Computers & Operations Research 76 (2016) 183–194

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

An exact approach based on a new pseudo-polynomial network flow model for integrated planning and scheduling

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ARTICLE INFO

Article history:
Received 15 July 2015
Received in revised form
20 June 2016
Accepted 11 July 2016
Available online 15 July 2016

Keywords:
Production planning and scheduling
Integer linear programming
Network flow models

ABSTRACT

The resolution of planning and scheduling problems in a coordinated way within the supply chain is very challenging. In this paper, we address the integration of medium-term production planning and short-term scheduling models. We particularly focus on a specific problem defined on parallel machines that has recently been explored in the literature. The problem is characterized by a set of jobs that can be processed only from a given release date onward, and which should be finished at a given due date. At a first stage, the problem consists in assigning the jobs to consecutive time periods within the planning horizon, while at a second stage, the jobs have to be scheduled on the available machines.

Our contribution consists in the description and analysis of a new detailed scheduling model based on a pseudo-polynomial network flow formulation that can be used to exactly solve real size instances. We explore different strategies to simplify the model and reduce its number of constraints. To evaluate the performance of our approaches, we report an extensive set of computational experiments on benchmark instances from the literature. The results obtained show that our approach outperforms, on some classes of instances, other state-of-the-art methods described recently in the literature.

1. Introduction

1.1. Integrated planning and scheduling problems

The importance and potential benefit of integrated optimization within the supply chain is well known. The integrated optimization of operations in companies contributes to their cost reduction and performance improvement. Hence, many authors have endorsed the idea of a wider coordination between planning and scheduling, from procurement to delivery [13]. Some studies consider the integration of operations over different functional areas. In [3,8,12,26], for example, the authors address the integrated optimization of machine scheduling and delivery. While the former occurs in the production area, the latter is related to the distribution area. In the present work, we instead explore an integrated planning and scheduling problem where all the decisions are made over the same functional area, namely the production area – the problem combines decisions that differ essentially in their scope and time horizon [15].

Our aim with this paper is to contribute to the efficient resolution of a specific integrated planning and scheduling problem studied recently by Kis and Kovács [15]. As referred above, we consider an integration over different time scales by focusing on the coordination of medium-term production planning and short-term scheduling models. We particularly address a problem that is defined on parallel and identical machines. Its planning part consists in determining the time periods (typically weeks) in which a given set of jobs should be processed, while the scheduling part consists in assigning the jobs to the available machines in each time period (on a daily basis). The details of this problem will be described in the next section. Different approaches have been proposed to solve similar problems. The work described herein is original in the sense that it proposes a new detailed scheduling model based on a different pseudo-polynomial formulation that we solve through a full-space method according to the taxonomy introduced by Maravelias and Sung [18]. In this section, we review the main contributions in the field, and we compare them to the specific approach described herein.

One of the main objectives of medium-term production planning is to set specific production targets to the companies' facilities, while short-term scheduling deals with the assignment of tasks to the production units of these facilities and their corresponding sequencing in order to meet the targets defined in the planning phase [18]. The interconnection between planning and scheduling relies essentially on the production targets, which are simultaneously the outputs of the planning phase and the inputs of the scheduling phase. These production targets determine both

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http://dx.doi.org/10.1016/j.cor.2016.07.008
0305-0548/

the feasibility and the optimality of the final schedules. As a consequence, the standard approach that consists in solving the planning and scheduling problems separately raises essentially two issues. The production targets may be impossible to meet given the available resources, and even when the scheduling problems are feasible, the global optimality of the solution in terms of its makespan or total production cost is hardly achieved. The only way to overcome these issues is through a coordinated approach to production planning and scheduling.

Integrated planning and scheduling problems are defined over a given time horizon, which is further partitioned into shorter time periods. As summarized in [18], these problems involve a set of items that have to be produced to satisfy client demands at given time periods. Each demand may totally or partially be satisfied through inventories. In this case, there are holding costs that are applied to each item, as well as material balance constraints ensuring the equilibrium between the levels of production, inventory and demand. Production is also naturally achieved under resource constraints. The decisions are related to the quantities of items that have to be produced and hold in inventory in each period of time over the whole time horizon. The objective is to minimize total holding and production costs.

