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● *Paper*

THE INTEGRATION OF PROCESS PLANNING AND MACHINE LOADING IN SMALL BATCH PART MANUFACTURING

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PART is a highly automated planning system in which both process and production planning functions are integrated. This paper discusses a method to improve machine tool selection in process planning by integration with loading. A method is presented to select the best process plan from a number of possible alternatives taking into account the limited availability of resources. Various aspects of the quality of a process plan are evaluated and expressed in the so-called evaluation time. To prevent redundant work, partly worked out process plans are considered as alternatives. The consequences of the different alternatives have to be estimated which includes the estimation of machining times. The loading problem is modelled as the minimization of the total evaluation time for a given order set, subjected to capacity constraints.

1. INTRODUCTION

Traditionally, process and production planning are treated as separate planning problems. In the early days process planning consisted merely of making worksheets to instruct an operator how to machine given parts. The sheets weren't very detailed, in fact leaving many decisions to the operator and giving a lot of freedom to the production planning department as regards the assignment of work to different resources in the planned time for manufacturing. This represented a considerable amount of flexibility in planning.

The introduction of numerical controlled machine tools has changed the process planning task tremendously. To be able to generate NC programs, process plans have to be worked out in full detail. Process planning has become more complicated and the amounts of information to be handled have increased. This asked for automation of the task.

Process plans became ever more machine tool specific as conventional machine tools were gradually replaced by numerical controlled machine tools. Due to the rapid developments in this area, subsequently acquired machine tools nearly always differ from older ones. This leads to a large number of different machine tools and controllers on the shop floor, which reduces the interchangeability of process plans. Something has reduced flexibility in planning, often resulting in bad utilization due to unbalanced loading of machine tools and the impossibility of reacting to disturbances.

Market developments urged a reconsideration of the production planning task as well. The required products have become increasingly customer specific, resulting in smaller batches, decreasing both the predictability of demands and the possibility of producing for stock. On top of this, the ever increasing requirement for shorter delivery times causes an everlasting pressure for shorter throughput times. Both the influences from the market and the high costs of modern manufacturing systems put high demands on production planning. This has frequently been recognized and in recent years much research has been focussed on the development of better production planning methods.

This paper focusses on the problems resulting from the reduced flexibility in production planning when machine tool specific process planning is required. First, both the process and the production planning problem are analyzed. Based on this, a solution is proposed. The solution consists of the generation of a number of partially worked out process plans, from which the best one is selected. For this, both the technical quality of the different potential plans and the corresponding load on the available machine tools is considered. The present work forms part of the development of an integrated planning system called PART (Planning of Activities, Resources and Technology) which is presently under development in the Laboratory of Production Engineering of the University of Twente. The scope of the system is dealt with in Section 3. Subsequently the method to select the most appropriate process plans, considering both the technical quality and the limited availability of resources,

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is described. Furthermore, attention is paid to the estimation of machining times which play an important role in the selection process. Finally some conclusions are drawn and subjects for future research are mentioned.

2. THE PLANNING PROBLEM

In the previous section, process and production planning have been described as two distinct problems being solved separately. A closer look at these two planning problems shows that both can be seen as sub-problems of one overall production control problem. In production control, a distinction is made between planning and control aspects. The planning function determines how production should be organized in order to reach the goals set. The usual separation of process and production planning can be explained from the need to divide the planning problem in a number of easier to solve sub-problems. Another reason for separation is that process planning is focussed on individual products, while production planning typically deals with a set of orders, competing for the available capacity. The disadvantage of the separation is that interdependencies between the two problems are not considered, which, in particular in small batch manufacturing, may lead to non-effective sub-optimizations and poor solutions of the overall planning problem.

To find a solution method which takes interdependencies into consideration, it is important to define what a dependency is. A dependency between problems exists when a decision taken in one problem reduces the solution space of the other problem. Dependencies exist between process and production planning where the selection of limited resources is concerned. In process planning, resources like machine tools, tools, jigs and fixtures are to be selected. A selection reduces the solution space of the remaining planning problems, especially as regards the loading of the machine tools. A selection based only on the technical suitability of resources may frequently lead to an unbalanced load and consequently a bad utilization of the resources. Therefore the limited capacity of the manufacturing system should be taken into account when solving the process planning problem.[1]

Not considering dependencies was justifiable in the case of the conventional factory. Dependencies weren't critical then since many machine tools were similar and most of the process planning was left to the operator. Apart from that, it would not have been possible to keep track of alternative solutions and the relations between them, not to mention the selection of the best alternative, without the use of information technology. Today there is both the need and the possibility to consider the dependencies.

