Computers and Chemical Engineering 77 (2015) 85–104

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

# A decision support system for the operational production planning and scheduling of an integrated pulp and paper mill

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ARTICLE INFO

*Article history:*
Received 11 November 2014
Received in revised form 22 March 2015
Accepted 24 March 2015
Available online 8 April 2015

*Keywords:*
Decision support system
Lot-sizing and scheduling
MIP-based heuristics
Pulp and paper industry
Continuous production

ABSTRACT

Production planning and scheduling in the process industry in general and in the pulp and paper (P&P) sector in particular can be very challenging. Most practitioners, however, address those activities relying only on spreadsheets, which is time-consuming and sub-optimal. The literature has reported some decision support systems (DSSs) that are far from the state-of-the-art with regard to optimization models and methods, and several research works that do not address industrial issues. We contribute to reduce that gap by developing and describing a DSS that resulted from several iterations with a P&P company and from a thorough review of the literature on process systems engineering. The DSS incorporates relevant industrial features (which motivated the development of a specific model), exhibits important technical details (such as the connection to existing systems and user-friendly interfaces) and shows how optimization can be integrated in real world applications, enhanced by key pre- and post-optimization procedures.



## 1. Introduction

The pulp and paper (P&P) industry is highly capital intensive, which means that investments in capacity can represent very long-term decisions. For instance, the modification of a single paper machine requires a planning horizon of at least five years (Martel et al., 2005). Paper products are commodities, with their price being determined in the market and characterized by small margins. Hence, companies must differentiate themselves by improving customer satisfaction indicators, while keeping production costs as low as possible. Furthermore, the P&P production process is also energy intensive. Producing one tonne of paper requires 5–17 GJ of process heat, depending on the type of paper and on the technology applied (Szabó et al., 2009). The P&P industry uses 84% of the fuel energy consumed by the forest products industry as a whole and is one of the largest producers of greenhouse gas emissions (Jankunaite, 2006). Therefore, it is of particular interest in the context of environmental discussions.

These three main factors (capital intensity, energy intensity and competitive market) make the production planning an essential activity in the quest for improvements in operational efficiency and consequently economic gains. However, the planning process poses a variety of challenges, both to practical and scientific fields (e.g. combinatorial nature of paper grades scheduling, shifting bottlenecks, variable production rates, etc. – see Section 2). If these challenges are successfully addressed, companies can achieve a true competitive advantage.

In most cases, production planning is addressed manually by practitioners, even in modern mills with sophisticated automated systems. That applies not only to the P&P industry, but to the process industry in general (see Harjunkoski et al. (2014)). Companies may use advanced tools for particular tasks, such as the planning of the paper reels' cutting, but when addressing the overall planning activity (e.g. size and sequence of paper campaigns, production rates, etc.) most practitioners rely only on spreadsheets. This manual process is time-consuming, sub-optimal (as only few alternatives are considered) and completely dependent on the planners' expertise.

Therefore, there is the need for optimization-based tools that support decision-making in the operational production planning of these mills. Some decision support systems (DSSs) for this particular industry were reported in the literature (e.g. Murthy et al. (1999), Respí cio and Captivo (2008)). Although these systems consider relevant industrial features and practical issues, the underlying approaches are far from the state-of-the-art in production planning, as they are based on simplistic models and heuristics.

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http://dx.doi.org/10.1016/j.compchemeng.2015.03.017
0098-1354/

On the other hand, more research-oriented work does not address the issues of an industrial implementation.

Even in other process industries, the literature on the implementation of this type of DSSs is scarce. Bongers and Bakker (2006) describe a scheduling problem in a medium size ice cream plant. However, the model has not been validated or compared against manual schedules. This problem was subject to further studies and improvements/extensions (Kopanos et al., 2012; van Elzakker et al., 2012), but it seems that they have not been implemented in practice. Janak et al. (2006) and Shaik et al. (2009) address production scheduling problems in large-scale batch and continuous plants, respectively, of a chemical company. Nevertheless, these papers have not reported any industrial implementation. Wassick (2009) is one of the few comparing manual schedules to schedules generated by optimization methods. The author has approached a variety of optimization problems in an integrated chemical complex. The problems included production planning, energy system scheduling, site reliability design and waste treatment network scheduling. For the same chemical company, Wassick and Ferrio (2011) have developed a generic formulation which they implement in a custom interface within Microsoft Excel and apply to different optimization problems, including storage management, production scheduling and container loading.

