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IMPLEMENTATION OF AN ENGINEER-TO-ORDER MANUFACTURING PLANNING SYSTEM (ETOPLAN)

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ABSTRACT. This paper describes a decision support system (EtoPlan) that can handle a concurrent processing of the technological and logistic planning within a complex engineer-to-order manufacturing environment. The system is capable of dealing with uncertainty, caused by incomplete and unreliable information. These two aspects are essentially present in the higher level planning activities in the specified manufacturing environment. Some Graphical User Interfaces are presented and explained in order to show the practical use of the system. The system is developed for implementing and testing a new approach on concurrent manufacturing planning and control.

INTRODUCTION

The ongoing demand for shorter delivery times and client specific products does invoke the need for more concurrency in the generation of the technological (engineering) and logistic (production planning) information. Within an engineer-to-order manufacturing environment, the co-ordination of the activities of the diverse disciplines is indispensable. In order to meet the company's global goals, it must be prevented that the departmental experts merely focus on local optimisation.

The research project reported here is carried out for manufacturing environments that deal with a huge variety of product types produced in small batches on general-purpose machine tools. This results in a dynamic and complex production process. A prototype implementation for concurrent manufacturing planning within an engineer-to-order environment has been developed. The system, named (EtoPlan), is capable of dealing with uncertainty, caused by incomplete and unreliable information. These two aspects are essentially present in the higher planning levels of the specified type of manufacturing environment. The technological and logistic information that is already available is presented by the system to the various planners (salesmen, process planners, and production planners). Important is what information must be presented and how (Kals and Lutters, 1998). Each planning activity requires its own representation of the information that is available at the various locations in the company. The system processes the information, tailored to the needs of the planning activity that is being performed. For instance, the system can provide the process planner with information about the expected availability of the resources that are taken into consideration for executing a given process step.

The first part of this paper briefly describes the concept for dynamically planning production orders. All manufacturing planning processes performed throughout the life-cycle of the order - from order intake until delivery - are being supported by the concept. The planning activities will be performed concurrently if possible. In order to be able to process the huge amount of information - a result of planning concurrently - several levels of abstraction are applied in the planning processes.

In the remainder of this paper, the prototype implementation is described. Attention is paid to the graphical views presented to the planners.

CONCEPT DESCRIPTION

Applying several levels of abstraction in the planning process is necessary for reaching the tactical goals while at the same time dealing with short term control issues (Washington, 1994). Likewise, it may prevent the undesired situation of too much replanning work. This is achieved by avoiding too much detail in the earlier planning phases. The production environment is too dynamic to plan newly entered orders directly in a detailed manner. Nevertheless, the aim is to recognise the probable occurrence of (capacity) problems as early as possible.

Within an engineer-to-order environment, a client order that enters the company initiates engineering activities resulting in various suborders that are subsequently planned and/or executed by the company. In this way, a hierarchical order structure is build up. Building up the structure requires a hierarchical planning strategy. First, a process planner performs the macro process planning tasks. In this planning phase, the rough routing of the product through the manufacturing process is determined. Some departments and possibly some subcontractors will be notified about the production activities that have to be performed. Subsequently, the process planners of the departments determine a more detailed routing. When the workstations required for the execution of the process steps are known, the micro process planning tasks - like NC-programming, tool selection, and fixture design – can be performed. Just like the process planning tasks, also the production planning tasks should be planned hierarchically in order to be able to follow the road from the long term planning horizon on to the short term planning horizon. Preferably, the higher level production planning tasks, e.g. capacity planning, are performed concurrently with the macro process planning tasks. In this way, the decisions to be taken can be tuned to one another. The EtoPlan system, as is described in the next chapter, supports the integration of the higher level tasks in both process and production planning. Because of the diversity in the existing definitions of 'capacity planning', let us clarify what is meant by capacity planning in this paper. *Capacity planning* is defined as a view on the aggregate planning of orders, considering the capacity and the resource availability constraints.

The level of abstraction in the plans decreases as the plans are further filled in. On the higher levels of abstraction, where the capacity planning task is performed, mostly rough planning decisions, related to method selection, subcontracting, and route determination, are taken. Because of that, the input information for capacity planning is often incomplete. It is not exactly known how much time a certain activity will take, as a result of:

- the lack of detailed process planning information, and
- regularly occurring disturbances.

