A collaborative process planning and scheduling system

Jan Kempenaers & Jos Pinte
WTCM/CRIF Mechanical Engineering Department, Celestijnenlaan 300 C, B-3001 Leuven, Belgium

Jan Detand & J.-P. Kruth
K. U. Leuven, Mechanical Engineering Department, Div. P.M.A., Celestijnenlaan 300 B, B-3001 Leuven, Belgium

Traditionally, process planning and scheduling have been rather separate activities within a company. Nowadays, the need for more flexible production and shorter production lead times urges for a close collaboration between these activities as a first step towards simultaneous engineering. This article describes the results of the ESPRIT project COMPLAN, which aims at the implementation of an integrated automatic process planning and scheduling system based on the concept of non-linear process plans. In addition to the use of NLPP for flexible load balancing and reactive rescheduling, a new collaborative approach is presented that is based on production constraints as a means to realize a feedback from scheduling to process planning. A process-planning kernel is described that integrates this concept of production constraints.

Key words: Computer Aided Process Planning (CAPP), non-linear process plans, collaborative process planning and scheduling, constraint-based programming, concurrent engineering.

INTRODUCTION

Traditionally, process planning and workshop scheduling have been two rather separated activities within the production organization. These activities are often performed in different departments, interfaced via a PPC (Process Planning and Control) system. Process planning on the one hand, determines how a product will be manufactured. It comprises the determination of an operation sequence (called process plan) to manufacture the part and the determination of the resources and process parameters of each operation of the process plan (called operation plan), an operation being an aggregation of operation steps that use the same resource. Scheduling, on the other hand, determines the most appropriate moment to execute each operation for the launched production orders, taking into account the due date of these orders, a minimum workshop inventory, a maximum resource utilization, etc., in order to obtain high productivity in the workshop.

A good production organization is a key factor in ensuring the profit of the company. In fact, each workshop has limited capacity but is expected to produce according to the orders, in time and with minimal costs. The scheduling department has the responsibility of organizing such a production. The schedule dispatched to the workshop should reflect the real capabilities of the workshop, it should be robust so that a small disruption on the shop floor does not disrupt the whole schedule, and above all it should aim at total production cost minimization. Schedulers, however, lack planning flexibility due to too stringent due dates put on the orders by PPC. Stricter delivery times often do not leave any room for selecting cost-efficient production processes.

The quality of process plans directly influences the quality of scheduling on two levels. Good time estimates, not only for machining but also for loading, unloading and machine set-ups, are necessary to build a reliable schedule. High quality operation routings should allow the scheduler to level the workshop loading and maximize workshop throughput at minimal cost, and yet respect all due dates. While accurate time calculation is a problem that is independent of scheduling, the quality of operation routings is not. In fact, process planning realizes a local cost minimization by generating a 'most performant' operation routing. However, if all process plans require the same
performant' machine, scheduling ends up with severe bottleneck problems. This is a typical problem in job shop batch production environments, where the work-shop contains a set of machines that have overlapping manufacturing capabilities. Therefore, a stronger integration of process planning and scheduling tasks would give mutual benefits.

World-wide, a number of research projects have addressed the problem of concurrent process planning and shop floor control. One approach is the dynamic process planning. Every time an operation has been finished on the shop floor, a feature-based workpiece description is investigated in order to determine the next operation and the allocation of resources. The drawback to this approach is that the process planning and scheduling departments in a company have to be completely dismantled and reorganized.

In the last few years another approach, the concept of non-linear process plans (NLPPs), has been elaborated and is now seen as a proper means to realize the integration between process planning and scheduling. Such process plans contain alternative operation routings, which offer a high degree of flexibility to scheduling.

This paper first explains the concept of non-linear process plan generation, and discusses its use in production organization. Despite their proven benefits, NLPPs, however, do not accomplish a full integration between process planning and scheduling. Collaborative process planning and scheduling is dealt with in the following section of this paper. This new concept of closed-loop production organization tries to remedy the remaining shortcomings of the NLPP-based production organization. A feedback loop from scheduling provides process planning with additional information that allows it to realize a high quality of NLPPs from the viewpoint of schedulers' needs as to flexibility. The concept of production constraints is presented as an implementation of this feedback, enabling a close and transparent integration between process planning and scheduling, within one distributed production organization system. The last section describes a process-planning kernel that is conceived to handle these constraints transparently, equally well in manual, semi-automatic and fully automatic process-planning modules.

