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Novel Models and Algorithms for Integrated Production Planning and Scheduling

Ph.D. Thesis Booklet

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1 Preliminaries

Advanced representation and solution techniques in production planning and scheduling received significant attention during the past decades, both from the part of research communities and the industry. These techniques hold out a promise of increased productivity, better service level, and lower production costs, by supporting the management to make smarter decisions on various levels of the planning hierarchy. Despite the attractive prospects, only a few of the recent research results has migrated into everyday practice. Although advances in operations research and artificial intelligence led to the development of novel modelling and solution techniques, industrial applications often require more: on the part of the researchers, richer models and more efficient algorithms. This dissertation is concerned with such issues.

The planning functions in make-to-order manufacturing environments are generally described by the three-level hierarchy presented in Fig. 1. The levels of decision making are called strategic (or long-term), tactical (medium-term), and operational (short-term). Every member of the hierarchy is responsible for realizing the objectives that characterize the given level, and the decisions made at a certain stage become constraints for the lower levels [Fle03].

Planning on the strategic level concerns long-term decisions, including the selection of plant locations and capacities, make-or-buy choices, and supply network planning. Based on demand forecasts, the required capacities of the machine and human resources are also determined on this level. In contrast, the planning tasks of the tactical level are already directly related to customer orders. The master planning module is responsible for the acceptance (or the rejection) of the orders, as well as for setting their due dates. Then, production planning assigns the production activities to time on an aggregate timescale. This assignment serves as the basis of the medium-term material

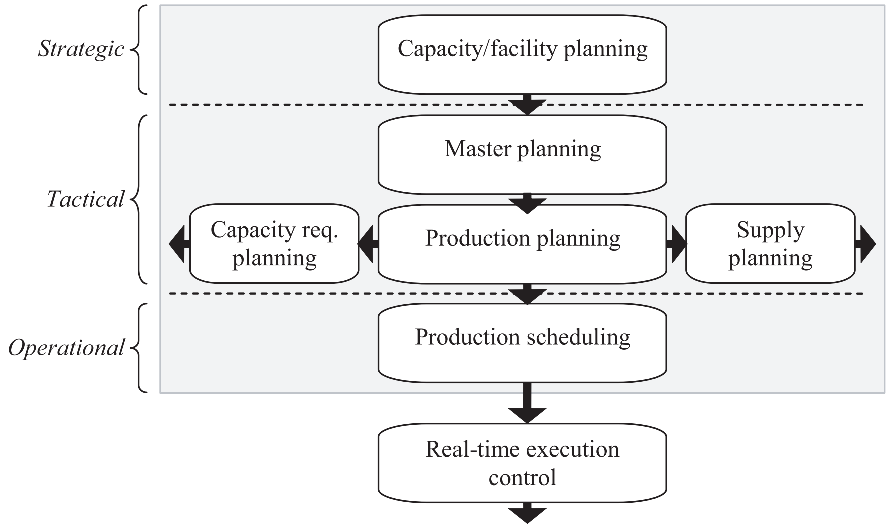

Figure 1: Levels of the planning hierarchy.

plan and the capacity plan. Finally, production scheduling on the operational level unfolds the first segments of the production plan into detailed resource assignments and operation sequences. Scheduling is performed on a detailed problem representation, for individual operations, with respect to fixed capacities.

In this dissertation, we focus on production planning and scheduling in make-to-order manufacturing systems. We assume that the exact description of the planning problem – the order set, resource capacities, raw material availability, and the detailed technological plans – is known for the medium-term horizon. We also assert that the presence of uncertainties is restricted enough to apply deterministic approaches. These assumptions will allow us to model the planning and scheduling problems as combinatorial optimization problems.