In applying capacity planning early in the process of concurrent manufacturing planning, i.e. on the higher levels of aggregation, some difficulties are encountered. The allocation of specific resources to the orders is often not possible on the higher levels of aggregation. In particular, order acceptance often has to quote an initial price and delivery date quickly, leaving no time for a detailed process planning at that stage. As a consequence, these quotations have to be based on rough capacity plans. Similarly, not all production orders are already known for a relatively long time period. Hence, it is impossible to perform resource specific loading or scheduling at an early stage in the traditional way.

In spite of the uncertainty and incompleteness in the plans, reliable information should be obtained about e.g. the contingency of capacity problems in the near future. Consequently, 'optimisation' strategies for production planning must take the unreliability into account. In order to draw up sensible plans, the uncertainty is integrated explicitly in the plans. Below, we describe how to model this uncertainty, making decision support possible and reliable.

Estimating the lead time

Let a denote an estimation of the minimum lead time, b an estimation of the maximum lead time, and finally m an estimation of the most likely lead time. A common way to characterise the variability of the lead time is to fit a Beta distribution on these three parameters. We define the mean value μ of the lead time by

$$\mu = \frac{1}{6}(a + 4m + b).$$

Similarly, The variance v is defined as

$$v = \left[\frac{1}{6}(b-a)\right]^2$$

It can be shown that the following Beta density function $f(x)$ has exactly the above mean and variance,

$$f(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)(b-a)^{\alpha+\beta-1}} \times (x-a)^{\alpha-1}(b-x)^{\beta-1}, \qquad a \le x \le b, \quad \alpha, \beta > 0,$$

with α and β chosen such that they satisfy

$$\mu = a + \frac{\alpha}{\alpha+\beta}(b-a), \qquad v = \frac{\alpha\beta(b-a)^2}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

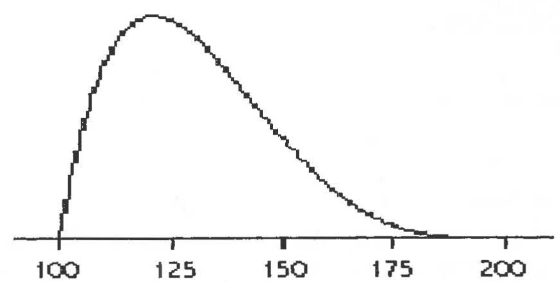

Figure 1. Beta distribution of the lead time of a (sub)order

In fact, the lead times of the (sub)orders are a result of the planning process. Based upon a characterisation of both the processing times and the waiting times (mainly caused by congestion due to capacity constraints), the lead times discussed above are estimations of the actual lead times. In an engineer-to-order manufacturing environment, it is difficult to generate exact values for the lead times because the process information is only roughly known. Therefore, the uncertainty of lead times is modelled by using PERT networks (Soroush, 1994). Stochastic critical paths indicate the probability of exceeding the due-dates. Beta-distributions of the lead times are defined, based on estimations of minimum, maximum, and most likely lead times (figure 1). Many authors have discussed the logic behind these formulas, which are used in the 'classical' PERT procedure (Lau and Somarajan, 1995). There is considerable confusion in the literature on what 'a' and 'b' should correspond to. To the original PERT developers (Malcolm, *et al.*, 1959), a and b correspond to the 'absolute endpoints' T_0 and T_1, respectively. However, the majority of current operations management textbooks state that that a and b should be T's 0.01 and 0.99 fractiles (Lau and

Somarajan, 1995). Lau and Somarajan propose an improved procedure, which is however based on preferably more than three fractile estimates. For the planning system described in this paper, it is assumed most practicable to apply the 'classical' PERT procedure, as defined by the above mentioned formula's. It is, for the performance of the system, of minor importance whether the absolute endpoints or the 0.01 and 0.99 fractiles are use for estimating *a* and *b*.

Estimating the processing times

In practice, also the processing times are often modelled by a Beta-distribution, fitted to the minimum, maximum and most likely value estimation, similarly to the procedure for the lead times. The EtoPlan system takes only the mean processing time values into account. The distribution is not useful, because, for capacity planning, the processing times are accumulated and compared with the available capacity. In this way, the activities that take more time than indicated by their mean values will be compensated by the activities that are finished earlier than specified. Because of the huge amount of orders that are planned in the same time period, this approach is justified. Further tests will be performed in order to check the reliability of the summed up capacity requirements calculated in this way. Note that the mean values, as derived above, often exceed the initially specified most likely values, since typically $a\text{-}m \geq m\text{-}b$, indicating that it is more likely that the process is delayed rather than shortened. Hence, some buffer against processing delays (e.g. quality faults) has already been included in the above procedure.

