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Denkena, Berend ; Tracht, Kirsten ; Battino, Alessandro

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Conference paper as: published version (Version of Record)

DOI of this document*(secondary publication): https://doi.org/10.26092/elib/3292

Publication date of this document: 20/09/2024

* for better findability or for reliable citation

Recommended Citation (primary publication/Version of Record) incl. DOI:

Denkena, Berend / Tracht, Kirsten / Battino, Alessandro. Dynamic Analysis of Process Chains as an Enabler for the Adaptive Process Planing. In: Proceedings of the 2nd International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2007). 2007, pp. 677-686, ISBN: 978-0-9783187-0-3.

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Proc. of the 2nd Int. Conf. on Changeable, Agile, Reconfigurable and Virtual Production

CARV 2007

Dynamic Analysis of Process Chains as an Enabler for the Adaptive Process Planning

B. Denkena[1], K. Tracht[1], A. Battino[1]

Abstract: Previous studies have proposed a deeper integration of process planning and production control in order to achieve higher levels of efficiency and reconfigurability in production. Nevertheless, a solid method to support the delicate decision making during reconfiguration phases is still missing. Thus, today mostly traditional, static process plans are still in use in companies. In this paper, an approach for dynamical evaluation of process chains based on a multicriteria analysis is introduced. The method constitutes a module within a wider framework for *adaptive process planning*. The theoretical approach as well as a first implementation of the framework is presented.

Keywords: Process Planning, Production Control, Reconfigurability, Decision Making

1 Introduction

In today's global market manufacturing companies must be capable of rapidly and efficiently respond to changes in their environment. Companies' functions dedicated to process planning and production control have made large progress in the last decades in order to meet this requirement. Nevertheless these two functions remain mainly separated one from the other. Changes and disturbances can occur between planning and manufacturing, so that process plans address conditions that may no longer exist at the time of execution.

The *adaptive process planning* (APP) framework introduced by the authors (Denkena, *et al.*, 2006) aims to increase reconfigurability in production through a partial integration with production control. The main implementation issue consists

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[1] Institute of Production Engineering and Machine Tools (IFW), Leibniz University of Hannover, An der Universitaet 2, 30823 Garbsen, Germany

in the analysis and evaluation of process chains, which have to be carried out not only in a first rough planning phase, but also dynamically during execution. In this way, current conditions and disturbances can be taken into account in the selection of processes.

The developed approach is based on a multicriteria analysis that considers quality, performance (including time and cost) and flexibility objectives. The implementation makes use of the well established *analytic hierarchy process* for decision making and *logistic characteristic curves* for production control.

In this paper, after a short overview of the current situation (section 2), the adaptive process planning framework (section 3) is introduced. The focus of the paper lies on the analysis and evaluation of process chains (section 4). Moreover an overview of the current state of implementation is provided (section 5). The paper closes with an analysis of achieved results and future developments (section 6).

2 Current Situation in Production Domain

2.1 Process Planning

Process planning is a key activity in all production companies, which heavily influences the subsequent phases of the product lifecycle. It is estimated that up to 20 % of the total production costs depend on decisions made during process planning (Eversheim 1998). This estimate does not take into account logistic costs and costs caused by disturbances in production, which can be heavily affected by process planning decisions as well.

In a survey executed by the IFW in 2006 it was found out that almost half of the interviewed companies have to modify more then 10 % of the process plans during production. Such problems are not always due to errors committed during planning, but mostly connected with one of its typical characteristics: future occurrences have to be anticipated in the selection of alternative procedures. Therefore, even excellent plans can later turn out to be no longer adequate due to meanwhile changed conditions. Disturbances such as break-downs, missing devices, broken tools or rush orders can arise between the planning and the execution of processes, significantly decreasing the business efficiency.

2.2 Production Control

Based on the developed process plans, manufacturing is mostly managed using Production Planning and Control (PPC) systems. The main aim of PPC is to guarantee short lead times and high schedule reliability; while not neglecting high capacity utilization and low inventory level (Wiendahl, *et al.*, 2000). PPC tools support the user, for instance through Gantt diagrams, in visualizing the planned schedule and reconfiguring it trying to meet the mentioned objectives. Such reconfiguration, however, is usually supported only by modifying the succession of orders queued for a resource (sequencing) or by rescheduling the order on another resource (routing). In both cases the planer is still using a process plan, which could have been produced even months before. At this stage technological aspects are usually not taken into consideration.

2.3 Integration of Process Planning and Production Control

The possibilities offered by PPC systems for reconfiguration are often not sufficient in order to react to changed conditions or disturbances in production. Various authors (Wang, *et al.*, 2005, Shin, *et al.*, 2001) claimed that reconfigurability can be significantly improved when alternative technological solutions are adopted during the replanning of manufacturing operations.

