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THE PROSPECTS OF PROCESS SEQUENCE OPTIMIZATION IN CAPP SYSTEMS

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Abstract—Automated process planning forms an important link in the integration of CAD and CAM systems. This paper gives an overview of the main types of computerized process planning systems. It demonstrates that part geometry, available machines and cutting tools as well as required cutting forces are the important factors that influence process sequence optimization. The paper proposes a new approach for process sequence optimization using artificial intelligence techniques. The feasibility of this approach has been demonstrated in the expert system developed by the authors.

1. INTRODUCTION

Creation of primary, real, tangible wealth is the basis and source of all other wealth in a nation. It increases the quality of life, employment, and general economic well-being of a country. In industrialized countries, manufacturing accounts for two-thirds of the wealth creation and therefore improvement of manufacturing technology is of primary importance. Of all various kinds of manufacturing technology being developed, researched, and implemented today, Computer Integrated Manufacturing (CIM) has demonstrated far greater productivity than anything that has appeared on the scene since the onset of the Industrial Revolution [1]. CIM centers around a manufacturing database consisting of four primary manufacturing functions: engineering design, manufacturing engineering, factory production and information management. All the subfunctions of these four main functions are illustrated in the CASA/SME wheel shown in Fig. 1. The goal of such a system is complete integration of the entire concept-to-market process.

2. COMPUTER AIDED DESIGN AND MANUFACTURING

Computer Aided Design (CAD) is the use of a computer to assist the design of an individual part or a system. The CAD system supports the design process at all levels—conceptual, preliminary, and final design. The design process usually involves computer graphics. The drawing of the object is usually displayed on a CRT and it can be stored for subsequent retrieval and modification as necessary. Part drawings can also be created using automatic drafting machines. Computer Aided Manufacturing (CAM) is the use of a computer to assist in manufacturing of a part. It can be divided into two main classes:

(i) on-line applications, namely, the use of computer systems to control the manufacturing systems, and
(ii) off-line applications, namely, the use of the computer in production planning and non-real time assistance in manufacturing of parts.

CAD and CAM, though effective in their respective areas of application, generally operate in isolation of each other. Thus, to realize CIM, integration between CAD and CAM is necessary. Process planning is the essential link between design and manufacturing.

2.1. Process planning

Briefly defined, process planning is that function which determines the sequence of individual manufacturing operations needed to produce a given part or product as well as associated machining conditions (feed, speed, etc.). In effect it is the subsystem responsible for the conversion of design data into work instructions [2]. The resulting operation sequence is documented on a form, along with the required machine tools, cutting tools and operation times. Such a form is