The ESPRIT project COMPLAN has implemented a prototype process planning and scheduling system that is based on the ideas presented in this paper.

FLEXIBLE SCHEDULING BASED ON NON-LINEAR PROCESS PLANNING

Non-linear process plans (NLPPs)

As opposed to traditional (linear) process plans, a non-linear process plan (NLPP) does not contain one fixed operation sequence, but a set of alternative machine routings in an AND/OR graph. Figure 1 shows an example of an NLPP. For representing the NLPP graphically, an enhanced Petri net model is used, which is a powerful mathematical graph-based model for simulations and control. This model allows indication of the following manufacturing alternatives:

- arbitrary sequence of operations (modelled through AND splits/joins)
- choice between various operations (modelled through OR splits/joins).

NLPPs will grow during the lifetime of the product. Other interesting alternative routings can be added later on. Feedback information coming from the workshop concerning performed times enables validation and improvement of the NLPPs.

The concept of process plans with alternative paths is taken over by STEP (ISO-10303). The STEP specification however currently supports only nets with corresponding joins and splits. NLPPs as described here can have a more complex structure.

Though one could imagine NLPPs also being used for flow shops and mass production, their advantages are most clear for job shops with smaller batch production. Calculating all possible operation sequences, and detailing them up to the level of operation planning, including NC planning and set-up planning in such an environment, however, puts a high workload on the process-planning department. In the perspective of lean manufacturing and optimal utilization of (human) resources the process-planning effort has to be decreased as much as possible. The scenario below describes how production organization can make optimal use of NLPPs.

More flexible planning scenario

For each new order, a non-linear process plan is generated,
i.e. a set of alternative machine routings is determined. At this stage, no alternative machine routing is detailed up to the level of detailed operation planning. For each operation though, a fair estimation is made of the time (and thus the cost) needed to execute each operation.

A load-oriented scheduling system selects one alternative from the NLPP, namely the routing that fits in best with the ongoing production. Criteria for this decision are due date and batch size of the order, cost of the alternative routings in the NLPP, the capacity of the workshop, and the optimization criteria for the schedule (maximum throughput, minimum lead time, etc.). Only for the selected routing, is the process-planning department ordered to elaborate the detailed operation planning. If later on, a new order is placed for the same workpiece, the load-oriented scheduling system will try to use the path already used, or if this does not fit, it asks for another one to be detailed. In this way, the NLPP grows with the lifetime of a product, since more and more information will be included.

Feedback coming from the workshop will indicate real performed operation times for routings in the NLPPs. Statistical analysis will then allow validation and improvement of the calculated (estimated) times in the NLPP. When a disruption occurs on the job floor, scheduling can take a decision by investigating the existing alternatives in the NLPPs. If possible, paths are selected for which a detailed operation planning already exists.

The instant availability of applicable alternative routings is a major improvement. Traditionally, the operator on the floor had to arrange quickly a solution for the particular disruption. Since an operator has only a limited view, he is unable to foresee all repercussions of his intervention on the rest of the schedule. Therefore, solutions were far from optimal. With the use of NLPPs, the scheduling department has information available on possible solutions, comprised in the alternative routings of the NLPPs. In that perspective NLPPs enable the (semi-) automated handling of disruptions, aiming for a global optimization.

Depending on the individual order mix and production environment, the above-described scenario can be adapted with respect to the number and nature of alternative routings that are elaborated. Intuitively, the reader can recognize that generating NLPPs for orders that are produced frequently is more beneficial than for orders being produced only once.

Increase of workshop productivity

The use of NLPP influences the workshop performance on two levels:

**Increase in schedule performance.** Investigations by Larsen and Kreuzfeldt with industrial data have shown that for a constant WIP (work in progress) an increase in productivity of 7.5%, and a decrease of 7% in the mean leadtime of orders can be reached, compared to linear process plans. For a constant productivity, the WIP can be reduced by 25% if NLPPs are used instead of linear process plans. This increase is due to a more equal distribution of the workload over the various machines.

Also in the COMPLAN project, research has been carried out in the area of scheduling algorithms, to make optimal use of NLPPs.