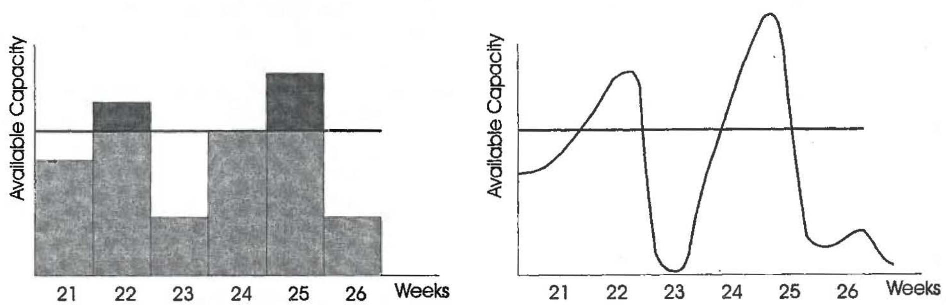

Figure 2. (a) Loading periods (b) Continuous loading profile

The planned start time

The planned start time depends on both the lead times of the preceding process steps and the number of other orders that compete for the same resources. If it is, for instance, not yet possible to determine whether a suborder will be executed in week 12 or week 13, this decision can be postponed to a later planning phase. In this way, maximum flexibility is maintained in the plans. Normally, loading period procedures are applied for this kind of aggregate capacity planning (figure 2a). However, these loading periods are set for mean time margins and do not discriminate between critical and non-critical orders. In order to be able to handle both critical orders with relatively little slack and e.g. production-to-stock orders with more slack, a different continuous planning strategy is applied (figure 2b). A mean start time is set for the (sub)orders and the necessary slack is integrated by assuming a normally distributed deviation over the start time. A small deviation is allowed for critical orders and larger deviations may hold for orders with more slack, depending on the individual characteristics of the orders. Apart from the possibility to distinguish between critical and non-critical orders, also the level of completeness of the technological plans and the level of uncertainty can be taken into account when determining the deviations over the planned start times.

As mentioned before, it is not useful to attempt to generate exact values of lead times, processing times and start and completion times of the suborders. However, an exception can be made for the

planning of very critical and therefore high priority orders. Other activities will be planned around such early fixed orders in a latter phase of the production planning.

Allocation of the resources

Like the determination of the production times, also the resource task has to deal with incompleteness of information. It is, for instance, often not known whether a resource is available at the desired time of production, due to e.g. operator unavailability, maintenance activities or rush orders. It is also difficult or even impossible to judge the capability of the resources for performing the production activity, if the technological requirements are only roughly known. Therefore, we apply the approach of 'least commitment'. That means that a resource is ***applicable*** if:

1) The resource is considered capable of meeting the already known technological requirements in the roughly defined process plans for executing (a part of) the suborder.
2) The resource is considered to be available during a time period that is roughly planned for executing (a part of) the suborder.

An Applicability Group (AG) is defined as the group of resources, which are applicable, as defined, to execute a given suborder (Giebels *et al.*, 1999).

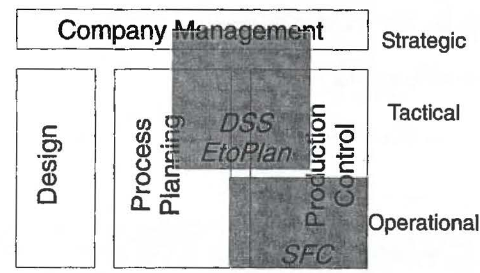

Figure 3. Positioning of EtoPlan and SFC, related to the planning and control functions.

