Plantwide Optimization of a Pulp Mill Process

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Abstract

An economic optimization study of a pulp and paper mill is presented. Costs and revenues associated with all unit operations are identified to formulate a suitable objective function. The existing control structure of the pulp mill is analyzed and used to develop an optimization-relevant model through a series of step tests. This model is then used with the objective function and the information about other constraints for process variables to devise a linear programming (LP) problem to find the most profitable operating conditions for the pulp mill process. The LP solution predicted an improvement in profitability of 47% compared to the nominal operating conditions of the pulp mill. In the next stage, an optimizer is interfaced with the existing control structure to transition the plant to the newly calculated, more profitable operating point. Simulation results showed a profitability improvement of 24% at the new operating conditions. The discrepancy is attributed to the structural limitation of the optimization-relevant model and the complex nonlinear behavior of the pulp mill process.

Introduction

Paper products are indispensable elements of modern daily life. The production of this essential commodity is also an important part of the global economy with annual revenues of 500 billion dollars from sales of over 300 million tons of products [1]. The production facilities to process the requisite amounts of timber into finished pulp and paper products are massive in size and are technologically very complex. A modern pulp mill with a production capacity of 300,000 tons per year is estimated to cost more than a billion dollars [2]. The principle of economies of scale is valid for the industry and high capacity mills are necessary to lower the cost of production. However, in recent years, changes in the global economy have affected the pulp and paper industry dramatically and resulted in serious price-based international competition. The high capacity producers are facing another challenge from the digital alternative media and storage technologies. The decline in demand combined with the international competition is forcing the sector to reductions in capacity. In the face of decreasing demand and excess capacity, it is essential for the industry to improve the productivity of existing mill operations.

The pulp mill process includes important material and energy recycle loops, which lead to highly interactive multivariate process behavior among different unit operations. This characteristic of the process motivates a plantwide approach to both control and optimization. Recently, a benchmark problem was provided for the operation of a complete pulp mill and an analysis of the benchmark problem for plantwide control was presented [3, 4]. There are also several publications in the literature that consider selection of optimal inventory levels and production rates for millwide operation using simple mass and energy balances [5, 6]. However, the development of an economic optimization system that can be interfaced with the millwide process control structure for real-time applications is lacking. In this work, such an optimization problem is developed and solved for a complete pulp mill process. The following sections detail the problem formulation, model development, economic optimization and simulation results. A discussion of these results and possible future work precede a conclusion section.

Optimization of the Pulp Mill Process

In this study, the benchmark problem given in [3], is chosen to provide a virtual pulp mill for the formulation of a plantwide economic optimization problem. In the first step, the costs and revenues associated with the various mill operations are identified along with a set of process variables involved in the process economics. This set consists of a total of 28 controlled variables (CV), 61 manipulated variables (MV) and 11 disturbance variables (DV) chosen from a total of 115 CV's, 82 MV's and 58 DV's of the pulp mill benchmark. The calculation of total steady-state profit from these variables generated the objective function for optimization. This information is then used to develop an optimization-relevant model by linearizing the benchmark problem at its nominal operating conditions to establish the steady-state relationships among the chosen set of process variables. Step tests are used to identify the relations between the selected CV's and MV's. During the tests, the supervisory control structures are disabled but the stabilizing controllers are kept functional. The linearized model and the operational limits for the variables forms the constraint set of the optimization problem as given below, where the 44 model outputs are denoted by *y* and 45 model inputs are denoted by *u*, corresponding to the 28 CV's and 61 MV's. The DV's are assumed to enter the problem through the coefficients in the objective function denoted by *c*.

$$\text{Max} \quad c1*y1 + c2*y2 + \ldots + c44*y44 \quad + \quad c45*u1 + c46*u2 + \ldots. + c89*u45 \qquad \text{objective}$$

subject to

$$\left[\begin{array}{cccccc|cccccc} -1 & & & & & & K1-1 & \cdots & \cdots & \cdots & \cdots & K1-45 \\ & -1 & & & & & \vdots & \ddots & & & & K2-45 \\ & & -1 & & & & \vdots & & \ddots & & & \\ & & & -1 & & & \vdots & & & \ddots & & \\ & & & & -1 & & \vdots & & & & \ddots & \\ & & & & & -1 & K44-1 & & & & & K44-45 \end{array}\right] \begin{bmatrix} y1 \\ \vdots \\ y44 \\ u1 \\ \vdots \\ u45 \end{bmatrix} = \begin{bmatrix} b1 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ b44 \end{bmatrix} \qquad \text{plant model}$$