The present paper focusses on the limited availability of machine tools and the dependencies between the planning problems resulting from that. The limited capacity of other resources such as operators and auxiliary equipment is left out for the present.

3. THE SOLUTION

To take into account interdependencies between two problems, it is necessary to solve either both problems as one integrated problem or to consider the consequences of decisions taken in one problem for the solution space of the other and to estimate their influence on the quality of the solution of the overall problem.

In the present case, the selection of machine tools is treated as one problem dealing with aspects of both process and production planning. The problem is referred to as the loading problem.[2] The decisions taken in loading reduce the solution space of a number of machine tool dependent process planning steps and the scheduling problem. The solution of the total planning problem is eventually embodied in a workplan, which includes a number of process plans and a schedule. The consequences of the decisions for the expected quality of the workplan are taken into account. In fact, the estimated quality of different alternative process plans and the influence on an eventual schedule are considered when selecting machine tools during the loading process. The quality is defined as the degree to which the goals set in process and production planning are reached in respectively the process plan and the detailed production plan (schedule).

In process planning the goals are the control of manufacturing costs, while in production planning the following partially conflicting objectives are strived after:

- short throughput times,
- reliable delivery dates and
- minimum manufacturing cost.

The goals strived after in loading are derived from those above and are dealt with in Section 4 where the loading process is described in more detail.

To consider the quality of the different alternatives, a lot of information is needed. The determination of this information is often not considered in present loading methods, which may be explained by the isolated treatment of the loading problem. Consequently little has been said about the way to obtain this information, although this is an interesting problem in itself.

The alternatives considered in loading may vary from a different machine tool for a set-up to completely different process plans. The estimation of the data for the different alternatives could be obtained by creating the corresponding detailed process plans. This, however, represents a large amount of redundant work, since only one of the alternatives will be used eventually.

In the present case a different approach is followed. A number of alternative process plans as regards the assignment of work to machine tools is considered. However, they are only worked out to the level of detail which allows an estimation of the machining times. This results in an acceptable amount of planning effort and redundant work. Something of this has been implemented in the PART planning system which will be dealt with in the next section.

3.1. *The PART system*

Figure 1 shows a reference model used for the development of PART.[3] It represents a modular system consisting of functional, auxiliary and service modules. The auxiliary modules include a CAD interface (CI), a product modeler (GPM), a feature recognition and parameter extraction module (FR) and an editing tool (VE).

Each functional module consists of a number of phases. These individually executable programs communicate via a relational database which is interfaced via a dedicated service module. The execution of the planning process is controlled by another service module, the supervisor. It interprets planning scenarios describing the order of execution of the phases, starts the phases according to that order and handles errors that might occur. The user may implement and select different planning scenarios allowing different approaches to the solution of the planning problem.

In the planning process the following three parts are distinguished:

- Those process planning functions which are performed before a machine tool is specified. These process planning steps are in general not time critical and are executed for each product type to be manufactured.
- The selection of machine tools: the loading task. In this part, a set of manufacturing orders, to be realized within a user specified planning horizon, is considered. In loading, the resoures to be used for the realization of the orders are determined. The loading will be elaborated on in Section 4.
- The process planning functions which generate machine tool specific data. These process planning steps are preferably performed shortly before actual machining takes place. This provides an increased flexibility to react to unexpected occurrences. Consequently, the execution of these process planning steps becomes rather time critical which is a disadvantage that can be overcome by automating execution, as is realized in the PART system.

In the following paragraphs, the most important process planning steps are described. An example of the sequence in which the different process planning steps and loading are carried out is depicted in Fig. 2. Other sequences may be defined by the user, specifying another scenario. Notice that the boxes shown in this figure represent process planning steps instead of phases. Each process planning step consists of a number of phases.

The functions of process planning steps belonging to the first group identified above, i.e. those that are taken before the loading is carried out, are:

- *Feature recognition (FR).*
  A boundary representation solid model is interpreted automatically, decomposing the product into features. Features represent volumes of material to be machined or part entities which can be

