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A mathematical model for water removal in the press section of a paper manufacture industry

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A production optimization problem concerned with the water removal in the press section in a paper machine is considered in the present paper. The proposed model seeks to determine the planning of production of paper in order to minimize a cost function that consists of replacement of the felts in the press section, cost of energy to operate the press and cost of energy in the drying section. The proposed model corresponds a mixed-integer nonlinear programming (MINLP) where the most important decisions in the paper machine are: a) the sequence of paper to produce, or when to produce the paper, b) the need to exchange the felts, and c) when to exchange the felts. Numerical examples are presented to illustrate the performance of the model.
This work was developed considering a real case with data from a Brazilian industrial paper plant. However, the optimized sequence calculated by the model was not implemented in practice. These results are just compared with the real sequence used in practice.

Keywords: Optimization, Schedule, GAMS, MINLP

1. Introduction

With increased interest in optimizing parts of paper machines in recent years, there has been much work addressing to solve those problems. Most of the works that has been reported have focused in optimizing different parts in a paper producing mill, for example in paper-converting [1]. Also, several authors have studied water removal in the press section, and we can find references using as a basis pressing defined for one nip of vertical flow [2]. Different models and mathematical models for that part of paper machine are reported in [3]. The process for the manufacture of paper is common to any plant, initially preparing the mass of the paper, following the formation sector, going to the press section for water removal the web of paper, and finally going to the drying sector for drying the web with hot air. In a paper machine, specifically in the press section, we have two important parts, the felts whose function is to carry the wet web through the press nip [4] and the nip which is the zone of contact between two rolls, where the water is transferred from the web to the felt. In the press section, which is the

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object of study of this work, the average life of a felt is different, depending on the type of the felt, but in general it is around 35-45 days.
We consider in this work the press section, which is an important part of the machine, affecting the properties of the paper, as well as having an impact on the final cost of manufacture. Low efficiency of this section causes difficulties like reduction of the tensile strength, increase in the steam consumption in the drying section of the machine, and in many cases, the reduction of the productivity due to reduction of the speed of the machine. It is more economical to squeeze water from the web in the press section than it is to evaporate water in the drying section [5]. A reduction of 1% of humidity in the leaf results in a reduction of steam consumption in the order of 4.5%. The web of paper in the wire section is within 99.5% humidity approximately. In the press section we can remove water of the web economically, approximately 20% of water, and in the drying section we can remove 45%. Recently, there has been significant improvement in the operation of presses meeting requirements such as economy in the operational process, increasing the water removal in this section, and at the same time keeping or improving the characteristics of the web of paper. This work described in this paper has the novelty of minimizing the replacement of the felts, by using an optimal sequence of paper production, in order to improve the water removal in press section. The main goal of this work is to optimize the change of felts in a paper machine, while determining the optimal sequence of the production for the different types of paper, the felts to be replaced, and the optimal costs of production. The model for optimizing the press section has as an objective to obtain better sequence of production of the reels, aiming at the increasing the water removal for the press section. Comparison of the model with actual industrial values will be presented.

2. Press section and felts

Motivated by the large replacement of the felts in the press section in the paper industry, this problem has received increased attention in the last few years. The press section of a paper machine is responsible for the removal of approximately 18 to 20% of water in the web of paper, which represents for 12% of the total cost of water removal in the machine. The maximum amount of water that can be removed by pressing the paper before it enters the drying section represents the largest potential savings since the section is responsible for drying and for 78% of the cost for water removal in the web of the paper.
Felts are responsible for leading the web, removing the maximum amount of water, smoothing the surface, and removing small marks left in the formation section. The felts are different in size, cost and physical characteristics. The lifetime of the felts depends on the amount of water they can remove during their useful life. Commonly the water removal from pressing is 20 times cheaper than the one from drying [7].

3. Problem Statement

The objective is to minimize the total cost which involves the cost of the new felts, the cost of steam for the press section, and the cost of steam to dry the paper. We assume that we are given a fixed time horizon, different types and quantities of paper that can be processed in the same paper machine, and new felts to be used at the start of the production.