$$y_{low} < y_i < y_{high}$$

$$u_{low} < u_i < u_{high} \qquad \text{upper and lower bounds}$$

The solution of this problem provides the optimal steady state values for the 89 decision variables defining a new operating region. According to model predictions this new operating region increases the steady state profit by 47% compared to the nominal case. The most significant contribution to the increase in profitability comes from the reduction of operating costs in the multi-effect evaporators and from the improvement of overall pulp yield. The optimization results suggest increasing the production rate, however the increase does not

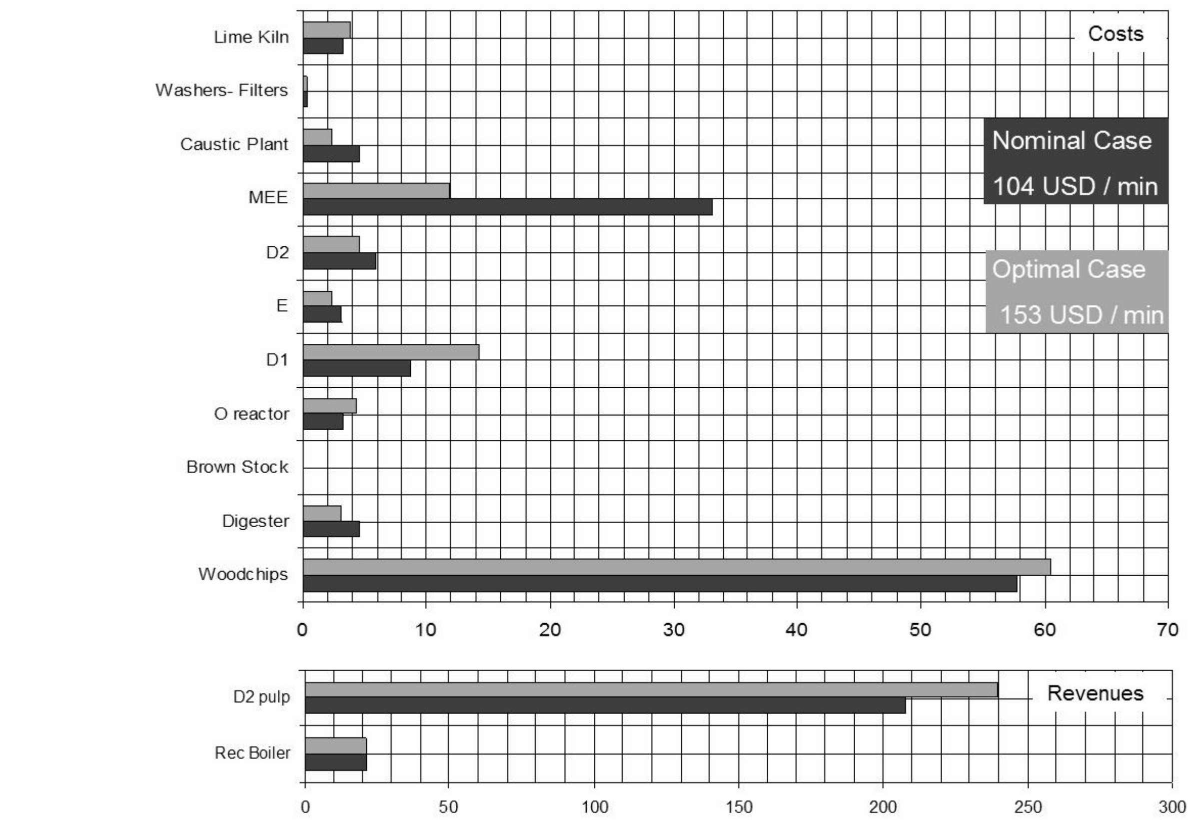

Figure 1. Costs and revenue comparison of the optimization results with nominal operation.

reach the highest allowable value. Figure 1 shows the comparison of costs and revenues between the nominal and optimal operating conditions for different unit operations.