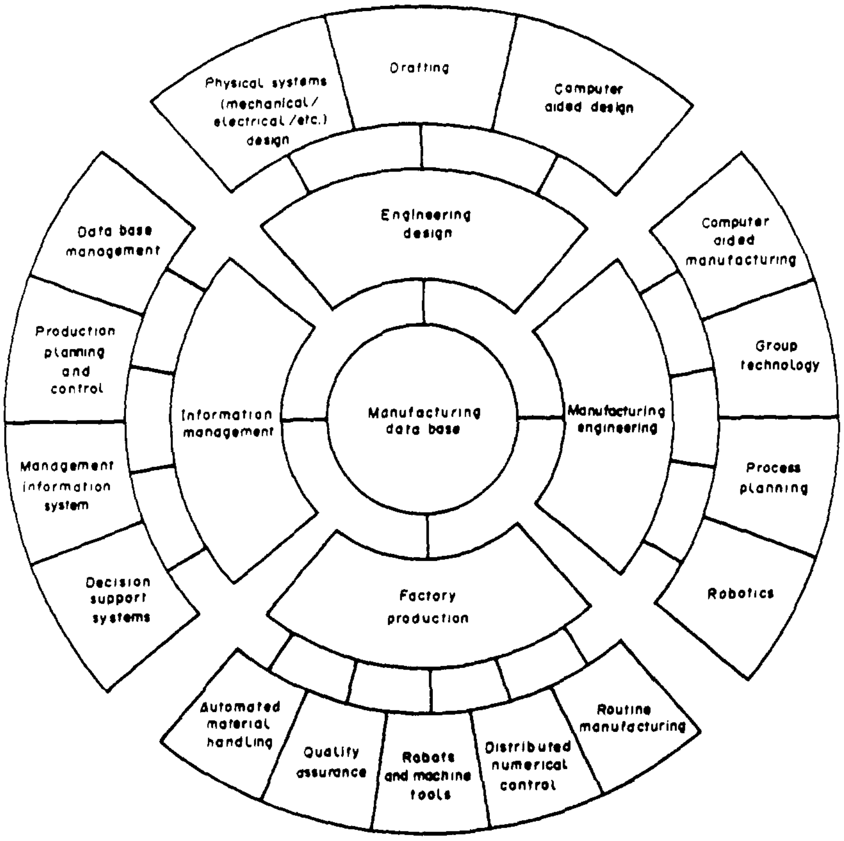

Fig. 1. Computer integrated manufacturing subfunctions.

known as a process plan. When a new part is to be produced at the shop, the manufacturing engineer prepares a process plan. The process plan is dependent on the experience and judgement of the planner. It is his responsibility to determine optimum process plans. Following are the different phases of process planning [2].

1. Selection of operations.
2. Sequencing the operations.
3. Selection of the machine tools.
4. Selection of the workpiece holding devices and datum surfaces.
5. Selection of cutting tools.
6. Determination of proper cutting conditions.
7. Determination of cutting times and non-machining times.
8. Editing the process sheet.

2.2. *Computer aided process planning* (*CAPP*)

Process planning is one of the basic components of the whole manufacturing system. As the automated manufacturing system tends to replace human operators by more efficient automated equipment in production, the bottleneck stage is transferred to the preparation departments. Therefore, process planning, which represents about 40% of the preparation time, has assumed much more importance. It is a detailed and difficult task traditionally carried out by highly skilled workers who have an intimate knowledge of a wide range of manufacturing processes and are themselves experienced machine operators. Many of the people with these skills are now past middle age and fast approaching retirement while there are few adequate replacements among the younger generation. It is also found that there is generally a lack of consistency among process plans prepared by different individuals with varying manufacturing backgrounds and levels of skill.

It is therefore imperative to automate the process planning function and this makes CAPP important even in the absence of CAD and CAM. By using a computer, the tedious and repetitive aspects of process planning can be speeded up and this helps to optimize the total manufacturing function by releasing the experienced planners and enabling them to concentrate on those aspects outside the scope of a computer [3]. At the same time, more consistent process plans can be obtained by applying a standard set of rules which increases confidence in the system and helps in the rationalization of production. To automate process planning, the logic, judgement, and experience required for process planning must be captured and incorporated into a computer program.

2.3. Types of CAPP systems

2.3.1. Variant process planning. This type of process planning technique uses part classification and coding along with the concepts of Group Technology. The parts are classified according to their geometric similarities and manufacturing characteristics. Standard plans for each part family are stored in a part family matrix. To obtain a process plan for a new component, the code for the part is determined and the plan is retrieved if a similar part is found in the part family matrix. The user can examine and edit the plan. The new plan can be put into the part family matrix for future reference. Some examples of variant process planning systems are MIPLAN [4], CAPP [5], and TOJICAPP [6].

The main criticism to be made of variant process planning systems is that they do not fundamentally solve the problem. They rely on expert process planners to develop standard process plans and therefore lock in many of the difficulties and problems associated with manual systems [7]. Variant systems do not generate new process plans. It is for this reason that generative process planning was developed. Variant systems are still dominant in industry however, because they are easy to implement, they can handle a wide variety of parts and conceptually, they are very similar to what has been in the past and therefore are easily accepted.

2.3.2. Generative process planning. In a generative system, an individual plan is created from scratch for each part. Based on an analysis of the part geometry, material and other factors which would influence manufacturing decisions, the system generates a new process plan for each part. The manufacturing logic, formulae to determine machining conditions and standard times will be used by the system to produce the process plan. Some examples of generative systems are AUTAP [8], ICAPP [9, 10], and TIPPS [11].