Yet, in most cases the current situation is characterized by a complete separation between process planning and production control. Rigid, sequential process plans are prepared directly after product development, without considering logistic issues like e.g. limited resource capacities.

The solution of integrating planning and control constitutes a big challenge for decision making during production. Production plans need to be evaluated against a number of potentially conflicting goals. A comprehensive framework is needed, providing not only a novel methodology for integrated process planning and production control, but also a tool for partly automated multicriteria decision making.

3 Adaptive Process Planning Framework

The idea of Adaptive Process Planning (APP) is based on the management method of planning on rolling horizons presented in the next section. In the subsequent sections the structure of APP and the scheduling of detailed planning tasks are described.

3.1 Management Method of Planning on Rolling Horizons

In management theory, a widespread method to deal with uncertainty consists in *planning on a rolling horizon basis* – method also known as *gliding planning* (Steinmann, *et al.*, 2000). The method is based on a hierarchical structure and plan-control-revision interaction. While traditional hierarchical planning methodologies comprise just two large planning phases (rough and detailed planning), rolling horizon approaches aim at dividing large problems into several smaller sub problems (time windows) (Sabuncuoglu, *et al.*, 2003).

The APP framework originates from the application of planning on a rolling horizon basis to the manufacturing process planning and control. Rough planning is carried out after the receipt of the order, while a detailed planning takes place simultaneously to production control. The timing between consecutive planning points is continuous: the replanning is triggered on the basis of information coming from the Manufacturing Execution System (MES).

3.2 Hierarchical Structure and Adoption of Nonlinear Process Chains

The hierarchical structure of APP is fundamental in order to allow integration in companies' legacy systems. Differently from other dynamical planning concepts, the presence of a rough planning phase permits to identify in advance a preferred route and pass the correspondent data to production planning systems in order e.g. to book the resources and estimate the production cost.

The first task of rough planning consists in determining the relative importance of the production objectives for a specific order. These values are later used in the evaluation of supply chains as described in section 4.

Afterwards, for each processing step all technological solutions complying with objectives and boundaries are identified. Therefore not a single process sequence, but a *nonlinear process plan* (Beckendorff 1991) will be generated by the planer using a graphical support as described in section 5.2. One method for a partially automated generation of nonlinear plans is presented in (Denkena, *et al.*, 2006).

Through a preliminary evaluation of every process chain contained in the "nonlinear net", a preferred route is identified, and then the time needed for detailed planning is calculated. This concludes the rough planning phase.

The detailing planning takes place directly before the start of each process step (Fig. 1.). Process chains are evaluated considering updated information about current conditions on the shop floor. In this way, a modification of the original rough plan follows (if needed) by selecting a different process chain of the nonlinear plan.

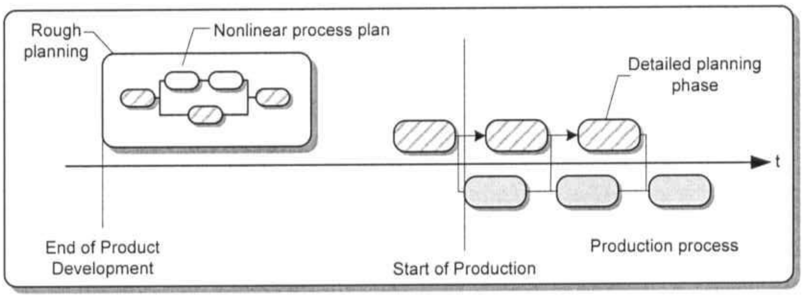


Fig. 1. Representation of APP phases in the time axis

Once a process chain has been selected, its first operation is detailed till the determination of the NC program and its simulation (see Table 1). Afterwards, the first process step can be executed. Meanwhile, the remaining process chains are re-evaluated, a new selection takes place and the detailed planning of the second step is executed. The detailed planning carries on "gliding" in this way simultaneously to execution and *adapting* itself to the current conditions until the achievement of the finite product.

3.3 Scheduling of Detailed Planning Steps

Since the detailed planning takes place mainly in parallel with execution, for its implementation, the duration of each detailed planning step has to be estimated in advance. Only through this information a scheduling of the steps can be set in such way that no delays arise in the execution of the processes.

In the present approach, the duration of a planning phase is calculated as sum of the time required for its constituting tasks. In general for each task a different method can be used, in order to estimate its duration (Table 1). Two main methods are adopted: analytical calculation and expert assessment. In the first case the duration can be calculated as function of certain parameters, and sometimes the calculation can be influenced by product features to be manufactured.

