Computers & Operations Research 40 (2013) 1804–1818

Contents lists available at SciVerse ScienceDirect

Computers & Operations Research

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

A hybrid VNS approach for the short-term production planning and scheduling: A case study in the pulp and paper industry

Gonçalo Figueira [a,*], Maristela Oliveira Santos [b], Bernardo Almada-Lobo [a]

[a] INESC TEC, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias s/n, Porto 4200-465, Portugal

[b] Universidade de São Paulo, Instituto de Ciências Matemáticas e de Computação, Av. Trabalhador São-carlense, 400, 13560-970 São Carlos, SP, Brasil

ARTICLE INFO

Available online 9 February 2013

Keywords:
Multi-stage lotsizing and scheduling
Production rates
Pulp and paper industry
Mixed integer programming
Variable Neighbourhood Search
Hybrid methods

ABSTRACT

Mathematical formulations for production planning are increasing complexity, in order to improve their realism. In short-term planning, the desirable level of detail is particularly high. Exact solvers fail to generate good quality solutions for those complex models on medium- and large-sized instances within feasible time. Motivated by a real-world case study in the pulp and paper industry, this paper provides an efficient solution method to tackle the short-term production planning and scheduling in an integrated mill. Decisions on the paper machine setup pattern and on the production rate of the pulp digester (which is constrained to a maximum variation) complicate the problem. The approach is built on top of a mixed integer programming (MIP) formulation derived from the multi-stage general lotsizing and scheduling problem. It combines a Variable Neighbourhood Search procedure which manages the setup-related variables, a specific heuristic to determine the digester's production speeds and an exact method to optimize the production and flow movement decisions. Different strategies are explored to speed-up the solution procedure and alternative variants of the algorithm are tested on instances based on real data from the case study. The algorithm is benchmarked against exact procedures.

1. Introduction

Research on the optimization of production planning has been more and more focused on increasing the detail and realism of mathematical formulations. Meyr [1] pinpointed the need to integrate lotsizing and scheduling (LSS) in production environments with sequence-dependent setup times, since the final available capacity is only known after the definition of both the size and the sequence of lots. Different LSS models have been proposed, either big- or small-bucket (a classification given by Eppen [2]). Since small-bucket models allow for only one changeover to be performed in each period, they always involve a larger number of periods when compared to big-bucket formulations. On the other hand, a higher level of detail can be incorporated into the former, as time periods are shorter. This is of particular importance in short-term planning.

Besides the integration of lotsizing and scheduling, researchers have been trying to extend traditional models, in order to include more specificities of the production environment [3]. One of those extensions is the multi-stage scenario, where the interdependencies between resources in different stages are taken into account. The production flow may have different structures (serial, divergent, convergent, loop) or combinations of them. In any of these cases, the respective models are naturally larger and more complex than the corresponding single stage variants.

The general lotsizing and scheduling problem (GLSP), originally proposed by Fleischmann and Meyr [4], attempts to reduce the size of models, considering micro-periods (or subperiods) of variable length embedded in macro-periods (or simply periods). However, the model's complexity considerably suffers in case the production rate of a given resource is a decision variable constrained to a maximum variation.

Clark et al. [5] identified the process industries as a promising research area for lotsizing and its extensions, in spite of the current changes in the philosophy of production planning and control (e.g. lean manufacturing, shift from make-to-stock to make-to-order, etc.), due to their very specific features. This paper investigates a case study in the pulp and paper (P&P) industry, where the short-term production planning is tackled. The P&P industry converts fibrous raw materials into pulp, paper and paperboard and may produce energy (in a chemical recovery process) for internal use or to be sold to electrical companies. In a first step raw materials are processed into pulp (in the digester) and in a second step paper and paper products are produced out of this pulp, in different grade runs to be sized and scheduled on the paper machine [6]. These two steps can be processed on

* Corresponding author. Tel.: +351 220414747.
E-mail address: goncalo.figueira@fe.up.pt (G. Figueira).

0305-0548/$ - see front matter
http://dx.doi.org/10.1016/j.cor.2013.01.015

separate plants (within the same company or belonging to different companies) or combined into a single mill. The latter can be formulated as a multi-stage lotsizing and scheduling problem (addressed here).

Research community tended to focus on a single production stage: either pulping (e.g. [7]), papermaking (e.g. [8,9]) or chemical recovery (e.g. [10,11]). As these approaches do not consider the interdependencies between the different stages, when applied to integrated P&P mills they may generate plans that are not only suboptimal, but also unrealistic, obliging managers to modify them manually to guarantee feasibility.

The work proposed by Santos and Almada-Lobo [12] is indeed the only, to the best of our knowledge, to integrate all the three main production stages, although it does not consider the cutting of the reels. This integrated production planning approach aims the synchronization of material flow as it moves through pulp, liquors and paper, responding to the need of integrating production decisions. The model describes a combination of all the aforementioned flow structures (serial, divergent, convergent and loop) and deals with the issue of production speeds constrained to maximum variations (in the digester). As the underlying problem is NP-hard, the authors implemented a stochastic MIP-based heuristic that provides feasible solutions. However, solutions are only of moderate quality. Thus, although the model can effectively reflect reality, useful plans may not be generated within feasible time.

