

## Process Simulation and Energy Optimization for the Pulp and Paper Mill

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A process integration model is developed based on mixed integer linear programming. The analysis is carried out using the reMIND software in combination with the commercial optimization software CPLEX. The steam production (heat recovery boiler, bark boiler and steam turbines) and the process steam consumers (digester, evaporation plant, bleaching plant as well as pulp dry machine and paper making machine) are modeled as separate modules and thereafter linked and are validated using the operation data from a pulp and paper mill in the Northern Sweden. The whole plant is simulated and initial optimization runs are performed in which the cost is to be minimized.

### 1. Introduction

The pulp and paper industry is an energy-intensive industrial sector where it is crucial to improve the material and energy efficiency to the greatest possible extent. Process integration methods represent useful tools for evaluating possible process alternatives. Many process integration studies in the pulp and paper industry have been carried out by using Pinch analysis (Ruohonen et al., 2010; Persson and Berntsson, 2009) and mathematical programming (Blanco et al., 2009; Klugman et al., 2009). However, the scope of modeling and simulation of the energy and material balances is not as complete as it is in other modern process industries. More detailed work is required especially as large efforts are currently put on turning pulp mills into bio-refineries. In our research group, a mathematical process integration model of a steelmaking industry has been developed to minimize the energy consumption, production cost, CO<sub>2</sub> emission, and residue material to landfill for the steelmaking industry (Larsson et al., 2006a, b; Wang et al., 2009). The developed model is based on mixed integer linear programming (MILP), and the analysis is carried out using the reMIND software (Nilsson, 1990) in combination with the commercial optimization software CPLEX. The model has been applied successfully in the steelmaking industry. In the present work, a mathematical process integration model is developed based on a pulp and paper mill in the Northern Sweden but also by considering a future expansion to the new production lines such as the including of bio-refinery. The steam production and the process steam consumers are modeled as separate modules and thereafter linked. The whole plant is simulated and

validated using operation data from the mill. Initial optimization runs are performed in which the energy cost is to be minimized.

## 2. Process description and validation

The pulp and paper mill can be divided into two major processing lines: fiber and chemicals recovery (Figure 1). The fiber processing line extends from the digester to the pulp bleaching/paper making section. The main task of the fiber processing line is to remove the lignin from the wood to achieve brightness pulp/paper. The chemical recovery cycle is necessary to make the process economically feasible. The by-product of black liquor is concentrated in a multi-effect evaporation plant and burned in the recovery boiler where the combustion of organics provides energy to produce high pressure steam and to carry out the reduction reactions to recover  $\text{Na}_2\text{S}$  and  $\text{Na}_2\text{CO}_3$ . The inorganic product of the boiler recovery is used to generate the  $\text{NaOH}$  and  $\text{Na}_2\text{S}$  needed for pulping by passing through the causticizing plant. The high pressure steam produced in the heat recovery boiler (HRB) and the bark boiler (BB) is expanded in a steam turbine producing 10 and 4 bar steams to be used in the process, and 30 bar steam is extracted from the turbine for soot-blowing in HRB. Biomass (bark or forest residues) and oil are used in BB. Oil is used to start up the HRB and a certain amount of 10 bar steam is used in the dry machine, but they are neglected in this work.

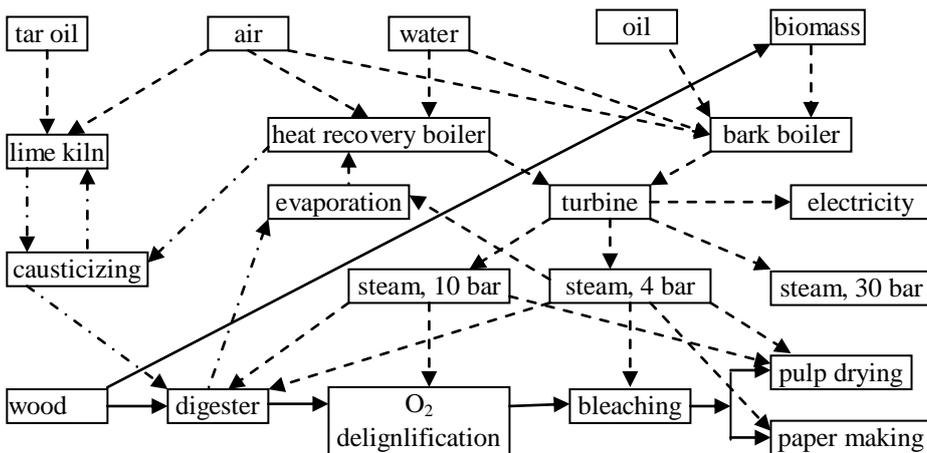


Figure 1: Schematic representation of the pulp and paper mill

To validate the model, the digester and the evaporation plant are modeled based on the data from the actual operation of a pulp and paper mill in the Northern Sweden. A detailed description for these two parts is described in the following text. The other processes are common for most of the pulp and paper mills and therefore not described. The digester is operated batch-wise in several steps, i.e. wood-chips filling, steaming, liquor filling, heating, cooking, displacement, and emptying (blowing). In current operation, 4 bar steam is used for chips filling, both 4 and 10 bar steams are used for the chips steaming up to a temperature of 108 °C, the white liquor is preheated with 10 bar steam from 90 to 122 °C, and 10 bar steam is used for the heating stage. The