IMPLEMENTATION

A prototype decision support system for integrated order planning (EtoPlan) has been developed. Its purpose is to analyse and test the conceptual ideas that have arisen from the research project 'integration of process planning and production control' (Giebels *et al.*, 1998). The implementation covers the planning on the higher aggregation levels where both macro process planning and capacity planning take place. Figure 3 displays the position of the EtoPlan system in a reference model for manufacturing planning and control. It supports the decision making tasks of both capacity planning and macro process planning in order to achieve concurrency in the planning. It is not aimed to completely automate the planning tasks. Various types of planning strategies can, thus, be supported. The EtoPlan system provides the user with information about both resource availability estimates for each individual order and capacity problems that are expected in the near future, independent of whether it aims to minimise throughput times or e.g. to maximise the overall throughput. Subsequently, a human planner can, possibly with the help of other planning tools, take the decisions necessary for meeting the company's goals. As indicated in figure 3, the EtoPlan system does not cover the lower levels of manufacturing planning and control, i.e. shop floor control and micro process planning. The EtoPlan system interfaces with a shop floor control system. The time horizon makes a strict division between the two systems possible. All suborders that are to be executed, e.g. in the next two weeks, are dealt with by the SFC system. The EtoPlan system continuously reports to the SFC system the new suborders that reach this time line.

The EtoPlan system has been developed using Microsoft Visual C++ Developer Studio 6.0 (Microsoft, 1998b). The system is build up in an object-oriented way. It provides different methods for handling the objects (orders, resources, methods). A tool for navigating through the decision-making procedures is not yet available. More research is currently performed in order to integrate a navigation tool. This tool will support the user in achieving the planning goals by showing the required route for decision making. The system itself does not make any decision.

A number of views on the order plans and the resource (groups) are created in order to supply the user with helpful information in a user-friendly manner, amongst others:

- Order-related views (routing, due-dates etc.).
- Capacity-related views on resources and Applicability Groups.
- Method-related views (e.g. capacity plans of the resources required for milling)

The main views are described in the following paragraphs.

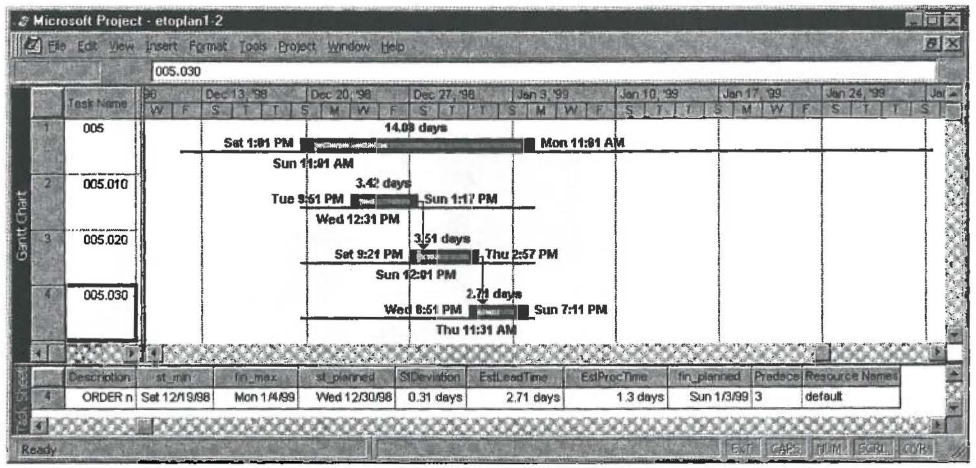

Figure 4. GUI – MS Project – Order Information View.

Order-related views

Order Information View. In order to support the process and production planners in making planning decisions, some views on the structure and the data of the orders are provided by the EtoPlan system. MS Project 98 (Microsoft, 1998a) is used for representing a Gantt chart of the main orders and the suborders belonging to the main order (figure 4). An interface between EtoPlan and MS-Project has been established by means of OLE Automation linking.

The following information about the orders can be represented in the Gantt Chart:

- Planning constraints: minimum start time, (internal) due dates, and precedence relations
- Planning data: estimations of the processing time (minimum, maximum and most likely), estimations of the lead time (minimum, maximum and most likely), the planned start time and the standard deviation over the planned start time.