2.4. Required advances in CAPP

It is the generative process planning system that can link CAD and CAM together, but the lack of a good interface with a CAD system is the greatest handicap the researchers are facing. Thus, most of the researchers, many from Computer Science are working in this area to develop automatic feature recognition systems. Meanwhile, the lack of a feature recognition system has slowed down the automation of the different phases of process planning described in Section 2.1. Though there are many systems that determine required operations, cutting parameters and production times, very few systems attempt to sequence the operations optimally or select jigs and fixtures. Another reason for this is the lack of universally accepted manufacturing logic for process sequencing and selection of jigs and fixtures. Most of the process planners use their experience for these phases of process planning. Nowadays, Artificial Intelligence (AI) systems are accomplishing useful practical results in science and technology. Expert systems, i.e. computer systems which use application-specific problem-solving knowledge to achieve a high level of performance in the field which we would think of as requiring a human expert, may be used to automate some phases of process planning. There are several expert process planning systems that have automated some phases of process planning that lead towards CIM. Some systems are SIPS [12], GARI [13], TOM [14], and EXCAP [15]. The rest of this article describes an expert system developed by the authors which optimizes process sequences. The authors describe the problems involved in process sequencing and briefly explain the working of their system.

3. PROCESS SEQUENCING

Process sequencing is the task of arranging the processes chosen to produce a part in a proper order or sequence, so as to obtain a reasonable process sequence (if possible, the optimum sequence) which can be used to manufacture the component. As already stated, there are very few accepted rules for process sequencing. Therefore, the authors conducted an industrial survey to study the process planning techniques being used in industry. The survey revealed that process sequencing does not lend itself to a perfect methodology. Bootawallah conducted a similar study on a family of 425 spur gears and obtained 377 different process plans [16]. This is not surprising because process sequencing is strictly a human oriented activity, highly dependent on individual skills, human memory and mood, and a mass of reference manuals. Though it is human-oriented, there are certain factors that must be considered while selecting a particular process sequence. The following is a brief description of such factors.

3.1. The part geometry

The part drawing shows the material of the work piece, geometrical shape of the part, the tolerances—both geometrical and dimensional—and surface finish required. This is required to know the different manufacturing processes required to manufacture the part of the exact specifications. For example, the tolerance, the roundness and the surface finish of a hole determine the different tools—pilot drills, boring tool, reamers, etc.—required to finish the component. Depending upon the material of the work piece, the routing of the work might change (for example, heat treatment and stress relieving). Many times, there may be operations that are dependent. In Fig. 2, it is not possible to produce the groove before step-turning is completed. In Fig. 3, before milling the inclined surface, the holes must be drilled because holes cannot be drilled accurately on an inclined surface. If the inclined surface has to be finished before drilling, an end mill should be used to obtain a flat surface perpendicular to the axis of the drill before drilling the hole.

3.2. The available machines

The machines that are at the disposal of the process planner will limit the size of the part being produced. Conversely, the size of the part determines the possible machines that can be used to produce the part. The capabilities of the machine can change the process sequence completely. An optimum process plan for machining on a three-axis machine will not necessarily be the optimum one for machining on a five-axis machine.

3.3. The available tools

The tools that are available and the tools that can be loaded onto a particular machine might change the sequence. This is especially true if complex features are to be produced. But the

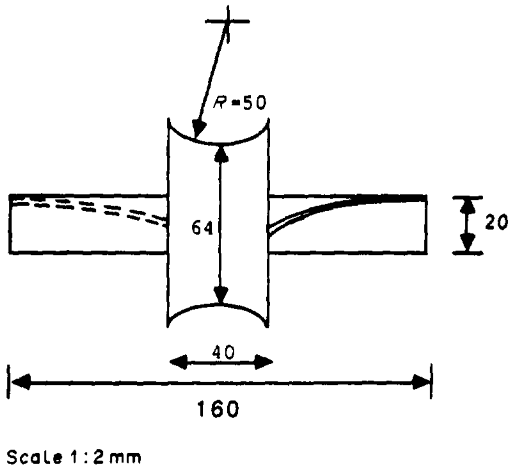

Fig. 2. A shaft with an oil groove and a concave contour.