Table 1. Duration estimation of each detailed planning task

Tasks of each Detailed Planning Phase	Method for Duration Estimation
Evaluation of process chains	Analytic
Operation planning; tool and fixturing selection	Expert assessment / knowledge-based
Setting of process parameters	Analytic / feature-based
Generation of NC file	Analytic / feature-based
Process simulation	Analytic / feature-based

The expert assessment has to be used for complex tasks depending on too many variables. Only if similar tasks have been already planned in the past a knowledge based system can be implemented.

Once the duration of each planning phase is available, the backward scheduling can be executed. The aim is to ensure the completion of each planning step just before the start of the corresponding production step. In general, the starting time for the planning of step n is set subtracting its duration from the starting time of the production step n. But, if for instance the duration of the planning step n is greater than the cycle time plus subsequent transition time of step n, this is taken into account anticipating the planning step accordingly.

4 Analysis and Evaluation of Process Chains

A key feature of the APP framework is the decision making about the route to be selected during production on the basis of production objectives. In the following sections, the critical aspects as well as the adopted approach is described.

4.1 Conflicting Goals

An essential requirement in tracking goals' fulfilment is a suitable choice of indicators and measures for assessment of production performance. The decision about a route to be selected in production is characterized by the conflicts between such measures. (Nyhuis, *et al.*, 2003) describe the contradiction between high schedule reliability, high machine utilization, low inventory level and short lead time as follows: high utilization level requires high inventory levels, but high inventory levels induce long lead times. As a result, schedule reliability decreases.

In addition, high machine utilization tends to produce more scrap, thus resulting in lower process quality. Besides high process quality, a high conformity to manufacturing tolerances needs to be maintained. To ensure high quality, quality costs would have to be increased, i.e. total production costs would increase. As a consequence, no single best solution to the selection problem exists.

The operational point should be therefore determined in relation to the strategic importance of each factor. The Analytic Hierarchy Process (AHP) was found to be a suitable decision making tool to deal with this multicriteria decision problem.

4.2 Application of the AHP Method and Criteria Hierarchy

The Analytic Hierarchy Process (Saaty, *et al.*, 2001) is a mathematical analysis technique used in multicriteria decision making processes to help people set priorities among alternatives. The AHP framework was defined in a way that it can deal with the common problem of uncertainties and lack of consistent data. AHP is favoured over other decision making methods due to the ability to assess quantitative as well as qualitative indicators. Moreover its use is simplified by the possibility to break down the decision problem into a hierarchical structure.

The top element of the hierarchy is the overall objective for the decision model. The hierarchy decomposes from the general to a more specific attribute until a level of manageable decision criteria is met. The lowest level of hierarchy is represented by a set of alternatives, which are decision options. In case of APP, the overall objective is the priority index resulting from the evaluation of process chains. The decision is characterized by a contradiction between the critical success factors: schedule reliability, performance, production costs, product and process quality and flexibility. Therefore for the second level of AHP, the criteria quality, flexibility and performance have been identified, and then decomposed in the lower levels (Fig. 2.).

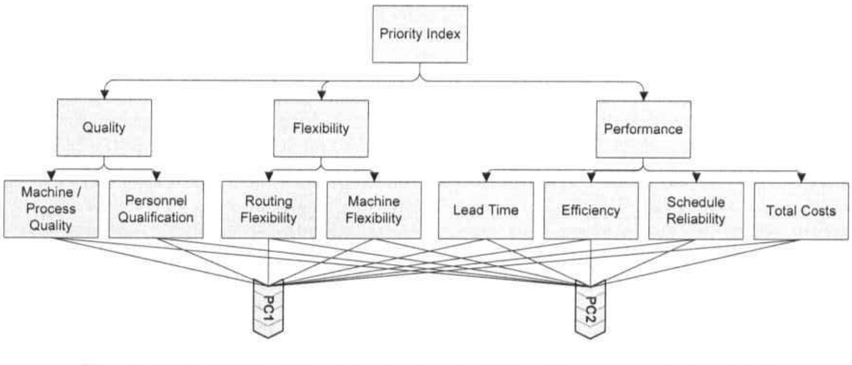


Fig. 2. AHP criteria hierarchy for comparison of process chains (PC)

4.3 Quality Criterion

The quality criterion comprises the accuracy that can be achieved from a machine (manufacturing tolerance, surface quality) or a process. Every job that does not lie within acceptable limits can either be reworked or is considered as scrap. While the process capability index represents the number of good parts in a sample, scrap and rework are the "actual" not compliant parts.

