... & \text{tight tolerance specified} \\ & \\ 0 & \text{no tolerance specified} \end{cases}$$

where i = 1, 2, ..., n

Figure 3 is an example part. In this example, an equal priority (1) is assigned to each feature with the specified geometric relationship which needs attention. We have

i	1	2	3	4	5	6	7	8
Feature	A	B	C	D	E	F	G	H
Orientation O'[i]	+1	0	-1	-1	-1	0	+1	+1
Relationship R[i]	0	1	0	1	1	1	0	0

Figure 3 goes here

If the features with specified relationships have the same natural orientation, no special tools or methods will be selected. We need not care about the setup for those features without a specified relationship from the viewpoint of accuracy. We also need not care about those features with two orientations because we can arrange them in any setup we think necessary. Therefore, we can multiply O'[i] and R[i] for each feature; the result (setup arrangement) is denoted by S[i]. If all non-zero S[i]'s have the same sign, it means that all the features with specified relationships can be machined in the same setup as their natural orientation. If we use '&' to represent this operation, then

$$S[i] = O'[i] \& R[i] \qquad i = 1, 2, ... , n$$

In our example, we get:

i	1	2	3	4	5	6	7	8
Feature	A	B	C	D	E	F	G	H
Setup S[i]	0	0	0	-1	-1	0	0	0

This means that the features with a specified geometric relationship will have the natural orientation (-1). Therefore, features B and F, which have two orientations, will be assigned this orientation. If we use O for the assigned orientations, then

$$O[i] = \begin{cases} O'[i], & \text{if } R[i] = 0 \text{ or } O'[i] \neq 0 \\ O'[j], & \text{otherwise} \end{cases}$$

where i,j = 1,2,...,n, $j \neq i$, and feature i and j have specified tolerance

Now in our example, we have:

Features	A	B	C	D	E	F	G	H
Orientation O[i]	+1	-1	-1	-1	-1	-1	+1	+1

All the features with the same orientation will be arranged in the same setup. This selection eliminates tolerance chains for the critical relationships, and maximally relaxes the requirements for machine tool and fixture accuracy.

It should be mentioned here that for the features to be machined in the same setup, the sequence of operations on them does not matter from the viewpoint of accuracy. No chain is formed. The criteria used to sequence will be economic ones such as least tool change, shortest tool path, or least machining time, etc. Because the setup and datum features have been clearly specified, the information about the fixture (shape, dimensions, tolerances, clamping mechanism and force, etc.) can be given in the process plan. The process plan generated (by IPPS) is shown in Figure 4.

Figure 4 goes here

4. PROCESS PLAN REPRESENTATION USING ALPS

The communication between the process planning module and the scheduling module is crucial in order to integrate process planning and scheduling. The transformation of information from process planning to scheduling is the focus of the scheduling interface. Based on our knowledge, almost no literature is available concerning research on the scheduling interface. However, the transfer of information between systems in the manufacturing environment has been studied. Current research at NIST is addressing integration issues for streamlined data integration to support flexible discrete manufacturing. Among the schemes under development, ALPS has been used as an interface between process planning, production management, scheduling, and control [22] [23]. In the IPPS project, ALPS is used in the pairing planning phase for process plan representation.

ALPS was designed to serve as a generic model to support process plans used with the discrete-process manufacturing industry. The need for such a generic model became apparent in the context of a series of projects initiated at NIST during the late 1980's addressing various aspects of Computer Integrated Manufacturing (CIM). The development of ALPS is taking place in parallel with international standardization efforts to define a standard process plan model. Two publications [24] [25] about ALPS are currently available. The basic structure of the ALPS model (schema) represented using the NIAM (Nijssen Information Analysis Methodology) diagram can be found in [25]. A companion specification for the schema also exists using the EXPRESS language [26], which provides a machine-readable form.

The ALPS language is based upon a directed graph structure, with nodes containing processing information on discrete manufacturing tasks. The nodes are connected to one another by directed arcs that indicate temporal precedence. There are seven major classes of nodes in ALPS: termination, task, split, join, synchronization, resource, and information. The roles and use of each class of node is explained in [24]. Figure 5 shows the directed graph representation for the process plan shown in Figure 4.