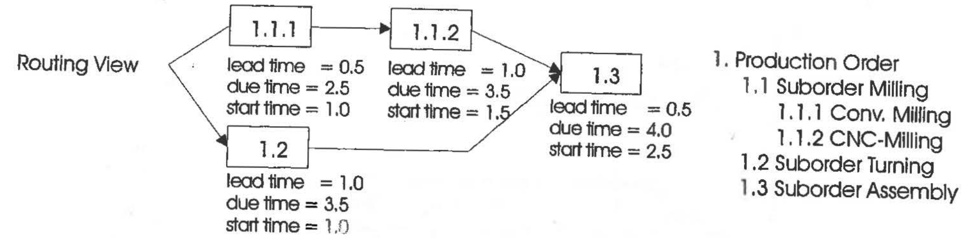

Figure 5. Order network

PERT network. As most information is uncertain, it is difficult to predict which activities will appear to be critical. One of the most important aims of production control is meeting the due dates agreed with the customer. A well-thought determination of the internal due dates of the suborders is therefore of critical importance. The chosen internal due date of a suborder depends on the estimations of the lead times of the suborders that succeed that suborder (figure 5). Because no exact values, but beta-distributions of the lead times are given, the internal due dates are planned on the basis of a required *target probability* of meeting the due date. If there are various internal routings within an order structure (as in the figure), it is not always obvious which internal routing will become the critical path of the order. A critical path refers to the internal routing in an order structure that causes the overall lead time of the order. Critical paths are especially useful for determining the start times of the first process steps of the order. Within stochastic PERT-networks more internal routings may, with a specified probability, appear to be critical paths (Elmaghraby, 1995). It makes the planning of the start times more complex, but also more reliable.

Capacity-related views

AG Availability View. Figure 6 shows an example of an availability view related to a specific order (011). An AG with 3 resources has been created for this order. The maximum capacity of this group of resources is 36 hours/day. The estimated availability (25 hrs) represents the maximum capacity minus an estimation of the idle times of the resources. The profile of the capacity requirement for executing order 011 is drawn on the x-axis. The shape of this profile results from integrating the processing time, the lead time, the start time, and the standard deviation over the start time.

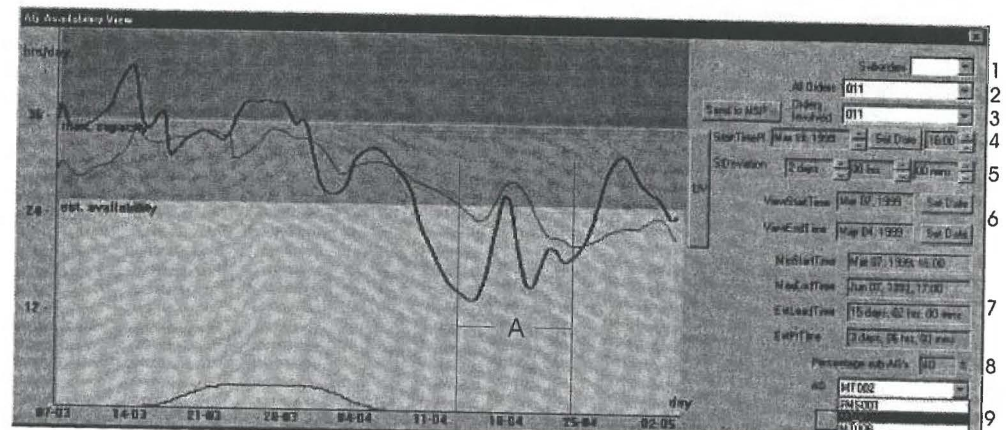

Figure 6. AG Availability View of order 011

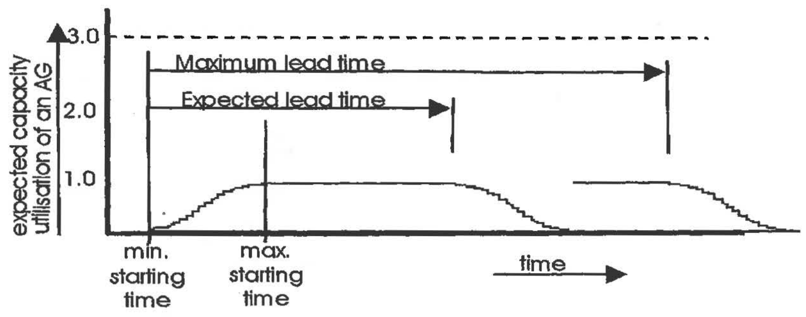

Figure 7. Order profile

Figure 7 shows the profile of an order. The profile represents the probability for the order of being executed at that moment in time. This probability obviously increases from 0 to 1 taking the lead times, the start time and the standard deviation over the start time into account. The first part of the profile (between the min. and max. start time) is established by integrating the Normal distribution of the start time with the standard deviation over the start time as set by the planner. In the AG Availability view (figure 6) only the profile with the expected lead time is presented to the user. For capacity planning also the expected processing time should be integrated in the order shape. The area under the order profile should correspond to the required processing time in order to evaluate the utilisation of the resources required for executing the order. Because the lead time is taken as the basis for building up the profile, the profile must become smaller in the vertical direction in proportion to the relation processing time / lead time.