displacement liquor is also preheated from 125 to 168 °C using 10 bar steam. During the cooking, the heat release due to the chemical reactions is considerable and the temperature can increase by 2-3°C. Because of the batch operation, the consumption of the steam is time-dependent. However, in the process modeling, the average steam consumption of a certain period for a fixed consumption of dry chips is used. The evaporation plant includes seven effects. The steam goes into effect 1, and then a part of generated liquor steam is used by effect 2. All steam generated from effect 2 is used by effect 3, and then the same for the other effects until the seventh. The steam generated from effect 7 is condensed using cooling water. The weak liquor (14.4 %) is mixed with the liquor from effect 2 before it goes into effect 4 first, then continues to 5, 6, and 7. After the heat exchange, the temperature of the liquor from effect 7 is increased and enters to effect 3, then to 2 and 1. After effect 1, the liquor is concentrated to 71.5 % and is used for combustion. In effect 1, a certain amount of liquor comes out and is mixed with ash and then transferred back into effect 1 at a lower temperature. Based on the process illustrated in Figure 1 and the specific processes for the digester and the evaporation plant, the performance of the complete plant is modeled and simulated. For the bleaching plant, because of the complicated water cycle and the lower steam consumption, a black box is used to represent the steam consumption. The same is done for the pulp drying and paper making machines. For the other parts, the mass and energy balances are described in detail, which gives the possibility to investigate the effect of the operation conditions of a sub-process, such as temperature, flow rate, etc. on the performance of the whole plant.

*Table 1 Simulation results and comparison with operation data*

Stream	unit	Calculation	Measurement
Heat Recovery Boiler (HRB)			
Air demand	kNm <sup>3</sup> /h	216.7	226
Steam generation, 60 bar	t/h	214.0	210.1
Bark boiler (BB)			
Bark	t/h	2.85	2.38
Air demand	kNm <sup>3</sup> /h	6.73	9.0
Digester			
Steam consumption, 10 bar	t/h	51.0	
Steam consumption, 4 bar	t/h	16.9	
Evaporators			
Steam consumption, 4 bar	t/h	72.9	72.5
Causticizing			
Tar oil consumption	t/h	1.7	1.74

The simulation results together with the real operation data (measurement) for the reference case are listed in Table 1 with reasonable agreement. For the digester, the total steam consumption of 10 bar for the chips steaming, heating, and preheating of the white liquor is measured with the value of 42 t/h, and the calculated result of the model is 41.9 with 2 % heat loss. For the consumers of bleaching plant, drying machine and

paper machine, each is described as a black box and the operation data is used to obtain the required steam consumption for a certain production level. For the O<sub>2</sub> delignification, it has been found that the heat release due to chemical reactions in Dence and Reeve (1996) is much lower than what is observed at the plant. Therefore, the chemical reaction heat release is re-estimated from the steam consumption.

### 3. Results of process integration model and discussions

Optimization is performed with the objective to minimize the total energy cost of the plant. The prices of the fuels and electricity are listed in Table 2. Two cases are illustrated in this work.

Table 2 Price of fuels / electricity used in the model

Fuel, purchased	price	electricity	price
Oil	3333 SEK/t	purchase	435 SEK/MWh
biomass	830 SEK/t, dry	sale	-300 SEK/MWh

- *Case 1. Consumption of steam for filling and steaming*

As described previously, steam of 4 bar is used for chips filling, steams at 4 and 10 bar are used for chips steaming into the digester. On the one hand, from the energy point of view, 4 bar steam should be used so that more electricity could be generated from the steam turbine. On the other hand, the injection of 10 bar steam will decrease the steaming time leading to higher pulp production. There should be an optimal operation point. Since the relation between the consumption of 10 bar steam and the time saving has not been investigated, only the energy saving is discussed.

With increasing use of 10 bar steam in the steaming step, the consumption of 4 bar steam decreases. Also the total amount of steam used in the steaming step decreases. The total amount of steam used in the steaming step affects the total amount of water in the digester, which will cause a difference in the consumption of steam in the heating step. To satisfy the requirement of the steam consumption, the BB will change its operation assuming that the black liquor is fully utilized in the HRB.