Figure 5 goes here

While the directed graph representation is intuitive for humans to understand, the formal respresentation of ALPS plans is in terms of a populated model according to the EXPRESS specification. By virtue of being defined in EXPRESS, ALPS plans can also be exchanged by means of an ASCII exchange file, as specified by ISO 10303-21 [27].

> ISO 10303-21 specifies an exchange structure format using a clear text encoding for product data. The file format is suitable for the transfer of product among computer systems. The exchange structure is described by an unambiguous, context-free grammar to facilitate parsing by software. The grammar is expressed in Wirth Syntax Notation. The form of product data in the exchange structure is specified using a mapping from the EXPRESS language. The exchange structure is not dependent on any particular application.

We have developed a prototype system which can generate process plans for rotational parts. The system has its own file format for storing process plans, which can be automatically translated into the ISO exchange file format for ALPS. The exchange file for the process plan of the example part is shown in Figure 6.

Figure 6 goes here

5. CONCLUSION

Over the past two decades, tremendous efforts have been made in the development of CAPP systems. While the goal of CAPP research remains the integration of design and manufacturing, significant changes have occurred during this period. The characteristic of the new generation CAPP systems is that integration has significantly increased in comparison to old generation CAPP systems. In this paper, we described an integrated process planning project -- IPPS. Two important issues (tolerance analysis for setup selection and process plan representation using ALPS) are discussed in detail.

Currently, we have developed a prototype system which can generate process plans for rotational parts. The system provides human readable process plan sheets as well as exchange files in standard format. However, the development of IPPS is still in the early stage. Automated feature recognition is not yet supported by the current prototype system, which means it is not yet integrated with the CAD model. Other future works include: (1) applying a standard approach for the design interface, (2) further developing the tolerance analysis approach for prismatic parts, (3) automatic generation of NC codes, and (4) using AI (Artificial Intelligence) techniques for knowledge acquisition and representation.

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LIST OF FIGURES:

```
--------------------------------------------------------------------------------
                          IPPS PROCESS PLAN
Part ID: Example_part                                   Time: July 11 1993
Planner: J.M.
--------------------------------------------------------------------------------
 P#   O#   Description
--------------------------------------------------------------------------------
           Turning process is needed.
 10 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
           Raw material storage
    10     Casting        Dmax = 100.00 mm    Lmax = 64.00 mm

 20 Turning  process  - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
           CNC Lathe A
           Setup  1:     Clamped on surfaces    C        X=  0.00
                                                         Ext.= 24.00
                                                D        D= 63.00
    10  Face shoulder     A     X=  22.000+0.100
    20  Turn diameter     H     D=  40.000-0.005
    30  Face shoulder     G     X=  12.000+0.100

 30 Turning  process  - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
           CNC Lathe B
           Setup  2:     Clamped on surfaces    G        X=  0.00
                                                         Ext.= 52.00
                                                H        D= 40.00
    10  Turn diameter     F     D=  20.000+0.005
    20  Face shoulder     E     X=  50.000-0.002
    30  Turn diameter     D     D=  60.000-0.005
    40  Face shoulder     C     X=  11.000+0.015
    50  Turn diameter     B     D= 100.000-0.050
--------------------------------------------------------------------------------
```

