An Integrated Cutting Tool Selection and Operation Sequencing Method

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Received on January 14, 1992

Summary.

Within the PART CAPP system, the selection of an optimum operation sequence is related to the modules which perform the machining method and cutting tool selection. This study analyzes the technical and economical aspects of operation sequencing and presents a method which is capable of generating an optimum solution on the basis of previously selected machining operations and alternative cutting tools per operation. Precedence relations between operations provided by the method selector are used as constraints which should not be violated. The operation sequencing method simultaneously assigns single tools from a list of alternatives to each operation and manipulates the operation sequence in order to minimize the total number of toolchanges and the number of required tools.

Keywords: CAPP, Operation Sequencing, Tool Selection.

1 Introduction.

PART (Planning of Activities, Resources and Technology) is a generative CAPP system developed at the Laboratory of Production Engineering of the University of Twente [1], [2], [3], [4]. This modular system covers all the major process and operation planning functions required for 2½D prismatic components which have to be machined on CNC machining centers.

The generative process planning system is aimed at small batch part manufacturing and its objectives are to:

- Integrate CAD (solid modelling) and CAPP functions using automatic feature recognition on imported solid models [4].
- Automate the process and operations planning functions while:
 - drastically reducing the lead time.
 - improving the quality of the generated process plans.
 - standardizing the use of fixturing and machining methods and their corresponding fixturing and cutting tools.
- Provide extensive tailoring facilities so that the system can be adapted to company specific requirements. This includes:
 - the sequence of executing the various process planning functions.
 - the features which the feature recognition module should recognize.
 - the definition of the machining methods and the required cutting tools for machining groups of features.

Figure 1. A schematic representation of the PART system.

- the specification of the tool-path generation strategies and the cutting condition selection functions.
- the specification of the output formats like setup sketches, tool-lists, etc.
- of course the contents of the database in terms of the company's manufacturing environment: machine tools and pallets, fixturing tools, cutting tool components and assemblies, etc.

2 The operation sequencing problem.

The purpose of the operation sequencing module is to determine an optimum sequence which satisfies both the technical and the economical constraints.

An optimum operation sequence is characterized by a minimum number of toolchanges and a minimum of tool travelling time. There are two studies dealing with operation sequencing: A method is suggested for selecting a sequence with a small number of tools from amongst possible sequence [5]. And an analytical method to minimize the cutting tool handling time is suggested by using the branch and bound method [6], based on an assumption that the cutting tools and their trajectories are given. However these studies do not consider the technical constraint. Within the PART system, the input for the operation sequencing module is generated by:

- the machining method selection module.
- the tool selection module.

It will be clear that these modules are strongly related. E.g. selecting a different machining method could result in the selection of a different type of tool. Selecting a different tool (e.g. different diameter) for a previously selected method, could influence the operation sequence if the same tool can also be used for other operations in the same setup. The next paragraph briefly describes the method & tool selection modules.

2.1 Method and tool selection.

The function of the method selector [2] is to select a machining method (i.e. a set of machining operations) and tentative cutting tools (i.e. a cutting tool type as well as ranges for its attribute values) for the machining of features. In addition to selecting operations, the module also generates precedence relations between individual operations. Figure 2 shows a simple example. The precedence relations result from either the "natural" sequencing constraints of operations on a single piece of geometry (for machining a hole: first centering, then drilling and finally boring or reaming) or are the result of the geometric relations between different features. These geometric relations are expressed in the compound feature hierarchy of the PART system [4]. If no other relations are generated by the method selector then the features are machined top-down.

The function of the tool selection module is to select exact cutting tools (alternatives can be generated) for each operation in the selected method. The module tries to combine attribute ranges (e.g. diameter) of individual operations which require the same type of tool by balancing:

- the number of required tools per setup.
- the "perfect" tool per operation.

These two aspects are conflicting. Sometimes all milling work can be performed with a single, very small, end mill but it would take ages. On the other end, using the "right" tool for each individual operation could result in a large toolset which exceeds the tool capacity of the machine tool and would introduce excessive toolchanges. The tool selection module negotiates a compromise [2] and provides the operation sequencing module with alternative tools per operation (usually less than 3).

The task of the operation sequencing module is to simultaneously select a single cutting tool for each operation and minimize the total number of toolchanges while making sure that none of the precedence constraints is violated. As a result of the large number of machining operation and the typically large number of tools required for components like the one shown in figure 10, the problem can best be dealt with by employing the computer (of course within the objectives of an automatic CAPP system there is no other option).