In rough planning just the process capability index (cpk) is considered as a parameter for the evaluation of process chains. The index, frequently available in companies' statistical control systems, is measured on the basis of process variation, magnitude of variation and degree of process centering. Usually, a sample of n = 50 is taken to calculate process capability. (Reinhart, *et al.*, 1996) suggest a minimum persistent capability index of cpk = 1.33. A process can be considered as very robust if the value is larger than 2.0 (six sigma quality).

Within APP these limits are therefore used in order to assess process quality. In addition, during detailed planning, also current values of scrap and rework rate, as well as results of simulation are taken into account. Whenever scrap and rework rate increase considerably, the correspondent process chain is thus automatically hindered in the comparison. Results of simulation can be included in the evaluation of critical and recurring processes. The aim is to predict unconformities in tolerance or surface quality (Denkena, *et al.*, 2007) and in case of detection hinder the selection of the correspondent process chain.

Besides the process capability, the worker's qualification can have an impact on process quality in a way that a more experienced worker can solve problems, such as breakdowns, faster than a less experienced worker. As it is difficult to describe personnel qualification quantitatively, a pairwise comparison is favoured.

4.4 Flexibility Criterion

There are many definitions of flexibility associated with manufacturing systems (ElMaraghy, *et al.*, 2005). Within this approach, only the flexibility that affects the machine behaviour is considered: the machine flexibility is the ease of changing tools, ability to be reconfigured, adjusting machine settings, making repairs and changing NC programs. The evaluation of resource flexibility is achieved through pairwise comparisons carried out by a group of experts.

A second aspect of flexibility is typical of the APP method: the ability to react on disruptions intrinsic in the nonlinear process plans is different for different process chains. The greater the number of routing options available for following steps, the more robust the process configuration. The index related is automatically calculated within the APP software and included in the evaluation.

4.5 Logistic Characteristic Curves for Performance Criterion

The performance criterion comprises the utilization level of production resources (efficiency), schedule reliability, total costs, the inventory level, and the lead time for a set of jobs. (Nyhuis, *et al.*, 2003) proposed the theory of *logistic characteristic curves* to describe the conflicts and dependencies between these measures. The theory provides a model for precise logistic controlling and helps solving the dilemma of operation planning.

Compared to the traditional logistic characteristic curve theory, the main objective of the APP approach is not the optimization and controlling of production processes, but the evaluation of production processes. Thus, the logistic characteristic curve theory is only utilized to describe the functional relationship between the main performance indicators. The basic logistic performance measures *lead time* (TL), *costs* (C), *schedule reliability* (SR) and *efficiency* (E) can be described as a function of *inventory* (I). The local minima and maxima for each performance measure are - as a matter of principle - not unifiable. Although the logistic characteristic curve theory does not provide *one* optimal solution, the decision-maker still gains knowledge about how the criteria are interrelated.

4.6 Utility Functions

The implementation of the AHP is based on pairwise comparisons between alternatives. Nevertheless, quantitative performance measures should be assessed with an absolute measurement model, i.e. gauge the alternatives against an established scale. By using intensities as surrogates for the comparison of alternatives, the number of pairwise comparisons can be considerably reduced.

The functional relationship between a given measure and its intensity of importance is expressed by a *utility function*. In general, the function can be of proportional, inverse proportional or exponential nature.

The first step of developing a utility function is to define the acceptable values, the optimum and the upper and lower bound for each criterion. The second step consists in identify a suitable function type. For each of the criteria presented above, utility functions have been defined so as to allow a partially automated evaluation of alternatives. For the logistic characteristic curve theory, for instance, the logistic positioning area is utilized to define a set of feasible values for lead time, performance, schedule reliability, and costs.

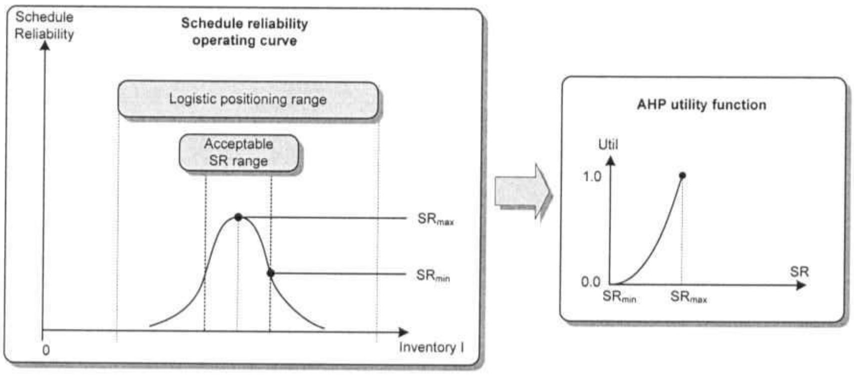


Fig. 3. Utility function for schedule reliability

As example, in Fig. 3. the determination of the utility function for the schedule reliability is represented. After the definition of an acceptable schedule reliability range, it is possible to identify extreme values for the inventory values and then to establish a correspondence with the utility function. In this case an exponential behaviour was selected.