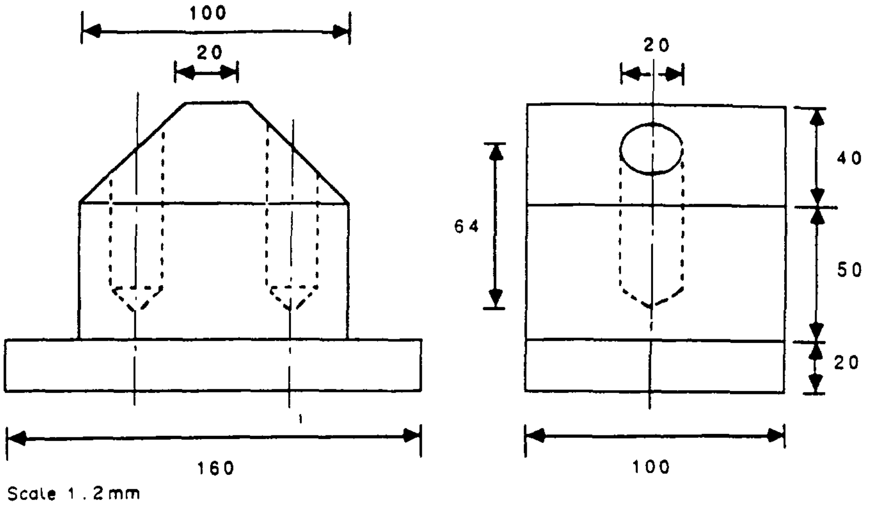

Fig. 3. Holes on inclined surfaces.

availability or affordability of a special tool depends on the batch size. Thus, batch size is also a factor that influences the process sequence.

3.4. *The cutting forces*

A particular process sequence is a function of the cutting forces and the rigidity of the work piece. Consider the part shown in Fig. 2. Before step-turning is done, the contour must be finished. If the step-turning is finished first, the cutting forces generated during contouring might bend the work piece. For similar reasons, in Fig. 4, the hole H2 must be produced before machining the slot. The cutting force depends on the material of the work and the machining parameters.

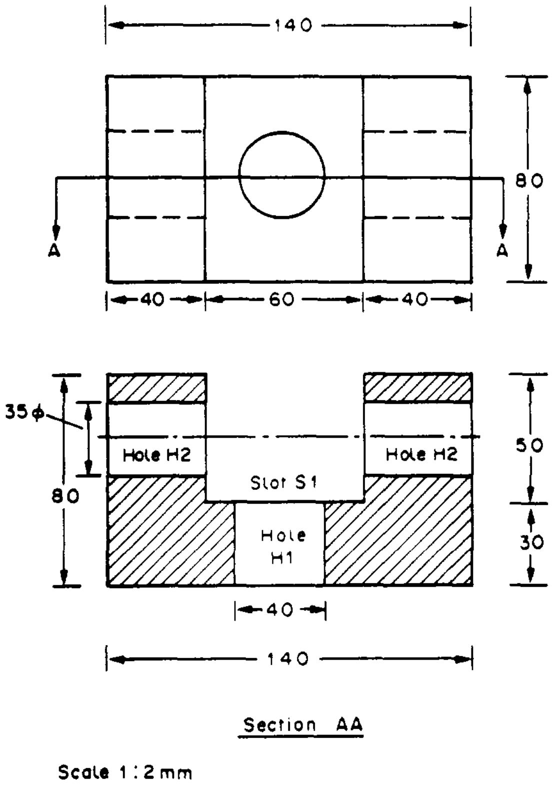

Fig. 4. A part with interdependent features.

4. PROCESS SEQUENCE OPTIMIZATION

The ultimate objective of process sequencing is to minimize the cost of production without sacrificing the quality of the product. The total production cost is given by [17]

$$C_{pc} = C_0(T_m + T_h) + T_m(C_t + C_0 T_{tc})\ T \qquad (1)$$

where

C_{pc} = cost per work piece (\$/piece),
C_0 = cost to operate the machine tool (\$/min),
T_m = machining time (min),
T_h = workpiece handling time (min),
C_t = cost of tooling (\$/cutting edge),
T = tool life (min),
T_{tc} = tool change time (min).