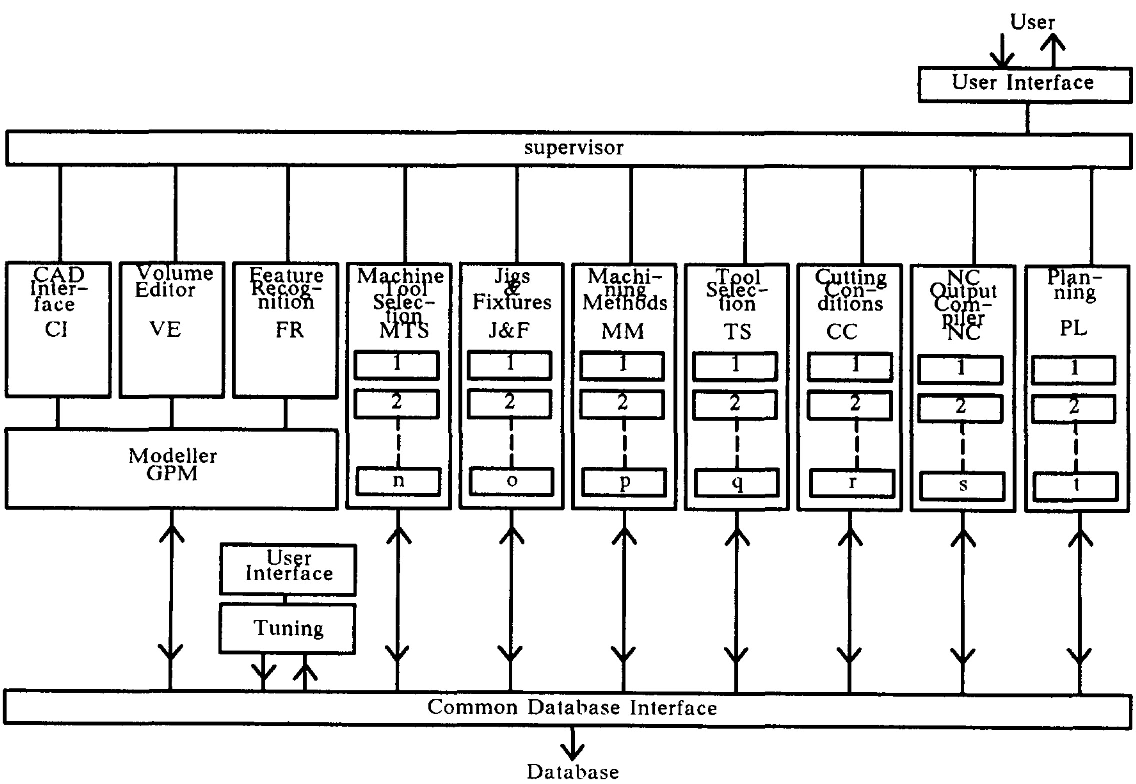

Fig. 1. The PART integrated process planning system.

