IMPROVEMENT OF COST EFFICIENCY IN PAPERMAKING WITH OPTIMIZATION TOOLS

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This paper presents a bi-level optimization approach for process design of the broke system in which both design and operation are optimized. On the design level, the capital costs invested in the process are minimized, and on the operational level, raw material costs, process runnability, and product quality are optimized simultaneously. The set of solutions consists of the optimal process designs with their optimal control sequences.

INTRODUCTION

As has been clear to all, the global paper industry has come to a turning point in the 21st century. Paper companies are interested in higher process profitability and lower capital costs at the same time. Various kinds of investments made to increase productivity are presented in [1], where a number of unidentified North American and European pulp and paper companies are analyzed from the investment point of view. In [2], the economic benefits of industrial symbiosis are evaluated using an optimization model. Other, more process engineering points of view are presented in [3], which considers the utilization of excess heat, and in [4], which describes energy savings achieved with filler addition.

Because papermaking processes are very complex and equipment is expensive, process improvements are usually tested first using simulators. With simulation results in hand, it is easier to make decisions about possible laboratory or pilot plant trials. Nowadays, paper mill modeling and simulation are performed using dynamic models and simulators. An extensive survey on the use of pulp and paper simulation software in Europe is presented in [5], and a review of the state of the art in modeling and simulation in the pulp and paper industry is presented in [6]. A more detailed description of paper machine modeling is presented in [7,8]. This research did not involve the development of new software, but a large paper mill model was constructed using the Apros™ dynamic process simulator. The entire papermaking process is modeled, including a TMP (thermomechanical pulp) mill, stock preparation system, the short circulation, and a paper machine from the headbox to the drying section. This model is very realistic and more inclusive than the models previously used in this kind of study.

Coupling of this process model with an optimization algorithm enables model-based optimization. Usually, optimization problems must be formulated with multiple objectives because papermaking processes are highly complex. In addition, process dynamics must be taken into account, which leads to a dynamic multiojective optimization problem formulation. Many existing studies describe papermaking process optimization, but usually a steady-state model is used, or the optimization addresses only one objective, as in [9] and [10], for
example. However, some studies of dynamic multiobjective optimization in papermaking can also be found in the literature. In [11], process operations are optimized during different production tasks, and in [12], broke system management is optimized.

This paper describes the application of bi-level dynamic multiobjective optimization to the papermaking process, or more accurately, to the broke system. In a bi-level optimization, there are two optimization levels: the upper level consists of design optimization, and the lower level consists of operational optimization. On the upper level (design), the costs of capital investment in the process are minimized, and on the lower level (operations), the operations are optimized so that the process maintains stability, runnability, and high product quality. A similar approach was studied previously in [12], but the process model used there is more exact, more realistic, and broader in scope than those used in previous studies known to the authors. The tradeoff is in computing time which is longer than with simplified models, but the results are more reliable and better suited for application to real processes, which is one important purpose of this kind of research.

This kind of optimization approach can be used for design of both new mills and rebuilds. Moreover, this approach is not limited to papermaking processes only. In the past few years, the paper industry has become interested in new products that require new production lines, such as biorefineries. A corresponding bi-level optimization problem can be formulated for the process design of biorefineries as well.

**BI-LEVEL OPTIMIZATION APPROACH**

As mentioned above, optimization tasks related to papermaking are usually formulated as dynamic multiobjective optimization problems. After numerous conflicting objectives have been solved for simultaneously, the result is a set of Pareto optimal solutions [13]. These solutions are mathematically equally good solutions, i.e., if one objective improves, another objective is degraded, and vice versa. However, usually a single solution must be chosen as the final one. Therefore, a decision-maker is needed who can compare the solutions and choose the best one based on his/her expertise. Sometimes the decision-maker is not needed because the best solution can be selected based on some kind of predefined information using classical scaling functions [14].

This paper considers a bi-level optimization problem with multiple conflicting objectives on both levels and over some predefined objectives on both levels and over some predefined time horizon (dynamics).

The term “bi-level optimization problem” means a problem having two levels in which the upper-level (design) problem includes the lower-level (operational) problem. Therefore, the upper-level solution affects the lower-level one, and vice versa. For example, the optimization variables on the upper level are used as constants on the lower level. Hence, the upper and lower optimization levels exhibit two-way coupling, as shown in Fig. 1.

After the simulation, the process state (e.g., time series of state variable values) is returned to the lower-level optimization, and the values for the operational objectives are calculated based on the state variables. After that, new values for the process control parameters are fed to the process model for simulation. This loop between the lower-level optimization and the process model is repeated until the optimal process control parameters are achieved. The optimal control parameters and the process state are then returned to the upper-level optimization, where the values of the design objectives are calculated. Based on the objective values, new process design parameter values are fed to the lower-level optimization. This loop between the upper-level optimization and the lower-level optimization is repeated until the optimal process design is achieved. Finally, the output of the bi-level optimization problem is the optimal process design with optimal control parameters.