In the above equation, C_{pc} can be reduced by reducing C_0, C_t, T_m, T_h and T_{tc}, or by increasing T. The value of C_o is dependent on the labor cost, the machine cost and the applicable overheads. Therefore, the estimated value of C_o varies from one industry to another. C_t, T, and T_{tc} are constants in a given situation and will not affect the optimization problem. Thus T_m and T_h are the most important variables to consider in trying to optimize the production cost C_{pc}. The values of T_m and T_h are fairly similar for a given combination of machine tools, cutting tools and workpiece material across industries. Therefore, for a general application program, it is possible to minimize C_{pc} by minimizing T_m and T_h. Thus, the objective is to minimize T_m and T_h to minimize the production cost. Of these, T_h is the one most significantly affected by the sequence of operations.

The authors have developed a program to sequence the manufacturing processes required to manufacture a component. The program, which is essentially an expert system for process sequencing, is called SEQUENCE. SEQUENCE is an extension of Interactive Computer Aided Process planner for Prismatic parts (ICAPP). Refer to Ref. [3] for details about ICAPP. The authors chose COMMON LISP to write the program so that artificial intelligence techniques could be used, which is very essential for process sequencing. The use of LISP has made the program more understandable.

The scope of SEQUENCE is process sequencing, and it tries to minimize the total handling time (T_h) and the total machining time (T_m). In other words, SEQUENCE works on "time" basis rather than on "cost" basis. The authors place the process sequencing phase just before the calculation of production times rather than placing it just after the selection of operations. (Refer to Section 2.1.) Thus, all factors on which a process sequence depends, as explained in Section 3 have been considered for process sequencing. SEQUENCE uses the following data about each operation required to produce the component. (These data are determined within ICAPP.)

1. An operation number unique to a particular operation: this helps to differentiate one operation from another if they are similar in all other respects.
2. The machine tool code: this code is the code for the machine tool on which the part is being produced.
3. The face number: this is the code for the face on which the operation is being performed.
4. The drawing code: this differentiates one feature from another.
5. The cutting tool code: this code determines the type of tool being used and hence the type of operation being performed.
6. The tool diameter.
7. A weighting factor: this is the ratio of the volume of metal removed to produce a feature to the total volume of metal removed to make the component.

4.1. Knowledge representation in SEQUENCE

The data about a particular operation is arranged as a list and thus a list of such lists forms the input to SEQUENCE. This is the "initial state of the data base". The "final state of the data base" contains these operations properly sequenced. Many "functions" in SEQUENCE will operate on the "set of objects" so as to arrive at the final state. Thus, SEQUENCE uses "State

Space Representation" for representing the knowledge about the operations. The initial set of states is a list of required operations given by

$$S1 = O_1, O_2, O_3, O_4, \ldots, O_x$$

where x = the total number of operations. Note that each operation is in turn defined by a list of the above seven elements.

There are many "functions" which operate on the initial set of states so as to obtain the goal state, which is the sequence in which these operations must be performed. Subsequently, an operation is represented as O_{ijk}, where

i is the machine tool number being used
j is the face on which the operation is carried out
k is the number of similar operations so far (inclusive).

Some important functions are explained here.

4.2. Initialization

When the total time a component spends on a machine is analyzed, it can be seen that the total handling time is about 70% of the total time and the total machining time is 30% [1]. This is shown in Fig. 5. Since handling time is more than machining time, handling time reduction is more important than machining time reduction. Total handling time can be divided into work handling time and tool handling time. Reduction of work handling time means that the number of times the component is reset on the machine must be reduced. Therefore, all possible operations that can be performed at a particular set up must be completed before resetting the work piece. Fortunately, this is an accordance with a manufacturing rule of thumb which says "try to finish as many operations as possible in one set up so that dimensional tolerances can be maintained." The function INITIALIZE arranges the operations in such a way that all operations to be performed on the *same face using the same machine* are grouped together. The arrangement of the operations after INITIALIZATION will be:

$$\begin{array}{l}
O_{111}\, O_{112}\, O_{113} \cdots\cdots\cdots O_{11p} \\
O_{121}\, O_{122}\, O_{123} \cdots\cdots\cdots O_{12p} \\
\ldots \; \ldots \; \ldots \; \ldots \qquad \ldots \\
O_{1n1}\, O_{1n2}\, O_{1n3} \cdots\cdots\cdots O_{1np} \\
\ldots \; \ldots \; \ldots \; \ldots \qquad \ldots \\
\ldots \; \ldots \; \ldots \; \ldots \qquad \ldots \\
O_{mn1}\, O_{mn2}\, O_{mn3} \cdots\cdots\cdots O_{mnp}
\end{array}$$

where

$i = 1, 2, 3, \ldots, m$ = number of machines.
$j = 1, 2, 3, \ldots, n$ = number of faces.
$k = 1, 2, 3, \ldots, p$ = number of operations on any face requiring the same machine.

Once the operations are arranged as shown above, the work handling time will be minimum.

4.3. Minimization of tool handling time

Operations on a particular face on a particular machine tool can be performed using different tools, which involves tool handling time. There are two types of tool handling times and minimization of both is explained in the following sections.

Fig. 5. Total time spent by a component on a machine.

4.3.1. Minimization of intra-facial tool handling time (T_{h1}). Intra-facial tool handling time is the time required for all the tool changes that take place in a particular set-up of the part on the machine. T_{h1} can be minimized by grouping all operations requiring the same tool together, so that the tool need not be changed. Also, if the operation can be done with a different tool, the tool diameter may have to be changed so as to minimize T_{h1}. For example, if there are different operations requiring center drills of diameters 3.5, 4 and 5 mm, all three centerdrill operations can be performed using the same center drill. The tools can be changed for other operations also, but one must be careful while doing this. For example, if the finished hole diameter is 25 mm, it must not be changed to 24 or 26 mm. Also, if threading and reaming should be performed, the intermediate diameters must be selected carefully. This part of the program which changes the tool diameters is called CHANGE-TOOL.

4.3.2. Minimization of inter-facial tool handling time (T_{h2}). Interfacial tool handling time is the time required to change tools when the setup of the part on the machine has been changed. The change of tool requires time. If the sequence of operations on each face is arranged such that the tool that was used for the last operation on face j can be used for the first operation on face $j + 1$, keeping i constant, then there will be some reduction in the tool handling time. This depends on the type of operation. For example, a twist drill cannot be used before using a center drill unless a pre-drilled hole is present. Threading cannot be done before drilling a hole. Therefore, the "precedence relationships" of the different operations are very important. It is very unlikely that all last operations on a given face j use the same tool as the first operation on the next face $j + 1$. But it is possible that some of the faces might be arranged so that the inter-facial tool handling time between two consecutive faces is zero. Thus, it is possible to obtain a combination of such faces which will be subsets of the complete sequence of operations. These combinations of faces can be appended to obtain the best possible sequence. It is at this point that Artificial Intelligence (AI) techniques are useful. Graph search method has been used to obtain the possible sequences. There are heuristics used to minimise the search effort. The heuristics include knowledge about the dependencies of features, the weighting factors of features, the total number of faces to be machined, the different types (and diameters) of tools used, etc.

4.4. Minimization of machining time (T_m)

After handling time has been minimized, the machining time reduction is considered. It should be noted that this is possible only if there are inter-dependent operations. Consider the part shown in Fig. 4. The slot S1 and the hole H1 are on the same face. If the slot is machined first, the machining time required to produce the hole can be reduced. Since there is no interface with a CAD system, the user has to answer a question interactively, which helps to arrange the operations so as to minimize T_m.

4.5. Selection of the final sequence

Before selecting the best sequence, the database will have a number of possible sequences. The best sequence is selected by considering the weighting factor for each operation. It is good practice in manufacturing for operations having a greater weighting factor to be finished first so that much of the heat is carried away by the chips and less material is left for further machining. The final sequence considers this and selects the best sequence. The final sequence given by SEQUENCE is the best sequence obtainable with the present depth of knowledge the system possesses.