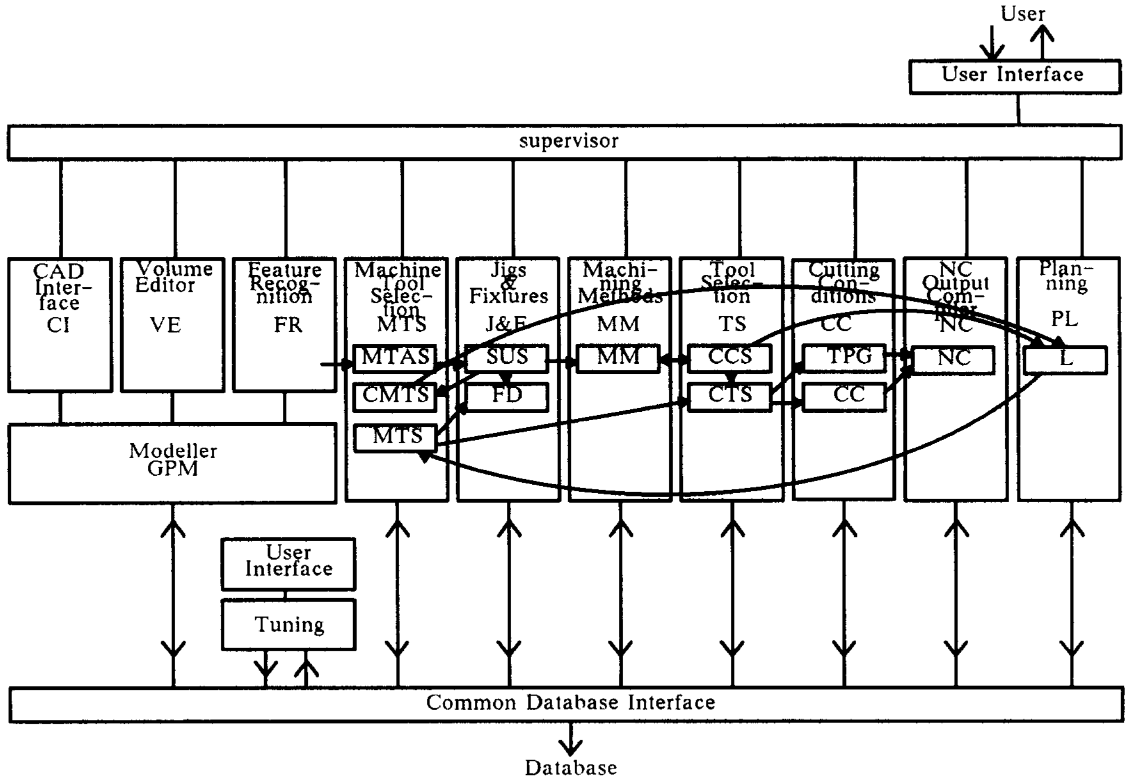

Fig. 2. The planning steps in the PART system.

used for fixturing or measuring purposes. A distinction is made between atomic and compound features. Atomic features are elementary shapes which can be described using a pre-defined set of parameters. Compound features consist of a hierarchy of atomic and compound features. The compound features are the basis for the selection of machining operations. For atomic features, parameters such as orientation, length, depth etc. including tolerances, are determined.[4,5]

- *Selection of machine tool axis configurations (MTAS).*
  Suitable machine tool axis configurations are selected, based on workspace and accuracy requirements of the product to be machined.
- *Set-up selection (SUS).*
  The features to be machined in a set-up are selected on the basis of the orientation of the features and the previously determined machine tool axis configuration. The feature orientations have to correspond with the machine tool axis. The features are grouped into set-ups on the basis of tolerance relationships. A set-up is defined as the complete set of operations to be performed while the part is locked in a single fixture.[6,7]
- *Selection of candidate machine tools for each set-up (CMTS).*
  For each set-up, the machine tools which are fit for the machining of the features are determined.
- *Method selection and the determination of the class of cutting tools*[8] *(MM & CCS).*
  Since the cutting tool class and the method selection are closely related, decisions concerning both of them are made in the same process planning step. The specification of the tool classes is given by the type of tool and attribute ranges such as diameter and working length. Depending on the planning strategy, cutting tools and methods may be selected before the machine tool.

After these process planning steps have been performed, information to perform the loading (L) is available or can be estimated. After loading is performed, the machine tools to be used are known. Then the process plans can be worked out in full detail. This is done in the following process planning steps.

- *Fixture design (FD).*
  The selection of fixture tools and the design of the fixturing configuration required to fix a product on a pallet or machine tool table are carried out.
- *Cutting tool selection (CTS).*
  The specific cutting tools, adapters and tool holders are selected.
- *Determination of tool paths and machining parameters (TPG & CC).*
  For each operation, the tool paths and the machining parameters are calculated.
- *NC program generation (NC).*
  The tool paths for the different operations in each set-up are put together and the NC program is generated.

4. LOADING

In order to describe the method of solving the loading problem, first some entities are defined and assumptions are made. The entities and the relations between them are visualized in Fig. 3.

The orders for a manufacturing system are supposed to have (internal) due and availability (release) dates, referred to as time windows.[9] An order describes the number of pieces of a specified part to be manufactured and the due date before which the required parts have to be ready. An order is split into a number of batches. A batch is a number of parts to be realized using a specific type of blank. To indicate the moment after which manufacturing of the batch can start, the availability date is added. A product, as considered here, is described by both a part and a blank model.

There are different reasons for splitting orders into batches. The most important ones are:

- the possibility of using different blank types for an order.
- the possibility of controlling the size of the batches.

The decisions to be taken in loading consist of the selection of the resources, in particular the machine tools. The possible assignment of work to machine tools is represented as a (partly worked out) process plan.

Alternative process plans can be provided for:

- different machine tool configurations (used for the determination of the set-ups);
- different groupings of features in set-ups;
- different machine tools capable of machining the features in a set-up.

In principle a process plan consists of a number of set-ups assigned to machine tools. The machining of features in a set-up on a machine tool for all the products in a batch is referred to as a job. The duration of a job (including load, unload and tool change times) is called the job time.

In loading, a process plan is selected for each batch together with the planning period in which the parts have to be manufactured. Combinations of process plans and planning periods are the alternatives considered in loading.

To select the best alternatives, the goals strived for in loading have to be identified. These are derived from the goals of process and production planning as mentioned earlier.

For loading the objectives are the realization of the orders before the due dates and the reduction of cost. The throughput times are not considered here because they are controlled by the due dates. To quantify the quality of the different alternatives with respect to these goals, the evaluation time is introduced, which will be discussed in the following paragraphs.