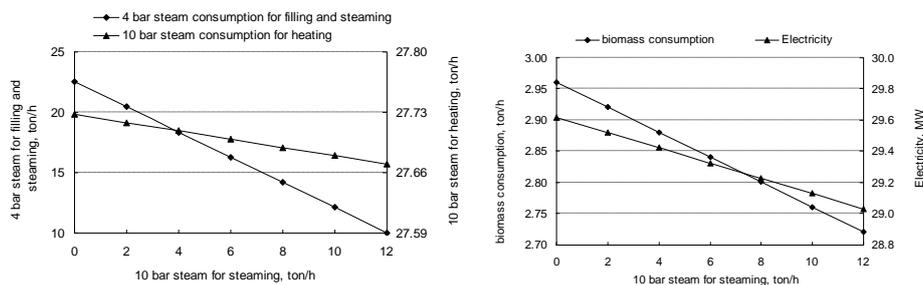


Figure 2: The effect of steam consumption (10 bar) in steaming on process simulation

Figure 2 shows the effect of 10 bar steam consumption used for chips steaming on the 4 bar steam consumption used for chips steaming together with a certain amount used for

chips filling, the 10 bar steam consumption used for heating, the biomass consumption in the BB, and the electricity generation from the turbine. Some tendency is obvious even without process simulation/optimization, but we should notice that the quantitative results from process modeling can be used to obtain an optimal operation point after we know how the consumption of 10 bar steam affects the time saving. In addition, the consequent results such as the effect on the BB and turbine can only be obtained from the process integration analysis with the given objective function. The current results are the first step towards the target, i.e. get a set of operation conditions to reach the lowest energy cost.

- *Case 2. Dry content of the black liquor*

For the evaporation plant, the steam consumption (4 bar) increases with increasing dry content of the black liquor out of the evaporation plant. For the HRB, the steam generation (60 bar) also relates to the dry content of the black liquor, and the steam generation will increase with increasing dry content of the black liquor. The model results show that a higher dry content of the black liquor will lead to a lower energy cost. In order to analyze such a result, several cases with different dry content of the black liquor are studied, and the result of each case is shown in Figure 3.

When the dry content of the black liquor increases from 68 to 75 %, the consumption of steam (4 bar) increases from 72.0 to 73.8 ton/h while the corresponding steam generation (60 bar) from HRB increases from 211.0 to 217.8 t/h. In other words, the increase of the dry content will cause 1.8 ton/h more steam consumption (4 bar) for the evaporation plant but 6.8 ton/h more steam generation (60 bar) in HRB. This observation gives the explanation why the higher dry content of the black liquor is preferred. Since the steam generation from the HRB and the steam consumption for the evaporation plant are different for each case, the corresponding results for the BB and the electricity generation from turbine are different, which is also shown in Figure 3. With a higher dry content of the black liquor, the consumption of fuel for BB is lower, while the electricity production becomes higher.

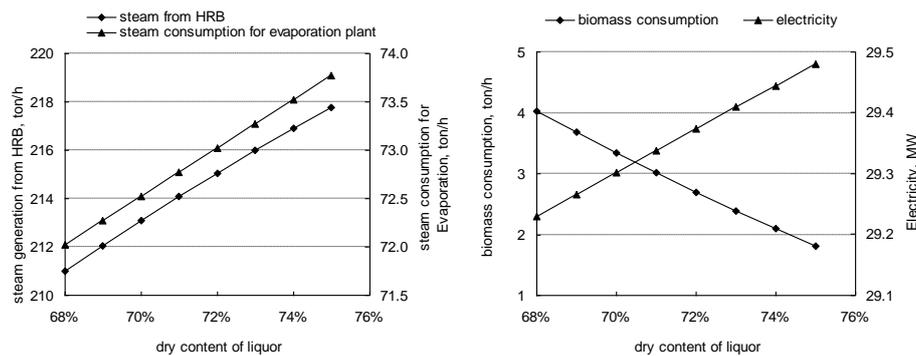


Figure 3: The effect of dry content of black liquor on process simulation.

In addition, because of the price listed in Table 2, biomass instead of purchased oil is always chosen as the fuel for the BB, and the model chooses to produce as much electricity as possible for both of these two cases.

#### 4. Conclusions

A process integration model for the pulp and paper mill is developed based on the Mixed Integer Linear programming in which the analysis is carried out using the reMIND software in combination with the commercial optimization software CPLEX. The steam production and the process steam consumers are modeled as separate modules and thereafter linked. Each part is validated using the operation data from a pulp and paper mill in the Northern Sweden. The whole plant is simulated and the initial optimization runs are performed with the objective of the lowest energy cost for a certain amount of product. The effects of operation conditions, such as the consumption of 10 bar steam for chips steaming into digester and the dry content of the black liquor, on the performance of the whole plant are obtained and analyzed. These results give the further understanding of the process and can be used as the base data for the process improvement.

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