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Scheduling of a continuous plant with recycling of byproducts: A case study from a tissue paper mill

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ABSTRACT

This paper considers an industrial scheduling problem. It involves profit maximization and the determination of the optimal cycle time, while meeting the minimum demands for the several products. Resource-Task Network-based formulations are employed and a detailed comparison between continuous- and discrete-time models is provided. Both have the improved capability of handling tasks with flexible proportions of input materials in order to consider the incorporation of different flowrates of byproducts that are recycled back to the first production stage. The continuous-time formulation is shown to be more efficient and the resulting mixed integer nonlinear program (MINLP) can be solved to optimality within reasonable computational time. A new recycling policy is proposed that achieves the double goal of making the process more profitable due to important savings on the more expensive raw-materials and also more environmentally friendly, due to the reduction of waste disposal requirements.

1. Introduction

Due to mounting competition in European tissue markets from retailers own private labels, manufacturers are focusing on key business areas, top performing brands and optimizing production in existing plants in search for competitive advantages. The forest-based sector is subject to a variety of threats and challenges, mainly due to increased global competition, changes in the energy market and the concern for the effects of climate change. The European forest-based sector is further under strong competition from parts of the world where forests grow faster, production costs are lower and markets are expanding quicker. To meet these challenges, an era that will build a more knowledge-based, more customer focused and more innovation oriented industry is needed (Forest-based Sector Technology Platform, 2006).

Global competition and rising energy prices are unlikely to get any easier over the next 25 years. The integrated pollution prevention and control (IPPC) (European Commission, 2001), which will come into effect in 2007, requires paper mills to adopt the best available techniques in order to reduce their environmental impacts. It is thus clear that the tissue manufacturing industry in Europe can only survive if it maintains and enhances its competitiveness in the face of global competition. The European forest-based sector is currently a global leader in related process technologies, but if that advantage is to be maintained, the development of technologically advanced, highly efficient manufacturing processes is a must.

One inherently important aspect in achieving highly efficient manufacturing processes is the efficient usage of available production resources. When maximizing profitability, the continuous development of production solutions and optimization of material flows are important factors in search of a competitive advantage. Advanced scheduling tools play a key role in achieving this goal and this has led to significant developments over the past 20 years, particularly in the area of short-term scheduling of batch processes. For a thorough analysis of the most important optimization techniques and solution methods the reader is directed to the excellent review paper by Méndez, Cerdá, Grossmann, Harjunkoski, and Fahl (2006).

While most advances have dealt with batch processes, some of the more recent, general mathematical programming formulations can also consider continuous tasks. Recent examples can be found in the works of Ierapetritou and Floudas (1998), Giannelos and Georgiadis (2002) and Castro, Barbosa-Póvoa, Matos, and Novais (2004). Likewise, in plants where demands are subject to rapid

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Abbreviations: BR, broke; DW, dewatering lines; MOW, mixed office waste; ONP, old newspaper; SP, stock preparation lines; TM, tissue machines; VF, virgin fiber.

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Nomenclature

Sets/indices

$I/i,i'$	tasks
I^{VR}	variable recipe tasks
R/r	resources
R^{BK}	broke resources
R^{EQ}	equipment resources
R^{FP}	final product resources
R^{IT}	intermediate material resources
R^{RM}	raw-material resources
R^{TM}	tissue machine resources
T/t	time points

Operator

$\Omega(\cdot)$	backward wrap-around operator

Parameters

c_r	value of resource r (negative for $r \in R^{RM} \cup R^{BK}$ and positive for $r \in R^{FP}$)
$ccg_{i,i'}$	relative changeover penalties between tasks i and i' being executed in $r \in R^{TM}$
co_i	operating cost of task i per unit amount of material produced
d_r^{min}/d_r^{max}	lower/upper bounds on the yearly demands of resource r ($r \in R^{FP}$)
ff_i	fiber factor over task i
H^{min}/H^{max}	lower/upper bounds on the cycle time
R_r^{max}	maximum availability of resource r
wd	number of working days per year
δ	duration of every time interval in the discrete-time grid
$\lambda_{r,i}$	coefficient for the rate of generation of resource r by task i ($r \notin R^{EQ}$)
$\bar{\lambda}_{r,i}$	coefficient for the rate of generation of resource r by variable recipe task i ($r \notin R^{EQ}$)
$\mu_{r,i}$	coefficient for the binary extent of resource r at the start of task i ($r \in R^{EQ}$)
$\bar{\mu}_{r,i}$	coefficient for the binary extent of resource r at the end of task i ($r \in R^{EQ}$)
ρ_i^{max}	maximum processing rate of task I