4.1. *Evaluation time*

In estimating the quality of an alternative, planners, consciously or not, consider many different factors. They are, however, not always equally important and have to be weighted against each other. To be able to take decisions automatically, the quality of the different alternatives has to be quantified. To ensure the acceptance of the decisions taken by the system, the quantification of quality must comprise all important factors.

In comparing process plans, the most important factor is cost. In evaluation time not only are the machine tool costs considered but auxiliary tasks are taken into account as well. These include the preparation of set-ups, tool changing and transport. From the production planning point of view, the moment of realization of an order with respect to the due date is a main point of interest. This aspect is also expressed in the evaluation time. All the factors are weighted and summed to obtain the evaluation time. The following paragraphs elaborate on the different evaluation time components.

4.1.1. Manufacturing costs. Although many costs are already fixed in the design of the product, manu-

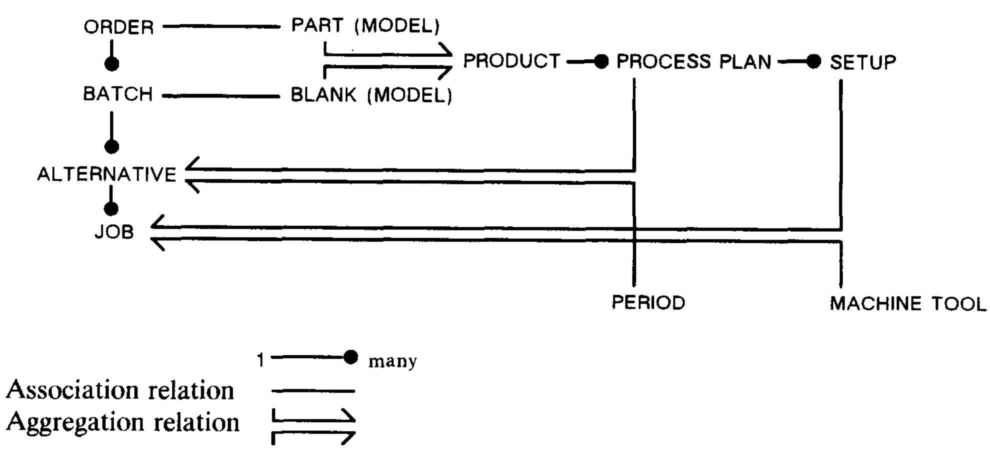

Fig. 3. The relations between the different entities in machine loading.

facturing costs depend partly on the process plan and in particular on the resources used. The latter can be influenced in loading.

By noticing that the resources are available anyway and that in the short term most of the costs are fixed, it can be seen that the cost per product can be minimized by maximizing the output. The maximum output can be obtained by claiming as little time as possible for resources that determine output, for each product to be manufactured. Identifying the machine tools as output determining, these times are called machine times, not to be confused with machining times which are merely part of the machine time along with other times such as tool changing times, load/unload times etc. The maximization of the output can thus be translated into the goal of minimizing the sum of the machine times for a total order set.

The application of this objective may result in heavy loads on the best and most powerful machine tools while other machine tools are idling. When certain machine tools tend to be overloaded, less suitable machine tools must be used too. This approach can be translated into the next optimization problem:

> minimize the sum of the machine times of all the manufacturing orders, with the condition that no machine tool is overloaded.

4.1.2. Auxiliary activities. In the approach described above, only the machine time needed for the realization of a complete order is considered. However, there are other factors that may influence the selection of an alternative. Examples are: the need to carry out auxiliary activities such as off-line preparation of set-ups, transport etc. which do not claim the capacity of a machine tool but significantly influence the efficiency of the manufacturing process.

An evaluation time component is added to be able to consider these activities when solving the loading problem. This is necessary for the following reasons:

- *The limited capacity of subsystems.*
  In the optimization method the machine tools are assumed to be output determining. To let this assumption hold, it is necessary to limit the load of the subsystems since in a carefully designed manufacturing system no excess capacity will be available. By considering the load on auxiliary equipment during loading, overload of the subsystems can be prevented.
- *The acceptance of the planning results.*
  Although production tasks will increasingly be performed automatically, man will always be responsible for the decisions made. This puts high demands on a planning system regarding the reliability and acceptability of the decisions taken. Decisions taken by the planning system must be comprehensible and largely respond to the insights of the planner. To obtain this, a transparent quantification of the relative quality of different development alternatives, comprising the influence of auxiliary tasks, is required.

The evaluation time consists of the machine time and additional "times" representing penalties for auxiliary tasks. The amount of "time" added for such a task depends on:

- The type of activity to be carried out;
- The duration of the activity;
- The subsystems used for the activity.