**Shortcomings**

As to the concept of CIM, an evolution is going on towards CAPP and automated scheduling. The emphasis is no longer put on the development of huge systems (General Problem Solvers) that cover whole production organizations. The concurrent approach favours individual solutions for individual problems, resulting in independent systems that cooperate through full two-way-information exchange. And this information flow is a weak point in the above-mentioned scenario.

Though NLPPs offer great flexibility to the scheduling department, the information flow is basically only one-way traffic: NLPPs flow from the process-planning department to the scheduling department. On one side of the wall, process planning does not really know which of the alternatives are of interest for scheduling: an arbitrary set is generated, based on the experience of the process planner. On the other side of the wall, scheduling only uses the alternatives that are available. The set-up of an information feedback loop could provide the process-planning department with detailed information on what scheduling really wants, and makes process planning work more efficiently. No more effort would be spent on investigating alternatives that are of no use. Moreover, the risk of overlooking important aspects is reduced. Within the ESPRIT project COMPLAN, an architecture has been elaborated that integrates the ideas of manual and automated process planning and scheduling, together with the idea of feedback loops.
COLLABORATIVE PROCESS PLANNING AND SCHEDULING

The goal of the ESPRIT project COMPLAN\[1\] was to develop a software system prototype that is capable of manual and automatic process planning and scheduling, based on NLPPs. The system architecture, outlined in the section below, closely matches the existing production organization in a company. Process planning, scheduling and workshop are considered to be autonomous departments. This is the case in most larger companies not only with respect to persons, but mostly also as to the location of the departments. In smaller companies, process planning and scheduling may have overlaps, but this is not in contradiction to the architecture that models the general case.

Architecture and organization concepts

Figure 2 shows the architecture of the system. Two concepts constitute the basis:

1. each activity has an evaluation module associated with it. The aim of that 'add-on' module is to improve, directly or indirectly, the quality of delivered work.
2. the idea of feedback is introduced on all levels. Since each of the modules/departments produces input for other departments (NLPPs have to be used by scheduling, scheduling has to be dispatched to the workshop), feedback information is used by the evaluation modules to improve the quality of delivered output.

The data flows similarly to the traditional scenario that was explained in the previous section, but there are some additional flows that feed the evaluation modules.

The Workshop Evaluator in fact captures the performance information of the workshop, i.e. the total time that was needed for an operation, the problems that have occurred (machine breakdown, problems with a process plan, etc.). This data is fed back to the process-planning and scheduling departments. The operation times are used to update the schedule, in order to ensure consistency between the calculated and the executed work. Workshop disruptions are recorded and appropriate measures are taken. If a machine breaks down, a quick rescheduling is done, by rerouting some of the jobs in the workshop by selecting alternative paths in the NLPPs of the influenced orders.

The Schedule Evaluator can be used to evaluate the performance of the schedule versus the results of the workshop. More important in view of collaboration between activities is its functionality to evaluate the current and future situation in the workshop. It deduces production constraints NLPPs have to meet, in order to provide scheduling with sufficient flexibility. On the one hand, a request can be launched to add an alternative to a specific NLPP to bypass a machine that has broken down. On the other hand, general constraints can be formulated, which all future process plans have to obey.

The Process Plan Evaluator takes all these feedback data into account. Operation times coming from the workshop are compared with the calculated ones. As a result of this statistical analysis, NLPP operation times are updated, and possibly the time calculation algorithms are corrected. An important task of the Process Plan Evaluator, however, is to deal with the production constraints coming from the Schedule Evaluator. NLPP generation has to take into account these constraints, on the one hand to add quickly an alternative to an existing one, on the other hand to streamline the overall process planning for new NLPPs. This mechanism of production constraint feedback is explained in more detail in the following section.

Another equally important issue is that the division of decision making between process planning and scheduling is not touched. Process planning and scheduling are two separate knowledge domains and it is therefore favourable that each department sticks to its own domain. The additional information flow however will result in more optimal decisions.

Feedback implementation based on production constraints

The implementation of the feedback loop from scheduling to process planning is based on the formalism of constraints. A set of constraints has been elaborated that allows the expression of demands from scheduling concerning the quality of operation routings. As shown in Fig. 3, the constraints denote the need for alternatives
for resources and/or, on a higher level, alternatives for manufacturing technology.