3 Precedence matrix.

3.1 Principles.

To express the precedence relations between the operations a matrix is used: the so called Pmatrix [7]. The operations are placed along the horizontal and vertical axis of that matrix. If an operation i has to be machined before an operation j then a '1' is positioned at row i and column j (see figure 3).

Figure 2. Precedence relations from feature hierarchy and machining methods.

The sequence of the operations can be read from the horizontal axis (from left to right) or from the vertical axis (from top to bottom). This sequence of operations should fulfil the constraints. To extract such a valid sequence from a randomly ordered set of operations the next method is used:

1. calculate the sum per column of the Pmatrix.
 2. put the first operation in the new initial operation sequence list which has a column sum which equals zero (could be more than one alternative).
 3. blank all the constraints in the corresponding row of the chosen column.
 4. stop if all operations are placed, otherwise go to 1.
- The matrix determined in this way is called the 'initial Pmatrix' (see figure 4). It represents a feasible but probably sub-optimum operation sequence.

Operations →		1	2	3	4	5	6	7	8	9	10
O p e r a t i o n	1		1				1				
	2			1				1			
	3				1				1		
	4										
	5										
	6				1					1	
	7										
	8				1	1					
	9		1							1	
	10							1	1		

For example : operation 1 has to be performed before operation 2 and operation 6 has to be performed before operation 4.

Figure 3. Example of a precedence matrix.

Left and right movement

The initial matrix represents only one of many possible initial Pmatrices (due to the fact that more than one column sum can be equal to zero as described in the points 1-4 above). To get the other possible Pmatrices in an easy way (without following the points 1-4) the left and right movement mechanism is used. This mechanism indicates the 'position freedom' of each operation related to the other operations in the Pmatrix (see figure 4): if for example the LM (left movement) of operation i is 5 and the RM is 10, this indicates that operation i can be placed on any column between 5 and 10.

Left movement: approach the column of which the LM has to be determined from the bottom, until the first '1' in that column : $LM = \text{found row} + 1$.

Right movement : approach the row of a certain operation from the left side, move to the right until the first '1' in that row, then $RM = \text{found column} - 1$.

Remarks :

1. the LM & RM of every operation has to be determined again each time the

2. the sequence of the operations along the horizontal and the vertical axis of the Pmatrix has to be the same.
3. assume the LM of an operation in column 10 is 5 (this means that the operation can be put in any of the columns 5 till 10), in case that operation is placed in column 5, the 'old' operation in column 5 is moved to column 6 etc., so shifting not swapping !

Operations →		1	6	9	10	2	3	8	4	5	7	LM	RM	
O p e r a t i o n	1			1		1						1	1	1
	6				1			1				2	3	2
	9				1	1						1	3	3
	10						1			1		4	6	4
	2						1			1		4	5	5
	3							1		1		6	6	6
	8							1	1			7	7	7
	4											8	10	8
	5											8	10	9
	7											6	10	10
		1	2	3	4	5	6	7	8	9	10			

Column numbers →

4 Cutting tool matrix.

4.1 Principles.

The T(tool)matrix is used to express the relations between the operations and the tools, along the horizontal axis the operations and along the vertical axis the cutting tools. Assume that the operation in column j can be performed by using the tool from row i then $Tmatrix(i,j) = 1$. In this way it is possible to express that different operations can use the same tool and that for one operation more than one tool is suitable (alternative tools). For the sequencing module these alternative tools are completely interchangeable. If the tool selection module prefers one tool over another for a given operation, then it should only return its favourite tool and not the less favourable alternative(s).

The sequence of the operations in a Tmatrix should be the same as the sequence of the operations in the corresponding Pmatrix (see figure 5).

4.2 Choice between alternative tools.

Before the total number of used tools and the number of toolchanges can be determined, a single tool has to be assigned to each operation for which alternatives exist [8]. How do we distinguish between alternative tools:

- chose that tool which is used by the most successive operations.
- if there are alternatives, then chose the tool which is used for one of the previous operations.
- if there are still alternatives, then chose that tool which appears the most often in the Tmatrix (i.e. can be used for the largest number of operations).

Figure 6 shows the results of this procedure applied to the matrix of figure 5.

5 Minimizing number of toolchanges.

As seen previously, the left and right movement of a certain operation can be determined. Every time an operation is shifted this could have consequences

Operations →		1	6	9	10	2	3	8	4	5	7
T o o l s	1	1					1				
	2		1					1		1	
	3			1	1						
	4					1		1			1
	5			1	1	1					1
	6		1	1					1	1	
	7			1				1			

for the number of toolchanges. So by shifting the operations, the number of toolchanges can increase or decrease. There are two strategies to get that sequence of operations in which the number of toolchanges is minimal :

1. Put every operation on every possible place in the Pmatrix and Tmatrix i.e. investigate every possible operation sequence (brute force approach).
2. Constructive way of placing the operations in columns/rows i.e. investigate only promising operation sequences (more intelligent search strategy).