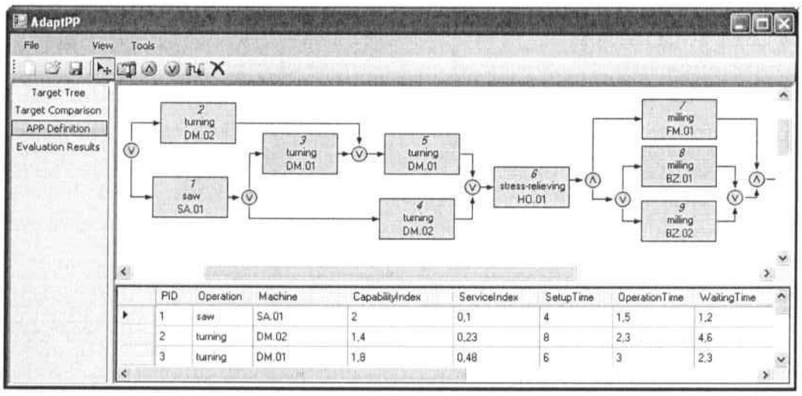
5 Current State of Implementation

In order to support the user in some tasks of the APP and to partly automate some other tasks, a software tool is under development at the IFW. The first implementation step was to realize interfaces for enterprise legacy systems. Two relational databases have been prepared, which reflect the structure of the databases used by Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES).

The ERP database is accessed in the first evaluation phase at the end of rough planning and contains quasi-static data about resources, long-term production plans and orders executed in the past. The MES database is accessed during detailing planning phases and contains current operational data about e.g. availability of resources, inventory and order schedules.

Moreover a third database is implemented in order to save information specific for the APP. Here are stored for instance the weights for the lowest levels of the evaluation hierarchy and the data about utility functions. This information has to be defined only once by a group of experts for a whole production department and then changed only when needed.

When a new order is received, the first task of the planer is to define the relative weights of the first level criteria, which can be done directly in the APP software. Afterwards, the software supports the user also in defining nonlinear process plans with a graphical interface through process blocks, connectors as well as "and" or "or" links (Fig. 4.). A connection with the resources database allows the user selecting an available resource on the basis of its process capabilities. The correspondent resource parameters are loaded and visualized in the user interface.



PID	Operation	Machine	CapabilityIndex	ServiceIndex	SetupTime	OperationTime	WaitingTime
1	saw	SA.01	2	0,1	4	1,5	1,2
2	turning	DM.02	1,4	0,23	8	2,3	4,6
3	turning	DM.01	1,8	0,48	6	3	2,3

Fig. 4. Screenshot of the APP application

Once that the plan is defined, an algorithm automatically identifies all enclosed routes (e.g. in the small section of a nonlinear plan represented in Fig. 4. 12 routes are enclosed) and carries out the evaluation. A list of the routes ranked on the basis of the priority index is presented as suggestion to the planer, who is then free to select the preferred process chain. This information is then passed to the production planning and control systems.

During execution, the evaluation of the process chains left after the current operation is executed by the software each time that the trigger signal comes from the module for the schedule of detailed planning steps (as described in section 3.3). Then, the planer is prompted to confirm the same process chain or to select a new one from the new ranked list. After this decision, the planer can begin to plan the step in detail.

6 Conclusions

The evaluation model proposed in this paper is an approach to aid decision-makers in the complex task of prioritizing nonlinear process alternatives in operations management. Since no single best solution exists, the selection of a preferred process chain is highly related to the strategic importance of each factor. Hence, it is necessary to derive an individual objective from a corporate strategy, balancing the weight of the mentioned critical success factors.

The AHP was found to be a suitable decision-making tool to determine the strategic implications of operation management decisions and an improvement over single operations research methods. An integrated model that combines quality and flexibility requirements with the logistic characteristic curve theory is suggested. The development of a first APP software prototype is under completion. The next implementation phase consists in testing the software and the whole framework using a real use case scenario.

7 Acknowledgements

The presented results have been achieved in the frame of the Collaborative Research Centre 653, which is funded by the Deutsche Forschungsgemeinschaft (DFG). IFW is partner of the EU-funded FP6 I*PROMS Network of Excellence.

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