4. Model

First of all we divide the programming for "reels in the end of the process", independently of the time of processing of each one. In this way the time horizon T given by:

$$T = \sum_{i=1}^{N} T_i \qquad (1)$$

Since in this work we do not assume unexpected changes or a plant recess for unexpected problems in the felts, the total time T is exactly independently of the processing order. However, the final humidity of each processed reel depends on the one that was dried before, which influences the felt used for drying. We define the binary variable for production of the reels as follows:

$$x_{ik} = \begin{cases} 1 & \text{for roll } i \text{ process in interval } k \\ 0 & \text{otherwise} \end{cases}$$

The following constraints them hold: each reel (or group of reels) can only be processed in one interval; each interval can only process one reel (or group of reels). These assignment constraints are, given by:

$$\sum_{k=1}^{N} x_{ik} = 1 \qquad i = 1, \ldots, N \qquad (2)$$

$$\sum_{i=1}^{N} x_{ik} = 1 \qquad k = 1, \ldots, N \qquad (3)$$

Therefore, the time for each interval is given by:

$$t_k = \sum_{i=1}^{N} T_i \cdot x_{ik} \qquad (4)$$

Where these variables are related to the time horizon T as follows:

$$T = \sum_{k=1}^{N} t_k \qquad (5)$$

Considering that at the beginning of the production all the felts are new, we define the binary variable y_{ik} for representing potential replacement of a felt in position j at the beginning at interval k . Each position is one of the press machines (there are four of them).

We then define the binary variable for exchanges of felts as follows:

$$y_{jk} = \begin{cases} 1 & \text{if the felt in position } j \text{ was changed at the begining of interval } k \\ 0 & \text{otherwise} \end{cases}$$

Since the production starts with new felts (at the beginning of interval $k = 1$):

$$y_{j1} = 1 \qquad j = 1,2,3,4 \tag{6}$$

In this model, the objective function includes the cost of new felts, the cost of energy in the press section, and the cost of energy in the drying section. Since we are using a fixed total time horizon, the objective function uses the mass of water removed from the reels in the drying section at each interval k, m_k, and not the mass flow rate, $\dot{m}_k$.
The objective function is then given by:

$$\min z = \sum_{k=1}^{N}\sum_{j=1}^{4} CF_j \cdot y_{jk} + \sum_{k=1}^{N}\sum_{i=1}^{N} CP_{ik} \cdot x_{ik} + \sum_{k=1}^{N} cs_k \cdot m_k \tag{7}$$

5. Results

To illustrate the application and computational effectiveness of the proposed MINLP model, we show the comparison of the results of the model with actual data from industry. There were 22 cases of felt exchange considered in this work. The values of the data are from industrial practice in the related year, and include demands and length of time horizon. Each case was solved with the proposed MINLP model. We first solved the model with a fixed sequence of the reel production (the same one used in the real industrial case), and next we solved the same model but allowed the selection of the optimal sequence. The model was implemented in GAMS, and solved with the MINLP solver SBB using CONOPT3 and CPLEX10 on an Intel 3.2 GHz machine. The size of the MINLP was 564 single equations, 548 single variables, 92 discrete variables, and typically required 206 min of CPU time. The results for water removal, felt lifetime, felt exchange and reel production are presented in the next section.

5.1. Water removal

The challenge faced by the proposed mathematical model was the reduction in the replacement of felts through the selection at an optimal sequence of the reel production, in this way increasing the water removal in the press section and thereby reducing the cost of energy in the drying sector. This represents an annual increase of the order of 5% in the water removal, which is a significant result.

5.2. Felt lifetime

The lifetime of the felts can also have a significant impact on the cost. The main issue in the replacement of the felts is to find a point where they can stay in the machine without losing much their capacity of absorption. Through the proposed model, we obtained an average increase of 15% in the useful life of the felt, using the optimal sequence predicted from the mathematical model. Hence, besides the increase of the water removal, we can have an increase of the useful life of the felt.

5.3. Felts replacement

The replacement of felts is one of the aspects of the paper machine where we have a higher cost of exchange, time loss and cost of purchase, beyond the "lost" time at production. Replacing the felts requires stopping the machine for approximately 1 hour and 30 minutes, and after this, additional time is required to start-up the machine for production. Therefore, with a better sequence in the production of the reel, we have improved conditions to minimize the exchanges carried through the machine of paper, and with this a significant increase in the production of the reels. We obtained a reduction of 46% in average in the reduction of exchange of the felts, clearly due to the increase of lifetime of the felts, because we have fewer replacements of felts in the machine.

5.4. Cost reduction

From the results we can also see a clear total cost reduction in the operation of the plant, the total cost was reduced by 4%. Some costs have not changed, like the costs in the press reduction, but the cost reduction in the drying section and the lower cost in the replacement of felts were the main reason for the total cost reduction.

6. Conclusions

The optimization to reduce costs and replacement of the felts were considered in the present paper. An MINLP model has been proposed to determine the replacement of felts in the press section in a paper machine. It was shown that the problem could be efficiently solved yielding better results. The improvement obtained for a case study with 22 cases of the felt resulted in a 5% increase in water removal, 15% increase in felt lifetime and 4% reduction in the total cost.

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