On the lower level (operational optimization), process control parameters are optimized over some predefined time horizon. This can be done, for example,

![Fig. 1 - Interactions between the optimization levels and a dynamic process model.](image-url)
of control parameters predicted (simulation horizon). This loop is repeated until the end of the total time horizon is achieved. Such a receding-horizon prediction principle is illustrated in Fig. 2.

On the design level, the capital costs of the wet and dry broke towers were minimized (approximation: cost = V^n). On the operations level, broke dosage was maximized, production losses were minimized, and variations in basis weight and filler content were minimized. All objective functions were implemented so that the differences between the current parameter values and the predefined target values were minimized. The optimization problems were solved using a differential evolution algorithm [16] on both levels. The population size was five on both levels, but the number of generations was eight on the design level and five on the operations level. The bi-level optimization procedure was carried out as described in the previous section. Relatively small populations were used to limit the computing time, but larger population sizes should produce more accurate results and

**PAPERMAKING CASE STUDY**

This case study illustrates how the bi-level optimization approach can be applied in practice. The case study involves design and management of a broke system with the aim of minimizing both capital and operating costs. The bi-level optimization procedure was based on a dynamic process model of a papermaking line generated using the Apros™ software. The model was a generic one, without reference to any real mill, but the process and product were comparable to a state-of-the-art supercalendered papermaking line. The model consisted of numerous submodels which represented the main process components from TMP production to the reel, as presented in Fig. 3. Because only the design and management of the broke system were studied here, the components of the broke system are presented below the overall process block diagram.

In this case, the broke system consisted of two parallel lines: one for wet broke and another for dry broke. The two broke lines were merged just before the broke was fed back to the process. This made it possible to control both the total broke dosage and the relative proportion of the broke types, which is interesting from both process design and quality points of view (effect of drying on fibers).
RESULTS

The bi-level optimization yielded two conflicting process designs, as presented in Table 1.

Because the designs are conflicting, a decision-maker is needed to choose the best one based on expert knowledge. Additional information about the process designs can be obtained from the results of operational optimization. Both process designs had optimal control parameters for broke dosage (Fig. 4) and for wet broke proportion of total broke which were defined by operational optimization over the time horizon $T_0 - T_{12}$. The objective on the operational level was to minimize operating costs by maximizing broke dosage and minimizing production losses, as illustrated in Fig. 4.

![Fig. 4 - Variations in broke dosage (upper) and production (lower) during the simulation.](image1)

![Fig. 5 - Variations in basis weight (upper) and filler content (lower) during simulation. Target interval is marked with dotted lines.](image2)

Figure 4 shows that the operational optimization was difficult because the objectives were conflicting. When the broke dosage was increased, production decreased, and vice versa. Therefore, variations in broke dosage were kept to a minimum, and production was increased as much as possible. Another operating objective was to minimize variations in basis weight and filler content, as shown in Fig. 5.

As Fig. 5 shows, paper quality remained well within the target intervals. Figures 4 and 5 show only one alternative to the optimal operations scenario because a scaling function was used on the operations level. The interrelationship between the operating objectives can be changed using different scaling parameters. In addition to the objective functions, the stability of the different process designs can be compared using the time series of liquid levels in the broke towers, as shown in Fig. 6.

Although the tower volumes were decreased, process operations were able to maintain stability without risk of over-

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**TABLE 1** Optimal values of the design objectives and their corresponding tower volumes.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Design 1</th>
<th>Design 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$: Cost wet broke tower [CU]*</td>
<td>307.0</td>
<td>305.7</td>
</tr>
<tr>
<td>$F_2$: Cost dry broke tower [CU]*</td>
<td>77.5</td>
<td>83.1</td>
</tr>
<tr>
<td>$V_{\text{wet broke tower}}$ [m$^3$]</td>
<td>3573</td>
<td>3551</td>
</tr>
<tr>
<td>$V_{\text{dry broke tower}}$ [m$^3$]</td>
<td>500</td>
<td>552</td>
</tr>
</tbody>
</table>

* CU = currency unit (approximation: cost = $V^{0.7}$)
flow or runout. This kind of tradeoff between upper- and lower-level objectives is interesting and reveals how much the values of the design-level objectives can be decreased without losing too much on the operations level. A tradeoff between capital costs and cumulative broke dosage over the total time horizon is illustrated in Fig. 7.

**CONCLUSIONS**

This paper has presented a bi-level optimization approach and its application to cost-efficiency improvement in the broke system. The results show that the approach was successful: capital costs were decreased while maintaining adequate process stability. However, the computing time requirements were relatively high; to reduce them, the operational optimization on the lower level could be performed using a slightly simplified process model. However, the differences between the upper-level model and the lower-level model should be as small as possible to maintain the accuracy and efficiency of the bi-level optimization. In future research, this bi-level optimization approach could be expanded outside the broke system, and more complex problems could be studied. In addition, it would be interesting to apply this approach to a practical process optimization problem.

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