Figure 4

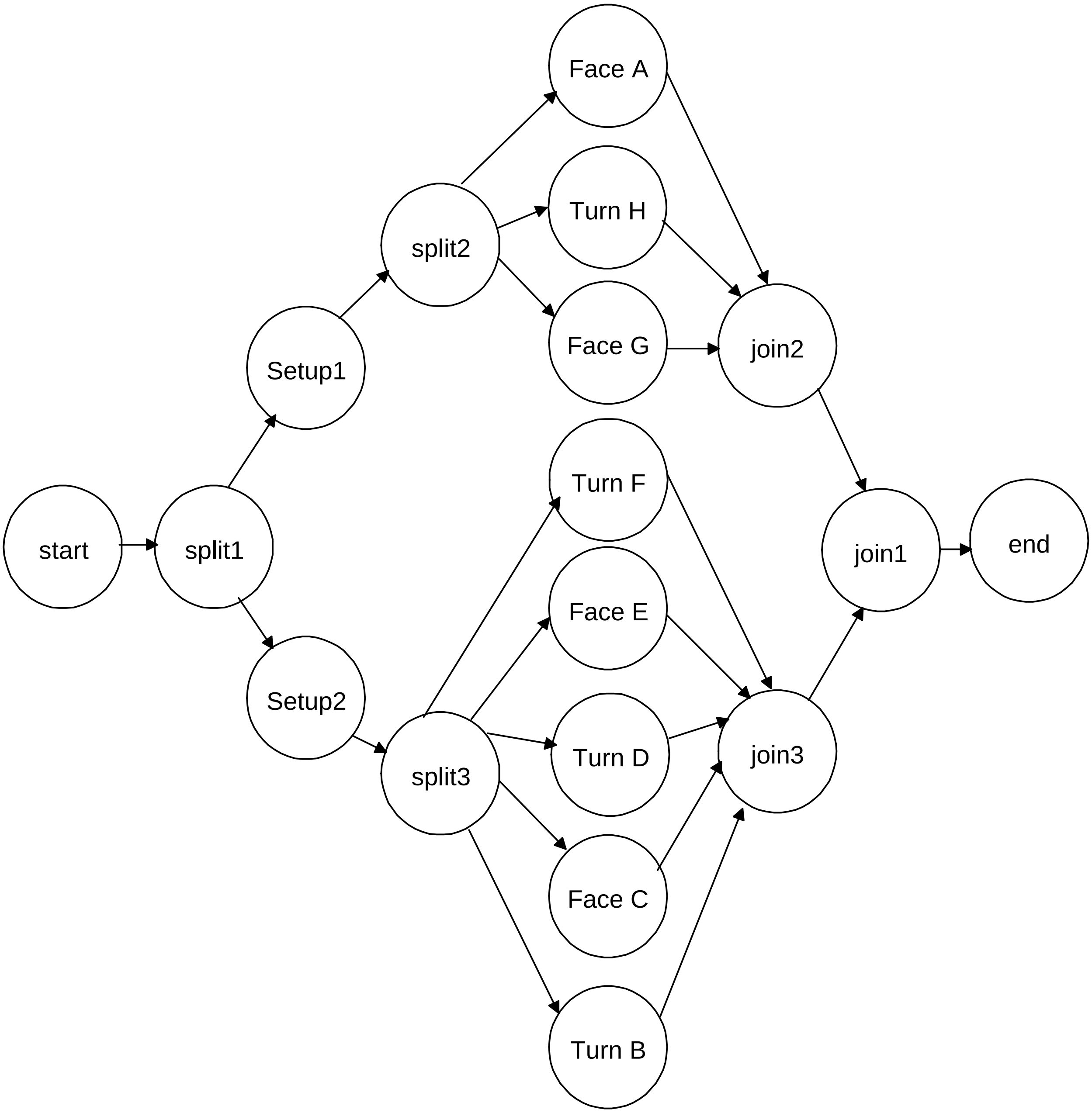
Face A
Turn H
split2
Face G
join2
Setup1
Turn F
start
split1
join1
end
Face E
Setup2
join3
Turn D
split3
Face C
Turn B