Simulation Results

Next, an optimization module is interfaced with the model predictive and regulatory control structures of the detailed benchmark simulator, as well as with free MV's to transition the nonlinear pulp mill benchmark to the newly calculated, more profitable operating regime. It should be noted that only 39 of the 89 optimization variables could be independently specified in the form of setpoints or free input values by the control structure. The transition between the operating conditions is performed in a series of steps as shown in figure 2. The overall transition took about 85 hours of mill operation to prevent the violation of process constraints and also to minimize the deviation of quality variables from their targets. The results show that the new operating regime improves the steady state profitability over the base case by 24%. The pulp production rate is increased by 14%, and although there is an increase in capacity use, operating costs of most unit operations are lowered. However, the large improvements in pulp yield and the threefold reduction in the cost of operation for the multi-effect evaporators predicted by the LP solution are not achieved. These results can be found in figure 3. In terms of the optimization variables, 64 reached the target values given by the optimizer but the remaining 25 settled at different levels. Out of the 64 variables that reached the target values, 25 are free inputs specified by the optimizer, 14 are CV's under MPC supervision, 12 are MPC MV's and 13 are MV's governed by the regulatory control structure. Generally, the accuracy of the model in predicting the MV levels are found to be lower than expected.

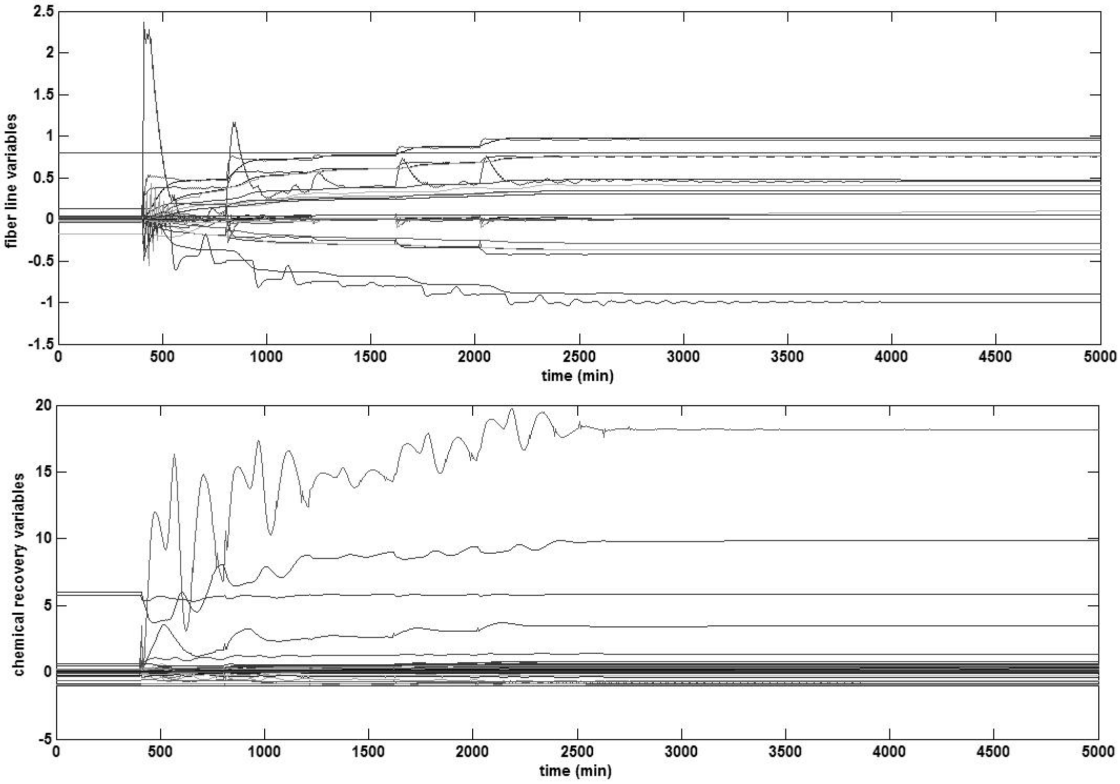

Figure 2. Dynamics of the pulp mill process during the operating region change.