Two types of production constraints can be distinguished:

1. General constraints are generated by the scheduling evaluator by considering the current and the predicted loading of the workshop. The aim is to prohibit repetitive resource overloading in the future. For example, "always foresee an (alternative) routing without machine XYZ, because this machine is frequently overloaded."

2. Specific constraints are formulated to solve a particular problem with a specific order. In this case the scheduler asks the process planning to regenerate the NLPP, taking into account the specific constraints that are formulated. Additional text can be added to explain the situation in more detail to the process planner. For example, "In NLPP abc, please foresee an alternative for machine XJU, because the machine has broken down, and the due date is rather soon."

Whether the constraints can be generated automatically or manually depends on the degree of automation of the scheduling system. For general constraints, it is likely that the schedule evaluator automatically proposes a set, that has to be reviewed by a human operator. A request for NLPP regeneration is more likely to be induced by a human intervention. The definition of the constraint formalism allows the process planner to handle this information, regardless of the fact that it was generated automatically or manually. Whereas the general constraints are to be loaded automatically by the process-planning system, specific requests for NLPP regeneration should appear to the user at login-time, or optionally even at run time. A process-planning kernel that integrates this concept of constraint feedback is presented in the next section.

### CONSTRAINT-BASED PROCESS-PLANNING KERNEL

Two requirements influenced the design of the process-planning environment of the COMPLAN project:

1. The system should support manual, semi-automatic and automatic process planning.
2. It should be integrated with the constraint formalism, regardless of the current mode of process plan generation (manual, semi-automatic or automatic).

The system being developed in the COMPLAN project has a hierarchical modular architecture. As shown in Fig. 4, the NLPP Editor Control Module (NLPP ECM) is the master module incorporating all interfaces to scheduling; the other modules communicate only with this module. The NLPP ECM consists of a graphical net editor offering the functionality to enter manually alternative operation routings. The user can, via a dialogue box, specify constraints which the NLPP he is currently generating has to meet. Production constraints coming from scheduling are automatically loaded, and can be handled in exactly the same way as own-generated ones. During editing, the user will be notified when he defines an operation that conflicts with the specified constraints. In addition, functionality is foreseen to check a previously generated NLPP for newly entered constraints, and to notify the conflicts.

From the NLPP ECM, the user can invoke a child process-planning module, for either generation or regeneration of an NLPP. The child modules offer (semi-) automatic process plan generation for a specific workpiece spectrum. Each module can be seen as an autonomous unit: it gets its input from the NLPP ECM, and delivers its output back to the NLPP ECM where the result can be visualized and further edited. Constraints are passed as input at start-up time. It is up to the child module itself how to handle the imposed constraints.

**Constraint-based automatic process planning**

One of the child process-planning modules that is being developed in the COMPLAN project, performs automatic generative process planning for prismatic parts. The core of the module is a search algorithm that looks in
Within COMPLAN, the following concepts have been implemented. The algorithm envisages a seamless integration of the number of features and manufacturing methods being controlled simultaneously at crucial moments in the search. At the start of the search, Concepts such as 'feature grouping', 'opportunistic process planning' and 'combined variant-generative approach' have been developed to deal with this problem.

An initial way to reduce the search space is to limit the number of features and manufacturing methods being considered. This is the case at the start of the search. Concepts such as 'feature grouping', 'opportunistic process planning' and 'combined variant-generative approach' have been implemented. The algorithm envisions a seamless integration between production constraints, process-planning constraints (e.g. induced by tolerances), and search-related constraints (including heuristics based on human expertise). In this way, optimal use is made of potential search space reduction comprised in the production constraints.

A third way to tackle the search space problem is to ask explicitly for human interaction. In the COMPLAN system, an option will allow the process planner to control the flow of the search. At crucial moments in the search (e.g. the choice of a next machine), the process planner will be prompted to make a choice. Within this approach, the constraints will act as watchdogs, excluding invalid alternatives from the selection list.

ACKNOWLEDGEMENTS

The presented research is sponsored by the European Union through the ESPRIT project 6805, COMPLAN. The authors would like to express their sincere gratitude to all partners involved in the project for their positive contributions to the realization and testing of these valuable ideas.

REFERENCES