Figure 5

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION($,$);
FILE_NAME($,$,$,$,$,$,$,$);
FILE_SCHEMA($);
ENDSEC;
DATA;
#1=PROCESS_PLAN($,$,'Process plan for Example_part: made by J.M. on July the 11th,
1993',#2);
#2=RESOURCE_TYPE('Casting with Dmax=100.00mm and Lmax=64.00mm',$,$,$);
#3=START_PLAN_NODE(#1,1,.ALPS_START_PLAN_NODE.,'start',$,$,$,(#4));
#4=PARAMETERIZED_SPLIT_NODE(#1,2,.ALPS_PARAMETERIZED_SPLIT_NODE.,'split
_1',$,$,$,(#5,#6),2,$);
#5=PRIMITIVE_TASK_NODE(#1,3,.ALPS_PRIMITIVE_TASK_NODE.,'Setup_1: on CNC
Lathe A: Clamped on surfaces C (X=0.00, Ext.=24.00) and D (D=63.00)',$,$,$,(#7),$,$,$);
#6=PRIMITIVE_TASK_NODE(#1,4,.ALPS_PRIMITIVE_TASK_NODE.,'Setup_2 on CNC
Lathe B: Clamped on surfaces G (X=0.00, Ext.=52.00) and D (D=40.00)',$,$,$,(#8),$,$,$);
#7=PARAMETERIZED_SPLIT_NODE(#1,5,.ALPS_PARAMETERIZED_SPLIT_NODE.,'split
_2',$,$,$,(#9,#10,#11),3,$);
#8=PARAMETERIZED_SPLIT_NODE(#1,6,.ALPS_PARAMETERIZED_SPLIT_NODE.,'split
_3',$,$,$,(#12,#13,#14,#15,#16),5,$);
#9=PRIMITIVE_TASK_NODE(#1,7,.ALPS_PRIMITIVE_TASK_NODE.,'Face shoulder A
(X=22.000+0.100',$,$,$,(#17),$,$,$);
#10=PRIMITIVE_TASK_NODE(#1,8,.ALPS_PRIMITIVE_TASK_NODE.,'Turn diameter H
(D=40.000-0.005',$,$,$,(#17),$,$,$);
#11=PRIMITIVE_TASK_NODE(#1,9,.ALPS_PRIMITIVE_TASK_NODE.,'Face shoulder G
(X=12.000+0.100',$,$,$,(#17),$,$,$);
#12=PRIMITIVE_TASK_NODE(#1,10,.ALPS_PRIMITIVE_TASK_NODE.,'Turn diameter F
