Strategy in Generative Planning of Turning Processes

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1. INTRODUCTION

Today, two important market trends, related to industrial manufacturing, have caused an increase in product life cycles and a growing demand for shorter delivery times. In order to keep up with these developments it is necessary to reduce stocks and work-in-progress inventories in order to reduce costs. This apparent contradiction can only be solved by a combination of high productivity and flexibility. However, productivity and flexibility are to a large extent negatively correlated. The high-productive flow-type, high-volume manufacturing systems, usually are rather rigid. In order to achieve a high productivity level, special machine tools are lined up along a transport system, while machining operations are carried out in a fixed sequential order. The products are limited and known beforehand. The process and operations planning usually is carried out during the design stage of the manufacturing system and the system is primarily directed towards maximizing the efficiency of the machining operations. Pre-production series are run in order to test and tune the different stations in the system. However, the flexibility of the system is severely restricted due to substantial re-programming and set-up times.

Typically, flexible manufacturing systems show a rather low productivity. In order to be able to produce a wide and unpredictable variety of products, general purpose machine tools are manned by skilled operators and usually are grouped according to type (function). Transport of products is not very sophisticated and severe bottlenecks exist because the sequence of operations can differ for every different product. Part and operations planning is a continuous activity that has to be directed towards the reduction of drop outs and the improvement of the reliability of the operations. In many cases a substantial amount of work-in-progress is found on the shop floor. Servicing of the contents of material files is emphasized. Modification of the product is very much restricted due to substantial re-programming and set-up times.

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3. GENERATIVE PLANNING SYSTEMS VERSUS MACHINABILITY DATA BASES

As every other product is different with respect to batch sizes, workpiece materials, shape, volume of material to be removed, added value by previous operations, surface quality etc., it is almost impossible to retrieve all necessary technological machining information from a data base, just by trying to find a similar machining situation.

As many different factors influence the machining process, the use of generalized mathematical models which describe the relationships between machining variables and the final result of the machining process is the best way to produce reliable and economic NC programs within a limited amount of time. Using generative process and operations planning systems in the best way to accumulate knowledge about the interdependence of the factors which control the machining processes. For instance, by providing the possibility to explain to the operator the reasons behind the preference for certain machine tools, tools or machining conditions, it becomes possible to detect whether the production system is well tuned to the product mix and consequently hamper productivity.

The problem of generative systems is that the greater part of the data is not available in the right form and have to be evaluated from measurements on the shop floor, which usually is very laborious. It is much easier to select technological data directly from a general handbook or data base, but it is obvious that this data does not take into account the constraints and possibilities of the specific situation [23].

4. STRATEGY: FEED FORWARD AND FEED BACK

In process and operations planning, decisions, made at early stages, may badly influence decisions to be made in later stages. For instance, when the set-up for the machining of a specific workpiece has been done, all details about the different machining operations have not yet been calculated. Hence it is difficult to decide, which set-up is the best from the technical as well as an economical point of view. However, a poor set-up can impose too heavy constraints upon the machining conditions and consequently hamper productivity.

On the other hand it is certainly not practical to investigate all possible variants extensively in order to be able to select the best solution. It is not possible to go back on decisions taken earlier, in order to avoid problems occurring at a later stage. To much feed back within a system of this complexity causes intolerable calculation times and costs.

Following a strategy which is mainly based on a feed forward approach, the need of excessive iteration can be avoided. In this way it is possible to make short cuts and to solve the problem in a limited period of time. Strategies should mainly be based on early elimination of unsuccessful branches in the decision-tree. This can be achieved by using coarse estimation models in the first stages of the planning process in order to weigh the consequences of selections in terms of costs. Convergence through model refinement in the subsequent stages leaves the possibility for optimization of the individual machining quantities, without excluding the possibility of final adjustments of cycle times for synchronization purposes.

5. ROUND, A GENERATIVE PLANNING SYSTEM FOR TURNING OPERATIONS

ROUND is a generative process and operations planning system for turning operations, which is being developed in the Laboratory of Production Engineering at Twente University of Technology. The system has been developed starting from a program which calculates economic cutting conditions into a larger system which covers the planning and information processing over the whole trajectory, from part definition to NC machining. A working prototype exists.

ROUND is built up out of a number of modules, each of them covering a distinct phase of the technological planning process. In the chapters 6 and 7 the modules which have recently been developed and the underlying strategies will be discussed.

6. THE CLAMPING MODULE KNOXP

A ROUND run starts with the execution of the input module RNDINP [5]. After the part has been specified the dimensions of the workpiece have to be defined. Specification of the blank will only be necessary when it is a casting or when it is pre-shaped otherwise. The material is based upon the design of the blank. The cutter-tool selection strategy is based on determination of feasible cutting conditions into a larger system which takes into account the constraints and possibilities of the specific situation [23].