In our paper we tackle the same problem using a different solution method. We propose a hybrid approach that combines approximate methods (heuristics and metaheuristics) with exact methods. In fact, metaheuristics are more tailored for combinatorial problems, whereas exact methods are relatively efficient in the optimization of continuous variables. Therefore, the latter are frequently used to decode (i.e. translate into a full production plan) a representation composed of only integer variables, which is managed by the metaheuristic.

Metaheuristics are high level frameworks that combine basic heuristics in order to efficiently and effectively explore the search space [13]. One of the main issues that metaheuristics have to deal with is the entrapment in local optima. Variable Neighbourhood Search (VNS) is based on a systematic change of neighbourhoods, which may be performed in different ways, resulting in several variants [14]. The basic VNS combines a standard local search with a stochastic shaking phase, thus escaping from local optima while avoiding cycles. Variable Neighbourhood Descent (VND) is a deterministic best improvement descent method, where the local search is shifted to another neighbourhood structure if a local optimum is reached in the current one. Replacing in the VNS the local search step by the VND results in the General VNS (GVNS). The reduced VNS (RVNS) is a pure stochastic method where random points in the neighbourhood are picked and the incumbent solution is updated in case of an improvement.

Guimarães et al. [15] proposed a hybridization of an RVNS and an exact method to approach the tactical planning problem in the beverage industry. Other papers (such as [16–18]) applied this kind of hybridization with other metaheuristics (either neighbourhood- or population-based) to extensions of the capacitated lot sizing problem (CLSP), which is a big-bucket model. Almada-Lobo et al. [19] has also approached an extension of the CLSP. The authors proposed a new VNS variant (combining GVNS and RVNS) for solving a production planning problem in the glass container industry. However, the literature is scarce for hybrid methods on small-bucket models. Meyr [20] is one of the few to address a small-bucket formulation with a metaheuristic combined with an exact decoding procedure. Nevertheless, the author has not focused his work on the neighbourhood structures and on the constructive heuristic and the underlying problem is of single-stage and has fixed production rates.

Our algorithm considers the pattern of setups on the paper machine as the representation to be managed by the metaheuristic and decodes the remaining variables using an exact procedure and a specific heuristic to determine the discrete digester's speeds. Broad neighbourhood structures are proposed in a GVNS design and different techniques to speed-up the expensive local search are employed. Tests performed on generated instances based on real data attested the superiority of the algorithm over a state-of-the-art commercial solver for large-sized instances.

The main contributions of our work are as follows. We propose here a hybrid solution method that is the first to deliver good quality solutions within feasible time for a real-world problem in the P&P industry. Both pure exact methods and MIP-based heuristics provide only feasible solutions of low or moderate quality. We also expect to give insights on the efficient resolution of other LSS problems, where the integer part consists of a setup pattern and/or a grid of production speeds (constrained to a maximum variation).

The remainder of the paper is as follows. In Section 2 the case study is discussed (including the general production and planning processes and the characteristics of the specific problem). Section 3 is dedicated to the solution method proposed for this problem. Computational experiments are given in Section 4. The paper ends with some conclusions and directions for further research.

2. The case study

2.1. Production process and problem specificities

The workflow of the integrated production system consists of seven interdependent sub-processes: wood preparation, pulping, paper recycling, bleaching, chemical recovery, papermaking and cutting.

In the first stage the wood is debarked and reduced to small chips, which are later cooked in one or several (batch or continuous) digesters in aqueous solutions with reagents at high temperature and pressure (chemical pulping), producing virgin pulp. Different types of pulp are characterized by different types of wood and incorporation ratios of recycled materials or even of non-wood plant sources.

In the pulping process a by-product is produced: the weak black liquor. From this point onwards, both products go through various transformation processes separately from each other (divergent flow). The weak black liquor goes to an intermediate tank before being concentrated in an evaporator. After this stage, the concentrated black liquor flows through another intermediate buffer and then to a capacitated recovery boiler, where it is burnt, providing high-pressure steam and regenerating the spent chemicals applied in pulping. The steam can either be used for the paper drying process or be led to counter-pressure turbines which produce electrical energy to be sold afterwards.

The virgin and recycled pulps may go through a bleaching phase and then stocked in their respective tanks, waiting for being pulled by the paper machine(s). From the tanks, these primary pulps are diluted and fed together into the paper machine (convergent flow), where the paper is formed and the water is removed. The dried paper, characterized by its grammage (measured in g/m^2) and type of pulp, is wound into a master reel (called jumbo). The configuration of the machine to produce a different type of paper (different grammage or pulp mixture) is sequence-dependent. Each setup leads to a loss in the production process in terms of time and quantity of a lower quality paper produced (as the machine is never