The penalties are calculated by estimating the duration of the activity and multiplying it with a user controllable weighting factor.

In the present case, weighting factors are introduced for transport, for activities performed at the set-up station and for tool changes. The introduction of other factors may be necessary in other cases. To determine the value of the weighting factors, the following methods are applicable:

- *Iteration.*
  Perform the loading procedure using initial values for the different weighting factors. Evaluate the quality of the resulting capacity plan with respect to the load on the subsystems. Enlarge the weighting factors on the overloaded subsystems and reduce the weighting factors for the underloaded ones. Perform the loading procedure again and repeat these steps until an acceptable capacity plan is achieved. Once the weighting factors are adjusted they can be used in future loading sessions as long as the system and order set characteristics don't change too much.
- *Estimation by the operator.*
  The operator considers the acceptability of the different auxiliary tasks and estimates the corresponding weighting factors so that the results comply with his experience.

A combination of both methods is also possible.

4.1.3. Assignment to time intervals. Loading not only comprises the assignment of work to resources but also to time intervals. Since exact sequences of jobs are not determined yet (a scheduling task), work is assigned to periods, usually corresponding to days or shifts. To control the period in which an order must be realized, another evaluation time component, the period-evaluation time, is introduced. The value is also controlled by a number of user definable parameters as shown in Fig. 4.

A rather large penalty, the Lateness Penalty, is added to orders trespassing the due date. The penalty increases with lateness at a rate depending on the Lateness Penalty Coefficient. To prevent orders from being late due to unexpected events, it is possible to influence the number of periods the order is realized before the due date (Number of Periods Early and Earliness Coefficient). The same mechanism is used to prevent too early realization.

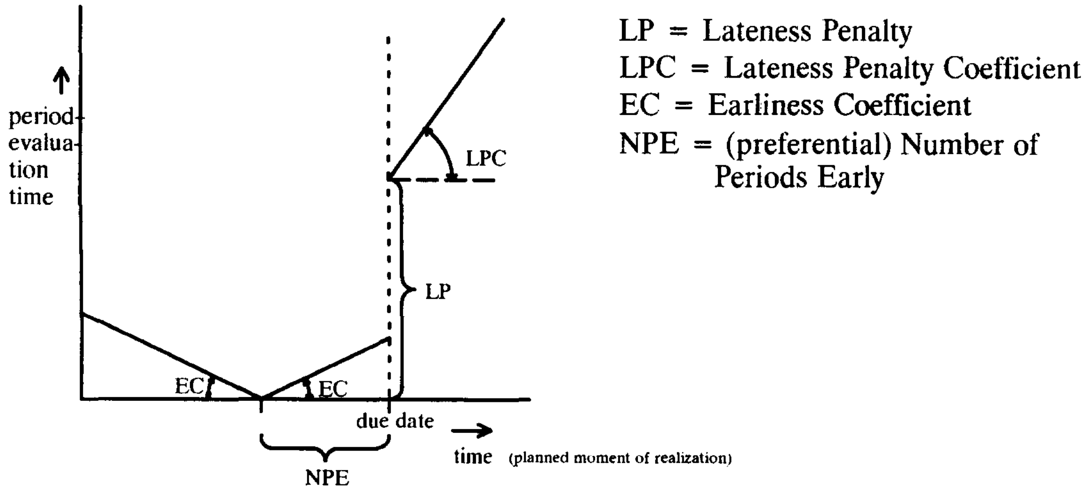

Fig. 4. Period-evaluation time as a function of the planned moment of realization.

4.1.4. Evaluation time components. For the calculation of the evaluation time, three time components are distinguished:

- The fixed evaluation time, which consists of the machine time and weighted penalty times for the auxiliary tasks directly related to the process plan (such as set-ups, transports etc.)
- The variable evaluation time, consisting of weighted penalty times for those activities that are not directly related to the process plan. For instance, the need to change tools not only depends on the tools needed for the machining of a given job but also on the tools available on the machine tool (which may in turn depend on the other jobs assigned to the machine tool).
- The period-evaluation time, which is the penalty time that depends on the period in which the order is realized.

These three time components are added up to obtain the evaluation time, which is a relative measure for the efficiency in use of a process plan as part of a work-plan.