5.1 First method.

The advantage of this way of searching for the optimum operation sequence is that it is relatively simple to implement. But it is quite clear that it can become an extremely computational intensive job, especially for large numbers of

operations and/or small numbers of constraints (this means that operations can be put on many alternative places in the matrix). So this method can only be used in special cases, therefore a second strategy is developed which should be suitable to solve the sequencing problems more quickly.

Operations →		1	6	9	10	2	3	8	4	5	7
T o o l s	1	1					0				
	2		1					1	1	1	
	3			0	0						
	4					0		1		0	
	5				1	1					1
	6		0	0					0	0	
	7			0				0			

- number of required tools is 4
- number of toolchanges is 6 - 2 (start + end)

Figure 6. A single tool has been assigned to each operation in a Tmatrix.

5.2 Second method.

The main goal of this way of searching is to minimize the number of operation shifts (and the corresponding determinations of the number of toolchanges). Two main aspects of this method can be distinguished (see figure 7):

1. 'Block' the Tmatrix.

The Tmatrix should be in a 'block structure' before the number of toolchanges is determined. Block structure means that operations are grouped together in a block, in such a block all operations use the same tool. The question is now: 'How do we put a Tmatrix in a block structure?'

Solution: The Tmatrix is scanned from left to right. Start with the first operation and search to the right in the rest of the matrix for an operation which uses the same tool as the current operation. Check the left movement of the found operation to see if it is allowed to put that operation next to the current operation, if it is, do so, if not search for the next operation which uses the same tool as the current operation. If no operation can be found (anymore) or if there is no operation for which the left movement is sufficient, this means that the current operation is the last one of a 'block'. Take the neighbour operation to the right of the last operation and re-apply this method. This should be done until the complete matrix is 'blocked', after this, the number of toolchanges can be determined. The column position of the first operation of a new block is called 'Tool Change Point' (TCP).

2. Choice of the first operation inside a block.

As just seen, the operation following the last operation of a 'block' is used as first operation in the next 'block'. This first operation inside a block has large consequences for the resulting number of tool changes. This means that the choice of a first operation within a block should be done in a constructive way and not randomly as described above. For each TCP a list of operations is created which are 'candidates' to be put on that TCP. Each operation of that list is placed once on the TCP and then skipped from that list.

5.3 Optimizations.

To reduce the calculation times even further, two optimizations are applied to the described method:

1. As soon as an 'optimum block structure' is reached for the Tmatrix the execution is stopped directly. An optimum block structure means that all operations which use the same tool are already grouped in one block, so there is no other operation which is not present in that specific block which uses the same tool (see figure 8^a and 8^b).
2. A candidate operation is only suitable to be placed on the TCP if it uses another tool than that used by the current operation on the TCP.

Operations →		1	2	3	4	5	6	7	8	9	10
T o o l s	1	1	1	1							
	2							1	1		
	3				1	1	1				
	4							1	1		

Figure 8^a. Optimal block structure

Figure 8^b. Non optimal block structure

5.4 Problems.

Despite the constructive searching method and the optimizations it is still possible that the required CPU time becomes unacceptable (e.g. in case of a large number of operations (> 100) in combination with a small number of precedence constraints). Therefore an absolute maximum is set to the number of times that the number of toolchanges is determined and a maximum is set to the number of times that the above mentioned calculations are allowed to return the same value (i.e. don't improve upon the solution).

6 Minimizing the cutting tool travel distance.

After determining the optimum operation sequence with respect to the minimum number of toolchanges, the sequence is optimized further with respect to the travel distance and machining direction for each cutting tool. During this second optimization session the following rules are important:

1. Of course it is not allowed to violate the precedence constraints, so before shifting an operation the left and right movement should be checked.
2. The number of toolchanges should stay the same (= the minimum).

6.1 Principles.

Inside every 'block' (set of operations which use the same cutting tool) the operations are rearranged in such a way that 'machining direction' blocks are created (in such a sub block all operations are performed in the same machining direction and don't require e.g. a table rotation from the machine tool). Furthermore the operations inside such machining direction blocks are rearranged in such a way that the traveling distance between two successive operations is minimal:

the Tmatrix is scanned from left to right, after the first operation in a certain 'block' is determined (see next paragraph), that operation from the remaining operations in the current block is searched for which is machined in the same direction and has the smallest distance to the current operation. The left movement is checked and the operation is shifted if allowed. The procedure is repeated for the found operation until the complete block is re-sequenced. This procedure is repeated for every block in the matrix.