After having selected a specific lathe there is only a limited freedom in selecting jigs and fixtures, because exchange or modification of hydraulic chucks and tailstocks is usually not possible. This repetition is based upon the layout of the system. In the chapters 6 and 7 the layout of the system, the generation of the system and an overall description of the system have previously been reported in CIPRP papers. Fig. 1 shows the layout of the system. The chapters 6 and 7 the modules which have recently been developed and the underlying strategies will be discussed.

The primary task of this module is to determine the sequence of set-ups.
length have to be available.

FIG. 3 THE POTENTIAL CLAMPING SURFACES.

FIG. 4 DIVISION OF THE VOLUME TO BE REMOVED INTO MACHINING AREAS.

Technological constraints are imposed by the required geometric accuracy of the part (concentricity, cylindricity, surface roughness, roundness etc.) but also by the required clamping forces in connection with the cutting forces and by inertial forces. The models to calculate the necessary clamping forces and maximum rotational speed are according to VDI 3106 [7]. This ensures the generation of set-ups which meet an accepted safety standard. The potential combinations of solutions are compared by using a cost model which can be tuned according to the experience, needs and circumstances of a specific company. Tuning is performed by adjustment of the safety- and balancing-factors. The predicted cost related to the machining of a product in a specific set-up is a sum of calculable costs and estimated costs. Factors which play a role in the calculable costs are order size, batch size, jaw-changing costs, jaw-setting costs, jaw-machining costs etc. The estimated costs are influenced by technological factors such as the clamping factor, the existence of axial contact between jaw and part and the necessity of grooving operations. The clamping factor is used as a coarse estimation of the relative quality of a combination of set-ups and is defined as:

\[
\text{kcl} = \frac{\text{vol}}{\text{vol}} = \frac{\text{A} \times \text{v}}{\text{Z}}
\]  

where vol stands for the volume of a particular area which has to be removed in a particular set-up, Z is the metal removal rate, A is the cross-section area of the chip and v is the cutting speed. The minimum cutting force \( F_v \), required to remove a chip with area \( A \) is calculated from:

\[
F_v = \frac{\text{Fchmax}}{K_{ch}} \times A
\]  

where \( K_{ch} \) is the specific cutting energy. The maximum cutting force is limited by the clamping force \( F_{cl} \) which can be applied by the chuck and can be calculated from:

\[
F_v = F_{cl} = \frac{(Kt + K_b)}{Kc}
\]  

where \( Kt \) is the reduction factor for torsion and \( K_b \) is the reduction factor for bending. The ratio between the components of the cutting force are estimated according to [11]:

\[
\frac{F_t}{F_v} = 0.4 \quad \text{and} \quad \frac{F_p}{F_v} = 0.2
\]

\[
Kc = \frac{1}{\left[\frac{\text{dch}}{\text{dc}} \times 0.16 \times \frac{\text{uch}\times \text{dch}^2}{\text{uch}}\right]}
\]

For \( \text{dch} \) > \( \text{dc} \) \( \text{Kb} = \frac{\text{dch} \times 0.67 + 0.5 \times \mu\text{cha}^* \times \text{dch}}{\text{lch}} \)  

For \( \text{dch} \) < \( \text{dc} \) or with additional supporting aids \( \text{Kb} = 0 \)

where \( \mu\text{cha}^* \) is the friction coefficient in tangential direction and \( \mu\text{cha} \) is the friction coefficient in axial direction, (estimations of these coefficients are found in [7]), \( K_{ch} \) is the safety factor for the friction \( (K_{ch} > 1.5) \), \( dch \) is the maximum cutting diameter, \( lch \) is the maximum distance between the respective points of application of the cutting force and the clamping force, \( dch \) is the clamping diameter and \( lch \) is the contact length between jaw and workpiece. The influence of the weight of the workpiece is neglected.

The available clamping force is calculated from:

\[
F_{cl} = F_{clmax} \times \frac{1}{K_{cl}}
\]

and the centrifugal force from:

\[
F_{cl} = \frac{n_{ch}}{2} \times \frac{1}{2} \times (2 \pi R^2) \times n
\]

where \( F_{clmax} \) is the maximum clamping force which can be applied by the chuck when the rotational speed is \( n_{ch} \). \( F_{cl} \) is the safety factor for the cutting force \( (K_{ch} > 1.5) \), \( n_{ch} \) is the safety factor for the cutting force \( (K_{ch} > 1.5) \), \( n \) is the mass of the jaws and \( R \) is the distance from the center of gravity of the jaw to the clamping surface. The sign of \( F_{cl} \) in equation (5) is negative for external clamping and positive for internal clamping.