4.2. *Problem formulation*

The loading problem is modelled as the minimization of the total evaluation time for a set of orders subject to capacity constraints. The problem can be formulated as described below.

$$\text{Minimize} \sum_{o=1}^{no} \sum_{b=1}^{nb_o} \sum_{p=1}^{np_{ob}} \sum_{t=1}^{nt} x_{obpt} \cdot e_{obpt}$$

subject to

$$\sum_{o=1}^{no} \sum_{b=1}^{nb_o} \sum_{p=1}^{np_{ob}} \sum_{t=1}^{nt} l_{mt'obpt} \cdot x_{obpt} \leqslant c_{mt'} \qquad m = 1 \ldots nm,\; t' = 1 \ldots nt$$

$$\sum_{p=1}^{np_{ob}} \sum_{t=1}^{nt} x_{obpt} = 1 \qquad o = 1 \ldots no,\; b = 1 \ldots nb_o$$

$$x_{obpt} \begin{cases} = 1 & \text{if batch } b \text{ of order } o \text{ is manufactured according to process plan } p \text{ and is planned to be ready in period } t \\ = 0 & \text{else} \end{cases}$$

where

- $l_{mt'obpt}$ load on machine tool m in period t' incurred by manufacturing products of batch b of order o according to process plan p, when planned to be ready in period t
- e_{obpt} evaluation time, related to manufacturing products of batch b of order o according to process plan p, when planned to be ready in period t
- c_{mt} capacity of machine tool m in period t'
- no the number of orders
- nb_o the number of batches of order o
- np_{ob} the number of alternative process plans for batch b of order o
- nt the number of planning periods
- nm the number of machine tools

5. ESTIMATION OF JOB TIMES

For the evaluation of the efficiency in use of process plans, it is necessary to estimate job times from partially worked out process plans. They not only play an important role in the evaluation time, but are also important for the calculation of the loads of the machine tools. The job time consists of the following components:

- The load/unload times, the values of which are supposed to be known for each machine tool or have to be estimated in cases where no pallets are used.
- The time needed for positioning the product with respect to the cutting tool before each operation, estimated on the size of the product and the number of features to be machined.
- The time needed for tool changing, depending on the number of tools needed and the machine tool dependent tool changing time.

- The machining time required to realize the features in the set-up. The machining times have to be estimated. How this is done in PART is described in the next section.

5.1. *Estimation of machining times*
Each product is decomposed into a number of features. Decisions concerning machining are based on these features, which provides the possibility to consider the individual features for the estimation of machining times.

To be able to estimate machining times automatically, research has been directed into the determination of relations between the machining time and the feature parameters in combination with the specifications of the machine tool. To obtain these relationships, the factors influencing the machining times have to be identified first. They include:

- the volume to be removed;
- the material of the product;
- the cutting tool used;
- the machine tool used;
- the required tolerances and roughnesses;
- the area in which the tolerances and roughnesses have to be realized.

In principle there are two ways to obtain the required relationships:

- By analyzing the technological models used for the calculation of the cutting conditions and the tool paths.
- By analyzing process planning results for different features and thus trying to find relationships between the planned machining times and the feature parameter values in combination with the machine tool characteristics.

The calculation of cutting conditions and tool paths is a very complex activity. There are many relationships, influences and constraints to be considered, which makes it very difficult to derive general relationships. Therefore, the latter method is currently applied, by which insights gained from analyzing the decision making process are used to predict the most important influences. To ease the finding of the relationships, a distinction is made between the time needed to remove the bulk of material and the time needed for finishing, i.e. to realize the required tolerances and roughness.

6. IMPLEMENTATION

A planning session in PART as visualized in Fig. 5 can be divided in three steps:

- *Preparation.*
  The input of all kinds of data, which are needed for the planning session.
- *Calculation and optimization.*
  The generation of alternative process plans, the calculation of machining, job and evaluation times and eventually the selection of alternatives.
- *Presentation.*
  The results of the preceding steps can be analyzed, evaluated and when necessary be altered by the user.

Each of these will briefly be described in the following paragraphs.

6.1. *Preparation*
The application dealing with preparation is supported by a user interface in the standard PART layout. The main functionalities correspond to the three main menu items: order management, session management and parameter setting.

Order management. Since the PART system has no direct link to a higher level production control system, production orders have to be entered manually. This is done by defining orders and subsequently specifying the parts that have to be manufactured. Order size and due dates are also entered. For each batch the number of products to be manufactured, the type of blank used and the availability date have to be specified.

Session management. A planning run is called a session in PART. Session management allows for the input of some typical planning data such as the planning horizon and the periods distinguished in it, along with the capacity of the different machine tools in the different periods. The user has to create a session by defining a set of subsequent periods, which in turn have to be defined by entering the begin and the end of the period. After that, the capacities of the machine tools in the different periods must be set according to the actual availability.

Parameter setting. The parameter setting screen offers the possibility to set the parameter values controlling the values of the different evaluation time components. After the data input steps have been gone through, the loading process can be performed. How this is done has been outlined in the previous paragraphs. How it is implemented is described below.