5. DISCUSSION

The operation of SEQUENCE as outlined above is based on the factors given in equation (1). There are a number of other important factors however which have a significant impact on process sequencing which are not accounted for in that equation. These factors result from interdependence between the various features and their associated operations. There are certain questions the user has to answer for these factors to be considered in process sequence optimization using SEQUENCE. The program makes appropriate inferences using these data. These questions are asked interactively and all that the user has to enter are the drawing codes (and only once, the face number). These are explained below.

5.1. "Do-before" function

This is used to determine the operation that must be performed prior to any other operation. In response to an appropriate question, the user enters two drawing codes, which the program infers as "do (dwcd2) before doing (dwcd1)." This helps to establish precedence relationships between interdependent features on a given face, which can be used to reduce the total machining time. In Fig. 4, the hole H1 must be finished after finishing the slot S1 so as to reduce the machining time. Note that this does not depend on the sequence in which the different faces are machined and that these two features are on the same face.

5.2. "Dependent-on" function

If there are operations that are dependent, then the sequence of operations must be selected carefully. Consider the part shown in Fig. 4. There is a hole going through a slot. If the slot is machined first, the cutting forces during machining the hole might bend the workpiece. Therefore, the hole H2 must be finished first. When the user enters two drawing codes interactively in response to the appropriate question, the program reads these as '(dwcd1) is dependent on (dwcd2)' and tries to sequence the faces accordingly. If the face containing the slot has to be machined first, the program prints a message for the machinist to insert a packing metal piece in place of the slot.

5.3. "Opposite-to" function

If there are through holes, they can be drilled from either end. The selection of a particular face from which this has to be done depends on the tools required for other operations on that face. Proper selection might reduce the handling time. When the user enters a drawing code and the opposite face number, the program evaluates it as "(face containing (dwcd) is opposite to (face no))". This will be used to switch the face from which machining is done. Also, this helps in obtaining an improved sequence in many cases. For example, if a face has a through hole having a counter-bore, the through hole can be produced from either of the faces, but counter-boring must be done from one face only. The sequence should be such that counter-boring comes after the drilling is done. Thus, if the face opposite to the face having a counter-bore is known, a precedence relationship can be established, so that drilling is complicated before counter-boring. Also, as stated earlier, depending upon the tools being used on the face having a counter-bore, the face from which the hole is produced can be switched, if it helps to reduce the handling time.

5.4. Overview

All the functions described above require the user to answer some questions interactively. In fact, many other data, if obtained, would be helpful to obtain the best sequence. For example, if a slot with a higher weighting factor comes near a corner, holding the piece might be a problem. Thus, the exact locations of the features is an important factor for process sequencing. But this might make the program cumbersome. Therefore, the authors are waiting for the interface with a CAD system, which will answer many more questions that help sequencing. Parallel research is being carried out to interface ICAPP with a CAD system and a system for NC machining.

The figures shown have been selected to explain the problems involved in process sequencing. A component of average complexity may not have all the features shown in the figures, but one cannot rule out the possibility of these being present in a component.

Currently, SEQUENCE works with the ICAPP process planning system. However it is an independent module which is capable of accepting input data (as described in Section 4.1) from any process planning system provided it is in the correct format. SEQUENCE would then operate on the data and generate the list of properly sequenced operations. The relevant process planning system could then take this as input for further processing. Most process planning systems described in the literature do not have the capability to sequence machining operations optimally. The few that attempt to do so concentrate on optimizing processes to produce a particular feature without considering interactions with the other features on the component. As shown, this can have a significant impact on the process sequence. The system described here clearly demonstrates an important advance in the capabilities of CAPP systems.

6. CONCLUSION

This paper outlined the importance of improved manufacturing technology. CAD and CAM were defined and it was demonstrated that CAPP was important for the integration of CAD and CAM. A review of several process planning systems—Variant and Generative—showed that very few systems were optimizing process sequences. It was shown that the important factors influencing a particular sequence are the part geometry, the available machines and cutting tools as well as required cutting forces. It was suggested that Artificial Intelligence techniques would help develop a process planning system capable of generating process plans with optimal process sequences. A methodology for process sequencing and the expert system developed by the authors for process sequence optimization were described.

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