The other two lines in figure 6 represent the loading profiles to be expected of the group of resources (AG) that corresponds to order 011. The **thick line** is a representation of the loading profile when the estimations of the expected lead times are considered. The area under the line (e.g. area A in the figure) corresponds to the required total processing time of the resources that belong to the AG during a certain time period. The order profiles (figure 7) of all the orders that need one or more resources (in their Activity Groups) that belong to the AG considered - in this case the AG of order 011 - are put together. The percentage of the number of resources, which also belong to the AG considered, determines the amount of the order shape that is accounted for when building the loading profile. If e.g. the AG of order 345 contains 3 resources of which only one also belongs to the AG of order 011, then the order shape of order 345 is for 33% added to the loading profile of AG 011. In the example, this procedure is applied if:

1) The AG contains three resources, but only one resource is required for executing the (sub)order. It is not yet known which one of the three resources will eventually be selected. If all resources do have the same probability of being selected, then all resources are saddled with 33% of the accompanying order shape. It is, of course, also possible that one resource is more likely to be selected. It can, in that case, be saddled with e.g. 80% and the other two resources with e.g. 10%.
2) The order will later be split up into three suborders. Each resource is required for executing one of the suborders. As long as details about the suborders are not yet known, it is presumed that the execution of all three suborders will require the same amount (i.e. 33%) of the processing time.
3) A combination of the previous two situations.

The **thin line** shows the loading profile providing that the estimations of the maximum lead times are considered. The latter will probably happen during the time periods with a high Work in Process (WIP). A peak in the thick line indicates that there is a high probability that a capacity problem will occur at that moment in time. This will go hand in hand with a high WIP. As a result, the lead time of most suborders involved will increase. As expected, the thin line (maximum lead times) shows a smoothing effect compared to the thick line (expected lead-times). If peaks in the thick line occur

and no sufficient corrective actions can be taken, it is likely that the thin line represents the actual situation that will arise.

The list boxes and the input buttons on the right side of the Graphical User Interface, as shown in figure 6, are used for planning some values of the suborder belonging to the Applicability Group considered. The control boxes indicated with a number in the figure are explained:

1) A combo box with the suborders of the order considered that are already initiated.
2) All orders in the system. The selected order (011) is the order that is currently being planned.
3) A combo box with all orders that influence the loading profiles. I.e. all orders which share one or more of the resources of the AG and which are to be executed, in this example, between March 7 and May 2. If the user indicates a smaller time period (e.g. period A), then the orders involved in this time period are shown in this combo box. This can be useful if the planner wants to be informed about which orders are critical, and therefore cause peaks in the loading profiles.
4) Used for start time/date determination.
5) Used for the determination of the standard deviation over the start time.
6) Setting the range of the time period that is shown on the x-axis.
7) Some information about the order for supporting the planner in making the planning decisions.
8) The percentage of the processing time of the order which is already planned in more detail by means of the suborders.
9) The resources contained in the Applicability Group that belong to the order considered.

Resource Availability View. In order to avoid critical overload on the individual resources, views on the utilisation expected in the near future are provided by the system. Figure 8 shows an example of such a view. The view looks somewhat the same as the AG Availability View, except that no orders can be planned in the Resource Availability View. Some other planning decisions can be taken on the basis of the information provided in this view, like

- Extending capacity by planning work overtime or hiring additional operators.
- Shifting operators between machine tools.
- Subcontracting some critical orders.

In the list box at the right of the screen, the orders involved in the loading profiles are presented. Again, it is possible to narrow the time period to look at, so as to detect the critical orders, which cause the peaks in the loading profiles.