6.2. *Calculation and optimization*

Determination of the order set. Based on the planning periods considered in the session and the time windows applying to the orders it is determined which orders have to be considered in the current session.

Determination of the product set. In the order set different orders may exist for the same product. Since most of the calculation phases have to be carried out only once for each type of product, it is important to

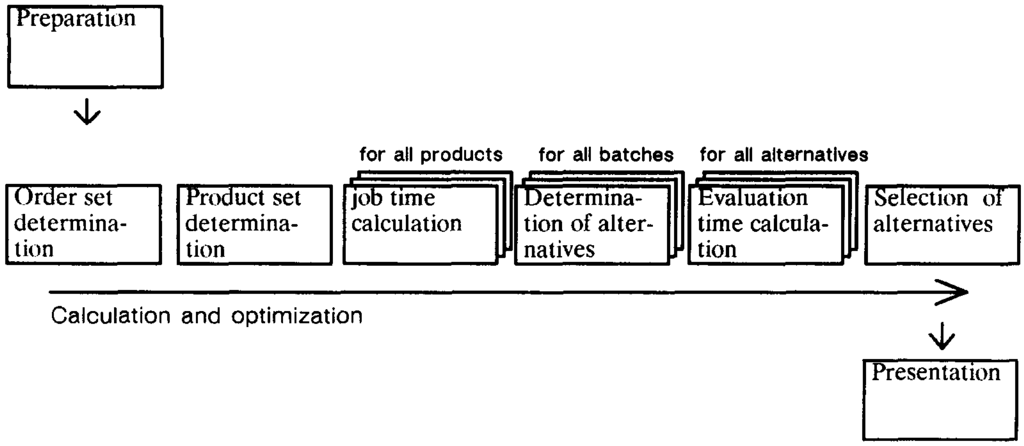

Fig. 5. The loading phases.

know what different types of products are concerned in the planning session in order to prevent superfluous work.

Estimation of job times. For each feature of a product, the machining times are estimated. For each job these estimates are used to calculate the estimated time required for the realization of the job.

Determination of alternatives. For optimization purposes, a number of partially worked out process plans is generated. Because of the large number of alternatives a pre-selection must be made. In doing this, the number of alternatives to be considered in loading is reduced by skipping alternatives that differ only slightly from other alternatives or that aren't likely to be selected due to the obvious bad quality of the process plan (i.e. too many set-ups required, too tight tolerance relationships between the set-ups etc.). The remaining process plans combined with the possible planning periods represent the alternatives considered in the optimization phase.

Evaluation time calculation. In this phase the evaluation times of the alternatives are calculated.

Selection of alternatives. The optimization is carried out by performing the previously described loading process. In selecting the alternatives, resources are implicitly determined. This provides the information needed to perform the remaining process planning steps.

6.3. *Presentation of the results*

The results of the loading process are presented in a user-friendly way, giving the operator the possibility to verify, evaluate and, when necessary, alter the decisions taken. The loads planned on the various machines are shown along with the values of the evaluation time components. For distinct batches it is possible to obtain the reasoning for the decisions made by the system. The contribution of the different jobs to the loads of the various machine tools is visualized. The influences of the selection of another alternative on the load of a machine tool and the corresponding evaluation times can be shown too. When the results are not satisfactory, the user is able to overrule.

7. CONCLUSIONS

The changes in manufacturing systems and market developments urge the reconsideration of process and production planning methods. To improve decision making in planning, these problems must not be solved separately, but dependencies must be taken into account by the integration of the planning tasks. One of the major dependencies results from the limited availability of resources. A method to take this interdependency into account has been described. It includes the generation of partially worked out process plans from which the best is chosen, considering the availability of the resources in the different planning periods and the auxiliary tasks to be carried out. The consideration of alternative process plans instead of alternative machine tools for individual set-ups also allows the consideration of alternative machine tool configurations, which provides extra flexibility. Although some effort is necessary to estimate the required data such as job times, the amount of redundant work needed to work out a number of alternative process plans in detail would be much larger. A drawback of this approach is that no alternative process plans are available at run time, reducing the flexibility of (on-line) scheduling. The automation of the process planning task allows for fast generation of process plans though, which may help to overcome this drawback.

The software is currently being tested and experimented with. The results so far seem promising but a subsequent use of real world data is necessary to give a better insight in the quality of the proposed solutions and to arrive at more thorough conclusions. Future research is directed towards the improvement of the estimation of job times, methods of pruning the set of alternative process plans to be considered in loading and the assignment of cutting tools to machine tools.

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