Maravelias and Sung [18] divided the modeling approaches proposed in the literature for integrated planning and scheduling problems into three groups. The first group consists in formulating the problem through a detailed scheduling model, either by using planning and scheduling variables linked through a set of constraints, or by resorting to a monolithic formulation in which the planning variables are replaced by scheduling variables. An example of the former can be found in [14] for production planning in petroleum refineries. Joly et al. [14] formulated nonlinear and mixed integer programming models, and solved them directly by using optimization solvers. A monolithic formulation was explored recently by Kis and Kovács in [15]. The authors solved it directly with an optimization solver. Additionally, they devised a hierarchical decomposition-based approach in which they solved by using a branch-and-cut algorithm. The approach described herein is comparable to the approach of Kis and Kovács [15] in the sense that we propose a detailed scheduling model based on a monolithic formulation, relying essentially on scheduling variables. As a consequence, the material balance constraints can be eliminated as in [15]. The difference in the approaches described in [15] is that we solve our model without resorting to any decomposition procedure.

The counterpart of the previous approaches is that the size of the models increases significantly for large scale problems, thus making their resolution up to optimality a real computational challenge. An alternative consists in using approximations of the original detailed model, either by considering a relaxed version of the model, or by aggregating it in order to reduce its number of variables and constraints [18]. The use of relaxations was considered in [19,17], while examples of approaches based on aggregated models can be found in [4,25]. In the approach described herein, we do not resort to any kind of aggregation or relaxation. Instead, we explore strategies to simplify our original model that have no impact on its optimal solution.

The third group of modeling approaches described in [18] relies on the off-line computation of constraints, characterizing the feasible solution space of a detailed scheduling model and on the estimation of the production costs. An example of such an approach can be found in [23]. Off-line calculations are not considered in order to build the detailed model described herein.

The main solution methods proposed in the literature for integrated planning and scheduling problems can be divided into hierarchical decomposition methods, iterative methods and full-space methods [18]. In hierarchical methods, the problem is divided into a master problem and lower-level scheduling subproblems. The master problem is used, for example, to determine the production targets and the subset of tasks that will be passed onto the scheduling subproblems. Detailed scheduling constraints are not considered in the master problem. The work described by Amaro and Barbosa-Póvoa [2] illustrates this type of approaches. Rolling horizon methods are considered in [18] as hierarchical decomposition approaches. The idea is to solve detailed scheduling models for a few of the earliest time periods, while the plan for the remaining periods is determined by solving an aggregate model with a lower level of detail. The input data is then updated for the next planning horizon, and the process is repeated. The main issue of these hierarchical methods is that it may be impossible to meet the production targets set by the master problem. The alternative is to consider a feedback loop between the master problem and the scheduling subproblems to overcome this potential infeasibility or sub-optimality. This feedback can be performed by adding valid inequalities to cut solutions of the master problem that lead to infeasible scheduling subproblems. This approach was followed in [15], for example. In [16], Li and Ierapetritou used a similar approach. They resorted to surrogate scheduling models and to approximations of the production costs, whose accuracy is revised iteratively in order to improve the quality of high-level planning decisions. In [11], the authors explored the planning and scheduling of single-stage multi-product continuous plants with parallel units. The problem has transition costs and delays which were due to the change from one product to another, and hence their problem definition is different from the one considered herein. Given the difficulty in solving their scheduling model for long time horizons, Erdirik et al. resorted to an iterative solution method that aimed at reducing progressively the optimality gap of their integrated planning and scheduling problem.

The third group of solution methods identified by Maravelias and Sung [18] are the so-called full-space methods that consist in solving directly the complete detailed scheduling model. This resolution can be based on standard methods as in [14] or on heuristics as in [27]. In this paper, we followed a solution approach associated with this set of full-space methods. We particularly considered the direct resolution of our model, using standard mathematical programming methods. Note that these approaches are by far the less explored for solving integrated planning and scheduling problems.

As referred above, the integrated planning and scheduling problem studied herein is similar to that described recently by Kis and Kovács [15]. The problem includes two standard optimization subproblems (the parallel machine scheduling problem and the 1-dimensional cutting stock problem), whose related literature is briefly reviewed in the next subsection. In [15], the authors also explored a monolithic formulation. Despite their promising results, their approaches encountered some difficulties in the resolution of the integrated problem, in particular, for the largest instances and when all jobs were long with regard to the length of the time periods. In this paper, we thoroughly compare our approach with the results reported in [15]. Our main contribution relies on the description of a new detailed model based on a pseudo-polynomial network flow formulation for this integrated planning and scheduling model. Our computational results show that our approach outperforms for some classes of instances the methods described by these authors in [15].

1.2. Related non-integrated problems: machine scheduling and cutting stock

The parallel machine scheduling and the 1-dimensional cutting stock problems are two well-known $\mathcal{NP}$-hard problems. Scheduling is an important and wide field in operations research and computer science that received much attention over the years. For example, Carlier and Néron [7] dealt with the resource-constrained project scheduling problem, which consists in scheduling optimally a set of non-preemptive activities requiring variable amounts of a certain