Variables

H	cycle time
$N_{i,t}$	binary variable that assigns the start of task i to time point t
$R_{r,t}$	excess amount of resource r at time point t
T_t	absolute time of time point t
$X_{r,i,i',t}$	continuous variable identifying the occurrence in unit $r \in R^{TM}$ at time point t of changeover between tasks i and i'
Δ_r	net production/consumption of resource r over the cycle
$\xi_{i,t}$	amount of material produced by task i at time point t
$\bar{\xi}_{r,i,t}$	amount of material produced by variable recipe task i at time point t that is due to resource r

change, by opposition to those where demands are stable over extended periods of time, the short-term mode of operation is the most favored. In such cases, it is convenient to simplify the operation and control of the plant by establishing a regular periodic schedule, in which the same sequence of operations is carried out repeatedly. Mathematical formulations dealing with periodic scheduling, some of them also considering design aspects, either separately or simultaneously, can be found in Shah, Pantelides, and Sargent (1993), Barbosa-Póvoa and Macchietto (1994), Schilling and Pantelides (1999), Heo, Lee, Lee, Lee, and Park (2003), Castro, Barbosa-Póvoa, and Novais (2005) and Pinto, Barbosa-Póvoa, and Novais (2005).

Scheduling problems have been highly systematized through the use of unified frameworks that are generally capable of representing and modeling the problem at hand. Well known examples are the State Task Network (STN) of Kondili, Pantelides, and Sargent (1993) and the Resource Task Network (RTN) of Pantelides (1994). Since their appearance, several authors have contributed to widen their scope as well as their computational performance. Due to the massive combinatorial complexity of large scale discrete-time formulations, and the fact that discrete approximation of the time horizon leads to suboptimal solutions by definition, Floudas and Lin (2004), continuous-time formulations have received significantly more attention during the last few decades. The most important development has, consequently, been the switch from discrete to continuous-time representations, involving a single (Maravelias & Grossmann, 2003; Castro et al., 2004) or multiple time grids (Janak, Lin, & Floudas, 2004; Giannelos & Georgiadis, 2002). However, continuous-time formulations are not necessarily more efficient than their discrete-time counterparts and the selection of the most efficient formulation for a particular problem is still very much an open issue. Generally, discrete-time models remain popular for industrial problems due to the fact that continuous-time models, applied to practical problems, often yield suboptimal solutions, either due to their poor LP relaxation or due to the fact that the number of intervals is unknown (Maravelias & Grossmann, 2006). Further details concerning discrete and continuous-time formulations can be found in the review papers of Floudas and Lin (2004) and Méndez et al. (2006) or in Pinedo (1995). It should also be pointed out that while STN-, RTN-based models have been developed for multipurpose plants they can also address sequential multistage processes (Castro, Grossmann, & Novais, 2006).

This paper deals with a production optimization problem concerning recycling of broke in a tissue-paper manufacturing mill. Broke contains valuable fibers and its misuse accounts for an important part of fiber losses in the tissue manufacturing industry where it is of utmost importance to decrease such losses and maximize the yield between raw-material in and end-product out. Broke produced in the mill is approximately 10% of the final product. At present time, the mill does not separate broke but collects it from different end products to later include it in low-quality products. The consideration of an alternative broke handling policy is justified when maximizing profitability, optimizing usage of raw material and minimizing disposal costs of unprocessed broke.

The periodic scheduling problem, occurring at a Scandinavian tissue paper mill (which has some resemblances to the order-driven short-term problem addressed by Roslöf, Harjunkoski, Westerlund, & Isaksson, 2002), consists of maximizing the profit of the plant and finding the optimal cycle time while meeting minimum demands for all products. It is successfully solved by a RTN-based continuous-time formulation but not so by a similar discrete-time formulation. The paper also considers an alternative recycling strategy for the plant byproducts that presents significant savings over the existing one.

The rest of the paper is structured as follows. Section 2 presents a detailed description of the process as well as its RTN process representation, featuring a new recycling policy. Section 3 presents the new continuous- and discrete-time formulations, where it can be seen that, although conceptually different, the latter requires only a subset of the variables and constraints of the former. The mod-