2 Objectives and Methodology of the Research

Today, most factories apply material requirements/manufacturing resources planning systems [Vol97] for medium-term production planning. These systems focus on the material flow aspect of production, and assume that products can be manufactured with fixed lead times. Hence, they completely disregard the actual load on production capacities. No wonder that in an age characterized by market fluctuations, the plans generated this way can be barely realized in practice. Recently, several approaches have been suggested to couple the capacity and material flow oriented aspects of production planning, see, e.g. [Han01]. A common characteristic of these models is that they apply a high-level description of the production activities and their complex interdependencies, which has to be encoded manually, by a human expert. The high-level formalism does not always reflect the context of the underlying processes, and even these methods cannot guarantee that the production plans can be unfolded to executable detailed schedules. Furthermore, the results depend largely on the proficiency and the mindfulness of the human modeler.

Our objective was to find a novel, aggregate formulation of the production planning problem which ensures that the generated plans can be refined into feasible detailed schedules. The representation of the planning problem should be generated automatically, from data readily available in de facto standard production databases.

The current industrial practice in production scheduling is also dominated by heuristic approaches, such as priority rule-based schedulers. In spite of this, well-known formal methods are available to describe what makes a schedule feasible, and also to optimize the schedule according to various criteria. The most promising branch of these methods, constraint-based scheduling emerged in the early eighties [BLN01]. It offers a rich and straightforward representation to model even the finest details of the scheduling problem. However, the solution of the vast instances of the resulting NP-complete combinatorial optimization problems challenges currently known algorithms [Wal96].

For short-term detailed scheduling, we decided for the application of the constraint-based approach. The objective of our research was to improve the efficiency of the currently known solution techniques, by the exploitation of typical structural properties of industrial problem instances. For this purpose, we applied so-called consistency preserving transformations.

During this research, we laid emphasis on solving real problems that arise in the industry. We developed a pilot integrated production planner and scheduler software, and used this system to test our algorithms on real-life planning and scheduling problems, originating from an industrial partner.

3 New Scientific Results

The new results are centered upon two fields of research: Theses 1 and 2 are concerned with aggregate modelling of production planning problems, while Thesis 3 addresses the solution of detailed, constraint-based scheduling problems.

Thesis 1: Aggregate Formulation of the Production Planning Problem

The ability to construct the aggregate representation of the production planning problem from detailed production data, by an automated aggregation procedure is of key significance. It can provide the clue to the executability of the production plan. The most important, though hard-to-achieve formal properties of an aggregation procedure are its feasibility (in our case, if the aggregate plans can be unfolded into detailed schedules) and optimality (if the objective value of the unfolded detailed schedule matches the theoretical optimum of the original, detailed formulation).

1.1 **Aggregate Formulation of the Production Planning Problem.** I have introduced a novel, aggregate formulation of the production planning problem in make-to-order project-oriented manufacturing and defined an aggregation procedure to construct this representation from detailed production and technology related data (see Sect. 2.3).

1.2 **Feasibility and Optimality of the Aggregation Procedure** I have formally proven that several relaxed versions of feasibility and optimality hold for the proposed aggregation procedure. These properties include time-feasibility, resource-feasibility per aggregate time unit, and a statement about the approximation of optimality w.r.t. work-in-process (see Sect. 2.3.3 and Theorems 2.1–2.3).

I demonstrated through experiments on real-life production data that the proposed aggregation procedure produces a compact representation of the planning problem that can be solved efficiently by a recently developed branch-and-cut algorithm [Kis05]. The resulting plans can be unfolded to detailed schedules that properly approach feasibility and optimality (see Sect. 2.6).

The thesis is presented in Chapter 2 of the PhD dissertation and it was published in [2, 3, 9, 14, 16].

Thesis 2: Tree Partitioning Algorithms for the Creation of Aggregate Models

I investigated a family of tree partitioning problems motivated by the aggregation procedure proposed in Thesis 1. The problems involve dividing a rooted tree into disjoint sub-trees (components) that respect a certain weight limit. The weight of the components can be measured according to a wide variety of component weight functions. The optimization criteria are the minimal height and the minimal cardinality of the partitioning, as well as the Pareto bi-criteria composed of these two. I have defined algorithms that follow a common bottom-up framework for solving the following problems.