6.2 Optimization.

Determining the first operation in the first block: the two farthest apart operations in the first block are determined; one of the two is arbitrarily selected to be the first operation. In each subsequent block that operation which has the same orientation and the smallest distance to the last operation of the previous block becomes the first one.

7 Results.

Figure 9 shows parts of the results generated by the method and tool selection modules. This information is stored in the relational data base of the PART system and is used as input for the sequencing module.

Figure 10 and 11 show screen prints of the user interface which presents the results of the sequencing module. Figure 11 displays the operations in their optimum sequence. Features, both intermediate (shown as F-##) and atomic (shown as AF-##), selected from this list are highlighted in figure 10.

The described method is implemented as a module of the PART system. It is programmed in the C language and tested on a VAX Station 3100 Model 38.

select * from operation_sequence_constraints where product_id = 235;		
Product_id	Operation_id	Previous_operation_id
235	2	1
235	6	1
235	3	2
235	7	2
235	5	3
235	8	3
235	4	6
235	10	6
235	4	8
235	5	8
235	etc.	etc

select * from mmts_alternative_tools where product_id = 235;		
Product_id	Operation_id	Tool_id
235	1	1
235	2	5
235	3	1
235	3	2
235	4	2
235	4	6
235	5	2
235	5	6
235	6	2
235	6	3
235	6	6
235	7	4
235	7	5
235	8	4
235	8	7
235	9	3

Figure 9. Results of the method and tool selection module stored in the relational data base used for the Pmatrix in figure 3 and the Tmatrix in figure 5.

Example of the performance :

- 200 operations (no alternative cutting tools per operation).
- 20 cutting tools.
- 240 precedence constraints.
- 11 min CPU-time.

Figure 10. Screen print of the visualization user interface.

8 Conclusions & Recommendations.

A method has been designed for the selection of an optimum machining sequence, based on the use of Pmatrices & Tmatrices and the Left & Right movement of operations within these matrices.

The method has successfully been implemented and generates an optimum sequence within an acceptable period of time.

The described method for minimizing the tool travelling distance is quite adequate but does not guarantee an optimum sequence.

The method for minimizing the tool travelling distance can be improved by applying linear programming techniques together with a more elaborate

Method Explanation Facility		
Session Edit Create Customize Options Atomic Classes		
Machining Methods		
Results of Method/Tool Selection and Operation Sequencing		
Feature	Operation	Tool
F-135	centering	Nc_centre_drill 10mm
F-130	centering	Nc_centre_drill 10mm
F-128	centering	Nc_centre_drill 10mm
F-126	centering	Nc_centre_drill 10mm
F-144	centering	Nc_centre_drill 10mm
AF-131	drill_small_hole	Twist_drill 10.0 mm
AF-129	drill_small_hole	Twist_drill 10.0 mm
AF-127	drill_small_hole	Twist_drill 10.0 mm
F-163	drill_small_hole	Twist_drill 10.0 mm
F-105	drill_small_hole	Twist_drill 10.0 mm
F-101	drill_small_hole	Twist_drill 10.0 mm
F-134	Brkchp_drill_small_hole	Twist_drill 10.0 mm
F-80	drill_small_hole	Twist_drill 10.0 mm
F-81	drill_small_hole	Twist_drill 10.0 mm
F-82	drill_small_hole	Twist_drill 10.0 mm
F-157	drill_small_hole	Twist_drill 10.0 mm
F-100	drill_small_hole	Twist_drill 10.0 mm
F-160	drill_small_hole	Twist_drill 10.0 mm
F-85	drill_small_hole	Twist_drill 10.0 mm
F-84	drill_small_hole	Twist_drill 10.0 mm
F-83	drill_small_hole	Twist_drill 10.0 mm
F-99	tap_a_through_hole	Machine_tap M12

Figure 11. Screen print showing the results of the operation sequencing.

strategy on where to start with a new cutting tool. The current implementation starts as close as possible to the position of the last operation performed with the previous cutting tool. However this strategy might be improved and should amongst others consider the tool change point on the machine tool.

Finally, further optimization of the search strategy described in paragraph 5 is required to improve upon the response times.

9 Acknowledgement

This work was done in the laboratory of Production Engineering of the University of Twente which Dr. H.M. Rho visited by a financial support of the Korea Science and Engineering Foundation.

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