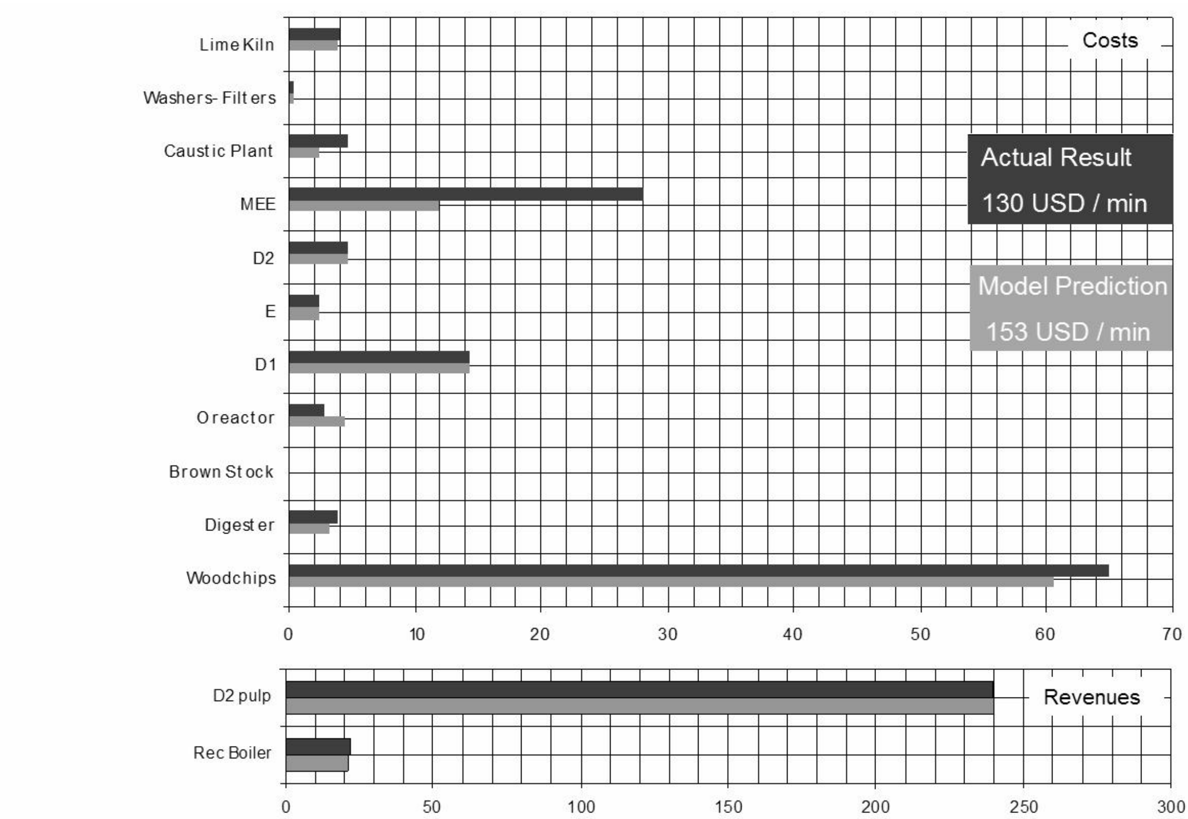

Figure 3. Costs and revenue comparison of the simulation results with model predictions.

Discussion and Future Work

The discrepancy between the profit improvement predicted by the optimization results, and the actual improvement obtained in simulations can be explained both by unaccounted relationships between the process variables, and by the change of model parameters at the new operating conditions. The actual benchmark model has 8996 states, corresponding to 8996 nonlinear model equations. Reduction of this value down to a linear model with only 44 equations has clearly resulted in moderate loss of accuracy. However, the 24% increase in profitability is a considerable achievement, and shows that the overall optimization strategy was successful. A number of different approaches can be used to improve the optimization strategy and the model accuracy. Another important application would be to devise an on-line scheme to update the solutions of the optimization problem during the operation of the pulp mill.

Summary

This work provides important insights for the understanding of the pulp mill structure for process optimization, and offers an analysis of the problem for advanced process control design. Such an analysis will be very helpful for the design of real-time optimization systems and their interface to the existing process control structures in the mill. Even though there is a difference between the predicted improvement and the actual results, a 24% increase in mill profits is significant and encouraging.

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