Substitution of the equations (2,9) in (1) yields:

\[
kcl = \frac{\text{vol} \times \text{Ksa} \times \text{Kc} \times (Kt + K_b)}{\text{vol} \times \text{Ksa} \times \text{Kc} \times \text{Kch}}
\]

where \( Kc \) is a cost factor which can be corrected for axial contact, grooving operations etc. The total cost per order, in relation with setting up is calculated from:

\[
C = \text{Cj} + \text{cm} \times \sum_{i=1}^{\infty} \left( \text{tj} + 12 \right) + \text{Ccl}
\]

where \( Cj \) is the cost related to the machining of soft jaws, cm is the cost of machining time, \( m \) is the number of set-ups, \( t1 \) is the jaw-adjustment time and \( t2 \) is the jaw-changing time.

7. THE MODULE FOR SELECTION OF MACHINING METHODS FOR ROUGHING OPERATIONS.

In this module the volume which has to be removed is divided into a number of areas, to each of which a specific machining operation, such as drilling, turning, facing etc. is assigned. In the prototype version the division in areas has still to be performed by the operator in an interactive way, as this module is still under development. First, the operator creates the areas to be machined by indicating them on the screen and subsequently assigns machining operations to them. One can select machining operations from a menu which includes fully specified standard operations, operations without specified direction and operations on grooves and recesses. The automatic version of the module will be able to present the systems own suggestions for division of the areas with the matching machining operations. The most economic division is shown first. As choice the operator may call a range of alternatives and select the solution which suits him best. An other possibility is to modify manually one of the suggested solutions.

8. THE SELECTION MODULE FOR ROUGHING TOOLS.

The task of ROUGH [18] is to select the best tools for machining the areas which are defined by the previous module. The objective is to obtain the most economic roughing tool set for the complete machining process. Selection of the optimum tool for every single area usually will produce a tool set which is far too large in relation to the number of available turret positions and thus will very much complicate tool management. The combination of both effects will lead to a limited, optimal tool set. As a particular tool is selected once its chance to be selected again is increased significantly because the cost of tool handling and set-up can be shared over more machining operations.
The problem of finding the optimum set of tools is now split up in two parts:
1) Finding all tools which can machine the respective areas which mainly is a geometrical problem.
2) Selecting the optimum set of tools from it, which mainly is a technological problem.

Due to the differences between roughing and finishing operations the algorithms which have been developed to select finishing tools (KNDFTL) [2] cannot be used to select roughing tools, although the same strategy is followed with some slight modifications.

FIG. 5 SOME EXAMPLES OF GROOVING OPERATIONS.

The selection of tools for the machining of grooves and recesses can be rather complicated. If it is not possible to machine the groove with a single tool, a combination of left and right hand tools and tools with a single tool has to be used. Some examples are shown in Fig. 5. The area of the groove has to be divided into a number of areas, each of which can be machined with a single tool. Usually there are more solutions of which the best one has to be selected.

Tool selection is performed in three consecutive steps:
1) Selection on the type of machining operation.
2) Comparison of the tool vectors with the part geometry (see Fig. 5). Usually there are more solutions of which the best one has to be selected.
3) Checks for collisions between tool holder and part.

When it is allowed to perform roughing and finishing operations with the same tool, the total number of tools-in-use can be reduced. Because tool wear, caused by roughing operations, influences the attainable accuracy and surface roughness during finishing, the decision depends on the required accuracy of the part, the size of the batch and the rules and habits of the company.

FIG. 6 THE TOOL VECTORS.

Reduction of the collection of tools which is available to the workshop does not only reduce the amount of invested capital, but also lowers the cost of tool management. An analysis of the frequency of use of the various tool types can help to compose the most suitable basic tool set for every individual machine tool. This minimizes the necessity of tool changes and tool setting and hence increases productivity. The use of block tools, together with automatic tool changing can be a solution when the number of available turret positions appears to be too small for the basic tool set. When the batch size is smaller than a specified number of products, at first only the tools of the basic tool set are considered for selection. If it is not possible to find a suitable tool for every area, the selection is extended to all other tools in store. The tools selected from the store are exchanged against some tools which belong to the basic tool set but are not used to machine this particular product. The frequency of use decides which tools are exchanged first.

As these steps incorporate progressive calculation times, they have to be performed in the given sequence. There are three possible routes to the next nodes. The figures above the arrows represent the costs to get from the left hand node to the right hand node. The smallest sum results from selection of the upper right hand node, so this will be a part of the optimum route. This principle the optimal route from node X(i) to the end node is known and the optimum route through the network from each of those nodes to the end node is known.