Method Availability View. Most macro process planning decisions are based on rough planning of methods of production. Generally, most attention is paid to the technological requirements and constraints, less attention is paid to the capacity requirements and no attention to the availability

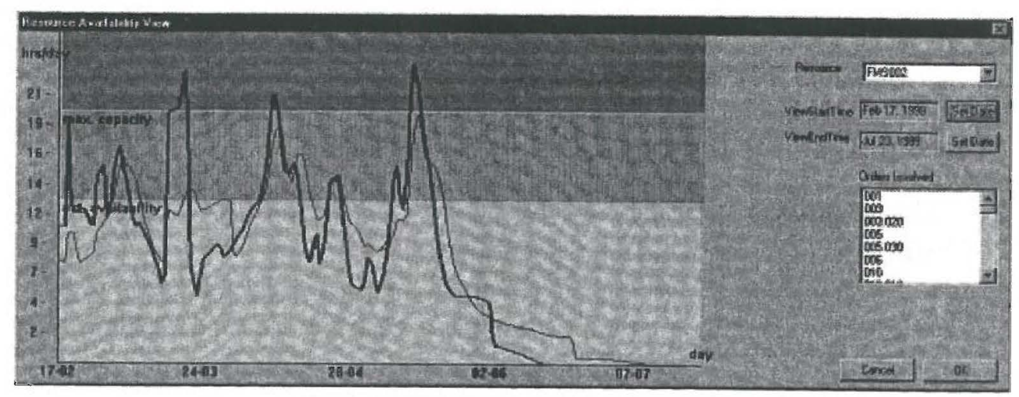

Figure 8. Resource Availability View

aspects. Because of this nearly one-sided approach, many process planning decisions are not as cost effective as often is assumed. Too many replanning activities due to capacity problems are the result of this approach. In order to inform the macro process planners about estimations of availability of method-related resource groups, the Method Applicability Groups (MAG) are created. On the basis of these static order-independent MAG's, the dynamic order-related AG's are drawn up. The Availability Views of the MAG's look almost the same as the Availability View of the resources as shown in figure 8. In this way, it can, in an early state, e.g. be decided to subcontract particular suborders of the product manufacturing process. Also, the people responsible for order acceptation are informed about the availability of the required production methods for the time period requested. This is specifically useful in an engineer-to-order manufacturing environment, because of a lack of detailed information about the required routing through the factory.

TESTS AND FUTURE WORK

Presently, the system is tested under laboratory conditions. Several goals are pursued for testing the system. First, it is examined whether the system adequately supports the human planners. Second, the influence on the throughput time and the reliability of meeting the due-dates is analysed. Third, it is expected that various performance indicators can be improved by a better co-ordination of the decision making process.

A navigation tool will be developed for supporting the process planners and the capacity planners in making the plans. The system must point out and represent a particular view on the information structure of the resources, methods or orders, whenever it is useful or required for making the desired planning decisions.

More information about the project can be found on the homepage:

http://www.opm.wb.utwente.nl/staff/mark/prom.html

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MULTI-PROJECT ROUGH-CUT CAPACITY PLANNING

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ABSTRACT. In many multi-project organizations, there is a clear need of hierarchical capacity planning. In the early stages of a project, only rough estimates of capacity requirements are available. For this purpose, we introduce the multi-project rough cut capacity planning problem. This problem aims to minimize the use of non-regular capacity, where capacity requirements are only stated in time units (*e.g.,* man hours). In addition several constraints must be satisfied, represented by precedence relations, time windows, and minimum durations. We propose two heuristic algorithms and show computational results for problems with different characteristics. Finally, we discuss the potential use of these algorithms for some extensions to the multi-project rough cut capacity planning problem, as defined here.

INTRODUCTION

In many organizations, project management has become a standard way to organize activities. The majority of these organizations simultaneously carry out several projects that are competing for common resources. In order to manage such a portfolio of projects and to ensure a timely completion, it is crucial to have suitable tools for capacity management.

In the literature, much attention has been paid to project scheduling problems at a rather detailed level. Typically, those problems consider a set of activities subject to precedence constraints. Each activity has a fixed duration and requires a constant number of resource units (the resource rate) from one or more resources. At this level, two categories of problems can be distinguished (see also Möhring, 1984):

- Resource driven project scheduling: constraints on the availability of each resource are given. In this category, we find the resource-constrained project scheduling problem (RCPSP) that aims at minimizing the project's makespan. The RCPSP has been a favorite problem and the number of publications that propose exact and heuristic methods to solve it is substantial (see, e.g., Demeulemeester and Herroelen, 1992, Kolisch et al., 1992, and Ozdamar and Ulusoy, 1995). Another problem that also belongs to this category is the