Our work helps to close the gap between research and practice, proposing an optimization-based DSS, which improves on manual planning and contributes to the literature in the following ways:

- exploring desirable characteristics of analytical models and methods;
- identifying relevant industrial features and how they should be included in the solution approach;
- extending models of the literature, considering practical constraints and objectives;
- exhibiting important data processing in both pre- and post-optimization phases;
- illustrating required connections to existing systems and desirable aspects in the user interface.

We start by describing the industrial system and the planning challenge in Section 2. This motivates the discussion in Section 3 on the different approaches to operational production planning in the literature. In that section we explore some desirable characteristics of optimization models and identify relevant features for industrial practice. Based on that, we choose an appropriate mathematical model and extend it in order to include the practical issues identified. Our formulation is presented in Section 4. Section 5 motivates and explores the solution method for an efficient yet simple and flexible resolution of this complex problem. Section 6 details the integration of the optimization in the decision support system, describing pre- and post-optimization steps, as well as the interfaces to the existing information systems and the final user. The usage of the DSS is also discussed. In Section 7 we compare a plan obtained with the DSS to one generated manually by production planners, and provide further details on the performance and usage of the DSS at the company. Finally, the last section summarizes the benefits of our DSS, discusses its applicability to other environments and shows possible directions for further improvement. Since the paper touches different fields and a variety of concepts, a complete list of acronyms is provided in Appendix A. The full mathematical notation is condensed in Appendix B.

## 2. The challenge

The P&P production process is illustrated in Fig. 1. The variables depicted in this figure will be introduced later in Section 4. In a first step, both virgin and recycled pulps are produced out of wood and recycled paper, respectively. These pulps are then stored in tanks, waiting to be pulled by the paper machine. The machine can produce different types of paper. Each type of paper (or grade) is characterized by its grammage (measured in g/m$^2$) and pulp mixture. The configuration of the machine to produce a different grade is sequence-dependent, for instance, changing from 170 g/m$^2$ to 200 g/m$^2$ is considerably less costly than from 115 g/m$^2$ to 200 g/m$^2$. 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 idle and the paper produced will not be homogeneous, nor completely satisfy the customer requirements). The wasted paper (setup loss) is dissolved and stored in the loss pulp tank, to be pulled again by the paper machine.

The master reel that results at the end of the paper machine, the jumbo, is cut into smaller reels. The paper wasted in the cutting stage (trim loss) is also fed back to the production process. Customers place orders for reels of different widths and grades. The orders may have different priority levels. The maximum priority is given to those that travel by ship, since the company has to schedule containers in advance and commit to a given due date. Then, the remaining is divided into normal and priority orders.

In parallel, a by-product of the digester's pulping process, the weak black liquor, is concentrated in evaporators and burnt in the recovery boiler to provide high-pressure steam and to regenerate the chemicals applied in the pulping stage. 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.

In other companies, the paper mill can be physically distant from the pulp and recovery plants. However, integrated plants, like that of the case study, represent 65% of the industry (CEPI, 2013) and are more capable of achieving high levels of both energy and economic efficiency, due to:

- energy conservation (e.g. direct use of steam in the paper drying process);
- absence of additional processes (e.g. pulp drying);
- material closed loops (e.g. recycling of paper machine setup and trim losses) which make it possible to reduce waste production and energy;
- tightly integrated equipment, which reduces the required capacity.

Nevertheless, an integrated mill poses additional difficulties. The complex production process described above (with convergent, divergent and loop flows) and the tightly integrated equipment, with limited intermediate storage space, result in multiple and shifting bottlenecks. For instance, the company under study produces two main products (KLB and VLB), which have major differences with respect to the incorporation of virgin and recycled fibres. Hence, the bottleneck stage clearly shifts according to the mixture being produced (for example, VLB quickly exhausts the recycled pulp mill, whereas KLB is typically restricted by the recovery boiler).

Moreover, the orders placed by customers put a great pressure on production, as the system operates in a make-to-order (MTO) policy. Still, adjusting the production sequence to better meet market needs has to be done carefully, since the desired production cycles will be disrupted, and some stages may be forced to drastically reduce their production rate or even to shut-down. The start-up of the process after these interruptions is typically problematic and requires a large expenditure of energy, increasing the environmental load of the mill. The rates of the various resources need to be as steady as possible, as rough changes can cause quality deviations and undesired wear of equipment. Therefore, the variation that results from production cycles is conveyed as much as