2.1 **Minimizing the height of the partitioning.** I have introduced a linear-time algorithm and I have proven that it provides optimal solution for the case of monotonous component weight functions (see Sect. 2.4.3 and Lemma 2.4).

2.2 **Minimizing the cardinality of the partitioning.** I have introduced a linear-time algorithm and I have proven that it provides optimal solution for the case of invariant component weight functions (see Sect. 2.4.4 and Lemmas 2.5, 2.6).

2.3 **Minimizing the height and the cardinality of the partitioning,** i.e., determining the set of Pareto optimal solutions according to the bi-criteria of minimal height and minimal cardinality. I have introduced a polynomial-time algorithm and I have proven that it provides optimal solution for the case of invariant component weight functions (see Sect. 2.4.5 and Lemmas 2.7–2.10).

These results were published in [1, 16] and in Chapter 2.4 of the dissertation.

Thesis 3: Consistency Preserving Transformations in Constraint-based Scheduling

One of the most efficient approaches to modelling and solving resource-constrained project scheduling problems (RCPSP) is constraint-based scheduling. The performance of this method highly depends on the transformations executed on the constraint program that produce an easier-to-solve representation of the original problem. I have introduced two new, so-called consistency preserving transformations of constraint-based scheduling problems that boost search efficiency by exploiting common characteristics of industrial scheduling problems.

3.1 **Progressive solutions of RCPSP problems.** I have defined the progressive solutions of resource-constrained project scheduling problems. Beyond the constraints of the RCPSP model, these solutions satisfy a number of additional precedence constraints. I have proven that every RCPSP problem instance has a progressive solution. Consequently, during the solution of such scheduling problems, the search space can be reduced to progressive solutions (see Sect. 3.2.2 and Theorem 3.1).

3.2 **Freely completable partial solutions (FCPS).** I have defined the notion of freely completable partial solutions (FCPS) to characterize components of constraint satisfaction problems which are relatively easy to solve and are only loosely connected to the remaining parts of the problem. I have proven that binding variables to their values in the FCPS is a consistency preserving transformation of the constraint program. I have introduced a heuristic algorithm to construct freely completable partial solutions for RCPSP problems (see Sections 3.2.3 and 3.2.4, and Theorem 3.2).

On the basis of a commercial constraint-based solver, I implemented a scheduler system that exploits both progressive solutions and FCPSs. Using this system, I demonstrated the efficiency of the proposed transformations by experiments run on industrial problem instances, in which these method decreased the size of the search trees by two orders of magnitude (see Sect.

3.2.5).

The thesis is based upon Chapter 3 of the PhD dissertation, and it was published in [6, 7, 8, 15].

4 Application of the New Results

In the dissertation, I addressed production planning and scheduling in make-to-order manufacturing systems. The targeted problems were specified and the applied models were worked out in the frame of the *Digital Factories* NRDP research project [MVM03], with the cooperation of a Hungarian factory of a multinational enterprise. This plant manufactures complex mechanical products for the energy industry. The scope of this project also included the demonstration of the industrial applicability of the theoretical results through a prototype system. The developed integrated production planning and scheduling system, named *Proterv-II*, was successfully tested on real-life problem instances received from the above enterprise.

Among the results published in the dissertation, we consider the aggregation procedure proposed in Thesis 1 to be of key practical significance. It allows the automated construction of the aggregate production planning problem representation from detailed data, readily available in de facto standard enterprise information systems. Furthermore, a part of the results are of interest beyond the scheduling context as well. Tree partitioning problems involving the minimization of height and cardinality of the partitioning occur, e.g., in telecommunication networks design, vehicle routing or database paging [MSN97]. The work on completable partial solutions in constraint programming can be considered as a part of current efforts to boost the efficiency of constraint program solvers on realistic problems by exploiting certain structural properties of the problem instances, see e.g. [WGS03]. Compared to some other widely applied consistency preserving transformations of constraint problems, completable partial solutions have the advantage that they do not necessitate the explicit description of these structural properties, hence, they are adequate means to exploit hidden structure as well.

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