(D=20.000+0.005',$,$,$,(#18),$,$,$);
#13=PRIMITIVE_TASK_NODE(#1,11,.ALPS_PRIMITIVE_TASK_NODE.,'Face shoulder E
(X=50.000-0.002',$,$,$,(#18),$,$,$);
#14=PRIMITIVE_TASK_NODE(#1,12,.ALPS_PRIMITIVE_TASK_NODE.,'Turn diameter D
(D=60.000-0.005',$,$,$,(#18),$,$,$);
#15=PRIMITIVE_TASK_NODE(#1,13,.ALPS_PRIMITIVE_TASK_NODE.,'Face shoulder C
(X=11.000-0.015',$,$,$,(#18),$,$,$);
#16=PRIMITIVE_TASK_NODE(#1,14,.ALPS_PRIMITIVE_TASK_NODE.,'Turn diameter B
(D=100.000-0.050',$,$,$,(#18),$,$,$);
#17=JOIN_NODE(#1,15,.ALPS_JOIN_NODE.,'join_2',$,$,$,(#20));
#18=JOIN_NODE(#1,16,.ALPS_JOIN_NODE.,'join_3',$,$,$,(#20));
#19=JOIN_NODE(#1,17,.ALPS_JOIN_NODE.,'join_1',$,$,$,(#20));
#20=END_PLAN_NODE(#1,18,.ALPS_END_PLAN_NODE.,'end',$,$,$,$);
ENDSEC;
END-ISO-10303-21;
```

Figure 6

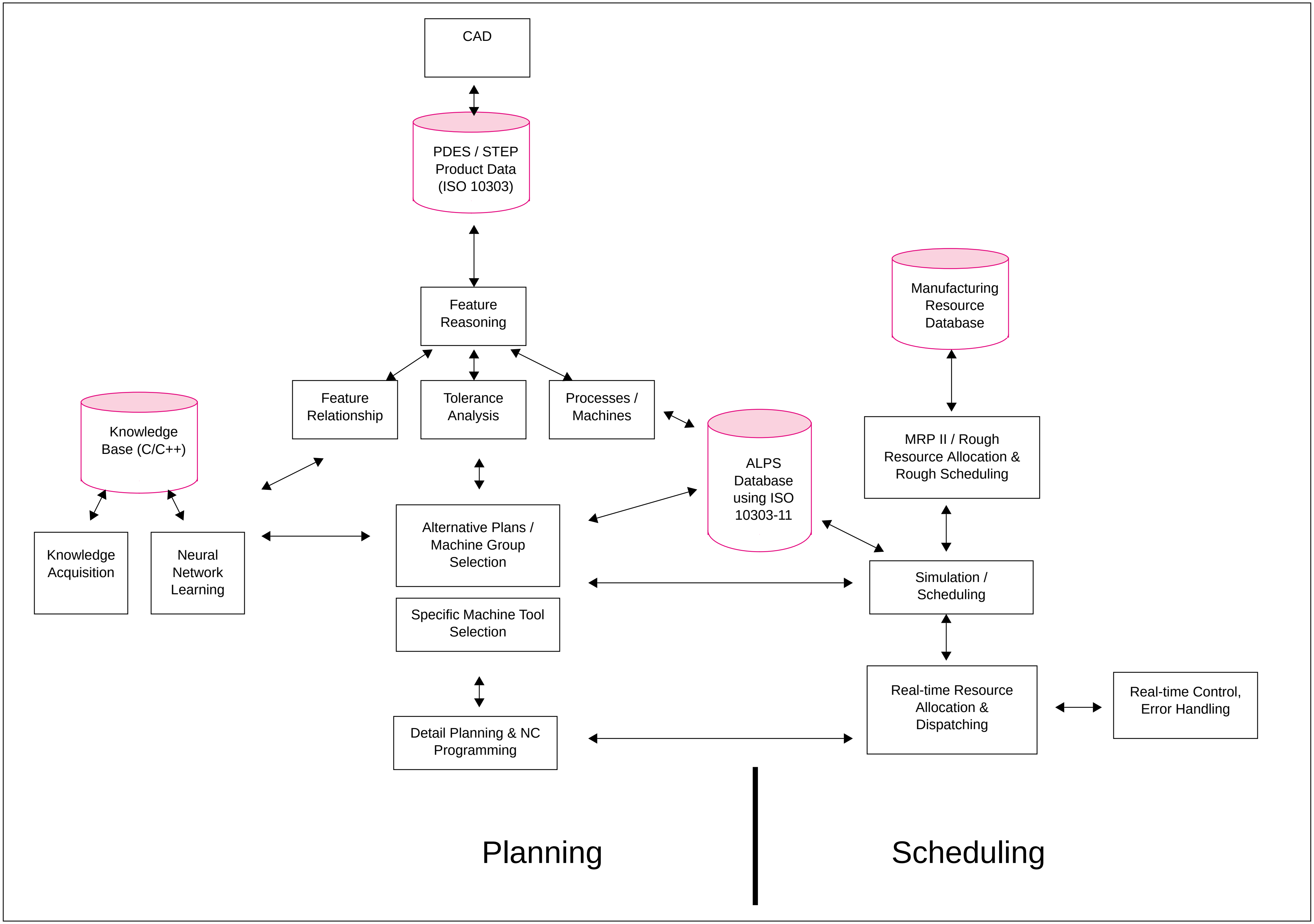
CAD
PDES / STEP
Product Data
(ISO 10303)
Feature
Reasoning
Feature
Relationship
Tolerance
Analysis
Processes /
Machines
Manufacturing
Resource
Database
Knowledge
Base (C/C++)
ALPS
Database
using ISO
10303-11
MRP II / Rough
Resource Allocation &
Rough Scheduling
Knowledge
Acquisition
Neural
Network
Learning
Alternative Plans /
Machine Group
Selection
Simulation /
Scheduling
Specific Machine Tool
Selection
Real-time Resource
Allocation &
Dispatching
Real-time Control,
Error Handling
Detail Planning & NC
Programming
Planning
Scheduling

Figure 1