The selection of a path involves certain costs. Fig. 8 shows the explanation of the principle. From the left hand node there are three possible routes to the next nodes. The figures at the right hand side represent the cost of the optimum route from those nodes to the end node. The figures above the arrows represent the costs to get from the left hand node to the right hand node. The smallest sum results from selection of the upper right hand node, so this will be a part of the optimum route.

The objective function is defined going backwards from the end node (the area with the largest volume), to the starting node. In order to be able to calculate the route with minimal costs, the cost of all paths have to be determined. A rough estimation of these costs will be sufficient at this stage as the only objective is to select the proper tools. The actual costs are influenced by the optimisation of machining variables, which is the task of the next module (OPTIE F3).

The total costs related to the selection of a particular tool result from the summation of tool management cost, tool changing cost, machining cost and the cost of the tool. Tool management cost is defined here as: all costs for having the right tool available on the right spot at the right moment. hen a specific tool belongs to the basic tool set of the machine tool or has already been selected before, no tool management cost have to be taken into account. Otherwise these costs are calculated from:

$$C_{TM} = \frac{C_{tm}}{N} \quad (15)$$

where $C_{tm}$ stands for tool management cost and $N$ for the batch size.

The tool-changing costs are composed of the cost for changing the insert due to tool wear and the cost for tool changing due to a limited number of turret positions. In PMU usually block tools will be used and tool changing will be automated. When the tools have to be changed manually it is very unlikely that a higher metal removal rate will justify several tool changes per product, unless the volume which has to be removed is extremely high.

The tool-changing cost can be calculated from:

$$C_{2} = cm \times \frac{ts}{tc/\left(2^{2^{m-1}}\right)} \quad (16)$$

where $cm$ stands for cost of machining time, $ts$ for tool changing time, $tc$ for actual cutting time, $T$ for tool life and $N$ for batch size. If the number of turret positions is sufficient then $N$ is set to 1/2.

The machining cost is calculated from:

$$C_{3} = wc \times \frac{ts}{tc/\left(2^{2^{m-1}}\right)} \quad (17)$$

where $wc$ stands for cost of the volume which has to be removed, $s$ for the feed, $a$ for the depth of cut, $v$ for the cutting speed, $L$ for the total length of all positioning movements, and $r$ for the speed of rapid feed motion. $Lr$ can be estimated from $L/\text{A/A}$, where $A$ is the area of the cross section of the volume to be removed.

The machining variables $a$, $v$ and $r$ are calculated by using a simplified optimisation algorithm, this being of the same
structure as the one used in RNDRTL. Only the most important constraints are taken into consideration, such as:
- the maximum feed and depth of cut
- the maximum torque and rotational speed of the machine tool
- the chip thickness in connection with chip removal and control.

Within the area created by these constraints, the feed and depth of cut are maximized and the cutting speed is optimized according to the applicable objective function. The algorithm uses approximating formulas and values for the whole machining operation. This will cause deviations from the actual machining conditions, but usually this effect shows the same tendency for all tools under consideration. In the tool costs only the wear of the insert is accounted for, because the depreciation of the holder is negligible. It is calculated from:

$$ C_A = Ct * tc/t $$  \hspace{1cm} (18) $$

where $C_t$ stands for the cost of a cutting edge and tool life $t$ is calculated from the simplified Taylor equation:

$$ T = (C/c)^{(1/n)} $$  \hspace{1cm} (19) $$

The sum of the cost related to the use of a particular tool can be calculated from:

$$ C = K1^2 + K2^2 + K3^2 + K4^2 $$  \hspace{1cm} (20) $$

where $K1$, $K4$ are balancing factors which can be used to adjust the cost equation in order to influence the selection procedure. When the objective function is minimum production time $K4$ should be set to zero.

The selection of roughing tools is implemented in such a way that it can be performed fully automatically. However, at choice, the operator can perform manual selection, based on geometric and economic criteria. For instance, it is possible to let the system select all tools which are capable, in a geometric sense, to perform a specific machining operation, while leaving the final selection of the 'best' tool to the operator. The user interface is menu driven and can supply alpha-numeric and graphic information on the subsequent steps of the selection procedure. Table 1 shows the example of the alpha-numeric representation of the network and the corresponding tool.

<table>
<thead>
<tr>
<th>AREAS</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>15000.</td>
<td>11000.</td>
</tr>
<tr>
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<td>5</td>
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**TABLE 1** THE ALPHA-NUMERIC REPRESENTATION OF THE TOOL SELECTION NETWORK

**FIG. 9** AN EXAMPLE OF A SCREEN IMAGE GENERATED BY RNDRTL.

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REFERENCES.