Third International Conference on Applied Energy - 16-18 May 2011 - Perugia, Italy
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pages 109-122

Simulation and energy optimization in a pulp and paper mill — Evaporation plant and digester

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Abstract
A mathematical process integration model of a pulp and paper mill in the Northern Sweden has been developed. The main modelling focus has been put on the two main steam consumers (the evaporation plant and the digester), for which detailed material and energy balances have been established. Operational data have been used to validate the simulation results. By implementing these submodels into the complete plant model, the influence of different operation parameters on the overall plant performance has been investigated. Furthermore, introductory studies with the main objective to minimize the plant energy cost have been carried out. The correlation and differences between economic and energy have been discussed.

Keywords

Pulp and paper mill, evaporation plant, digester

Introduction

The pulp and paper industry is an energy-intensive industrial sector that faces several challenges such as increased competition and rising feedstock and energy prices. To address this, it is crucial for the industry to improve the material and energy efficiencies to the greatest possible extent. Process integration methods provide useful tools for evaluating possible process alternatives. Several studies of paper and pulp mills have been carried out by using pinch analysis [1-7] and mathematical programming [8-13]. However, the scope of modelling and simulation has not been as complete as it is in many other process industries. More detailed modelling is required especially as large efforts are currently put on turning pulp mills into bio-refineries.

In our research group, mathematical process integration models with detailed material and energy balances have been developed for both steelmaking [14-18] and mining [19, 20] industries based on mixed integer linear programming (MILP), in which the analysis was carried out using the reMIND software [21] in combination with the commercial optimization software CPLEX [22]. Recently, the research was extended to a pulp and paper mill in the Northern Sweden. [23]. The work was carried out in close cooperation with the plant engineers. A model was constructed with the aim to produce results that were useful for practical plant decisions. The initial discussions indicated that the model should include very detailed sub models, especially of the evaporation plant and digester. This work had to be carried out very carefully, as the risk of errors and undiscovered bugs increases dramatically with increased degree of complexity and detail. A stepwise method was chosen where the sub models were

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first created individually and validated after each step. They were then merged into a total MILP model which was also validated against plant data and experiences.

The main objectives of this work are to describe the practical development of this detailed model as well as to present some examples and results from its application for optimisation of plant parameters.

Process description and model construction

A schematic process description of the studied pulp and paper mill is shown in Figure 1. In order to produce bright pulp, the lignin in the wood-chips is removed by passing through the digester, the O_2 delignification and the bleaching plant before the pulp is used for paper making. The by-product extracted from pulping the wood-chips in the digester, the black liquor, is concentrated in a multi-effect evaporation plant and burned in a recovery boiler (RB) where the combustion of organics provides energy to produce high pressure steam and to carry out the reduction reactions to recover chemicals by passing through the causticizing plant. Biomass, in form of bark and forest residues, as well as firing oil is used in a bark boiler (BB) to provide additional high pressure steam to satisfy the steam demand. The high pressure steam produced in the RB and BB is expanded in a steam turbine producing electricity and process steam of 10 and 4 bar. 30 bar steam is also extracted for soot-blowing in the RB. The main steam consumers include digester, pre-bleaching by O_2 delignlification, bleaching plant, pulp drying machine, pulp making machine, evaporation plant, and other users.

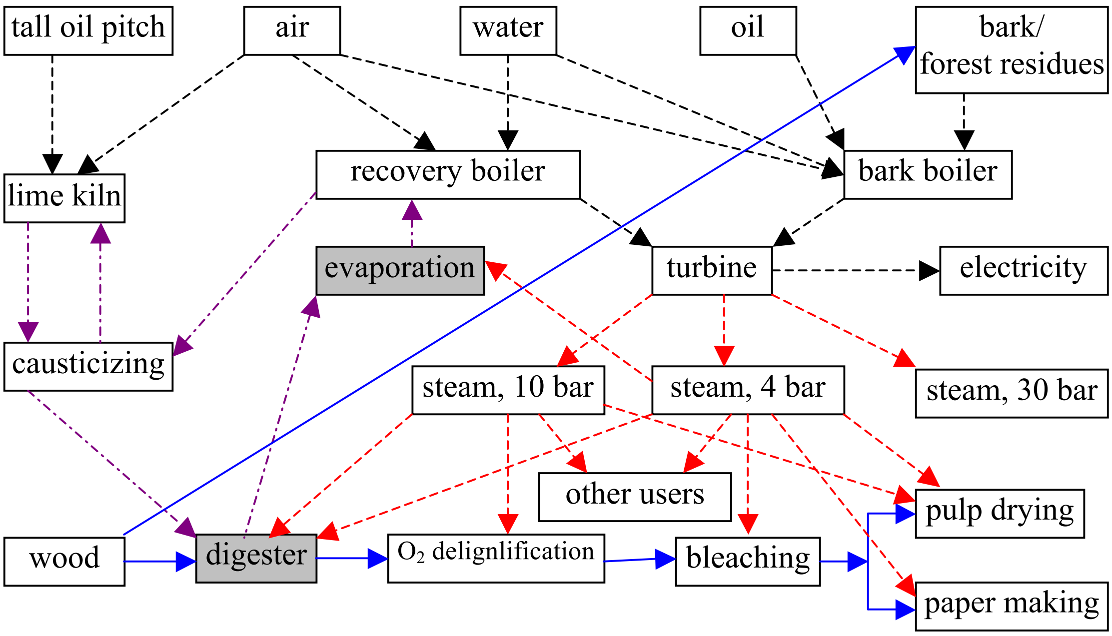

Figure 1: Schematic description of the pulp and paper mill

To perform process integration investigations, each process unit was modelled as separate modules and thereafter linked. The module construction was on the basis of a Java based programming - reMIND, where the mill is constructed as a network of nodes to represent process units. The nodes are connected with branches to represent energy/material flows to/from each node. Each node contains linear equations to express the material and energy balances for each unit.

There are two options to express material and energy balances for each node, i.e. representing them theoretically (option 1), or obtaining linear equations from measurements under a set of condition (option 2). For option 1, the energy balance of a node is calculated from the properties of input and output flows with assumption regarding heat losses, the temperaturedependent heat capacities of the flows, etc. The material balance is based on matter conservation. This work requires knowledge on process and operation principles as well as measurements to verify the assumption. For option 2, an empirical linear equation is used to represent the material and energy balances, respectively, and the accuracy depends on the measurements. Once the operation conditions are changed, new equations should be used, for example, different equations for different seasons of the year.

As the aim of this work was to produce a model that in a first stage could be used for the integration of the current mill, it should also be possible later on to include models for investigation of new alternative production routines and implementation of new parts, e.g., biorefineries. To accomplish that, option 1 was chosen for the detailed modelling of the energy intensive process units. For other process units, option 2 was used temporarily.

Detailed modelling of evaporation plant

A schematic layout of the evaporation plant is shown in Figure 2. The liquor flows through effects 4, 5, 6, 7, 3, 2 and 1 in which the temperature of liquor after effect 7 (E7) is increased before entering effect 3 (E3). The liquor concentration increases from 14.4 to 71.5% (mass). Live steam is only used in effect 1 (E1), and the generated liquor steam in an effect is used for the next effect. From E1, a certain amount of liquor comes out and is mixed with ash and then transferred back into E1 at a lower temperature. A part of the generated liquor steam is used for stripping (f_2).

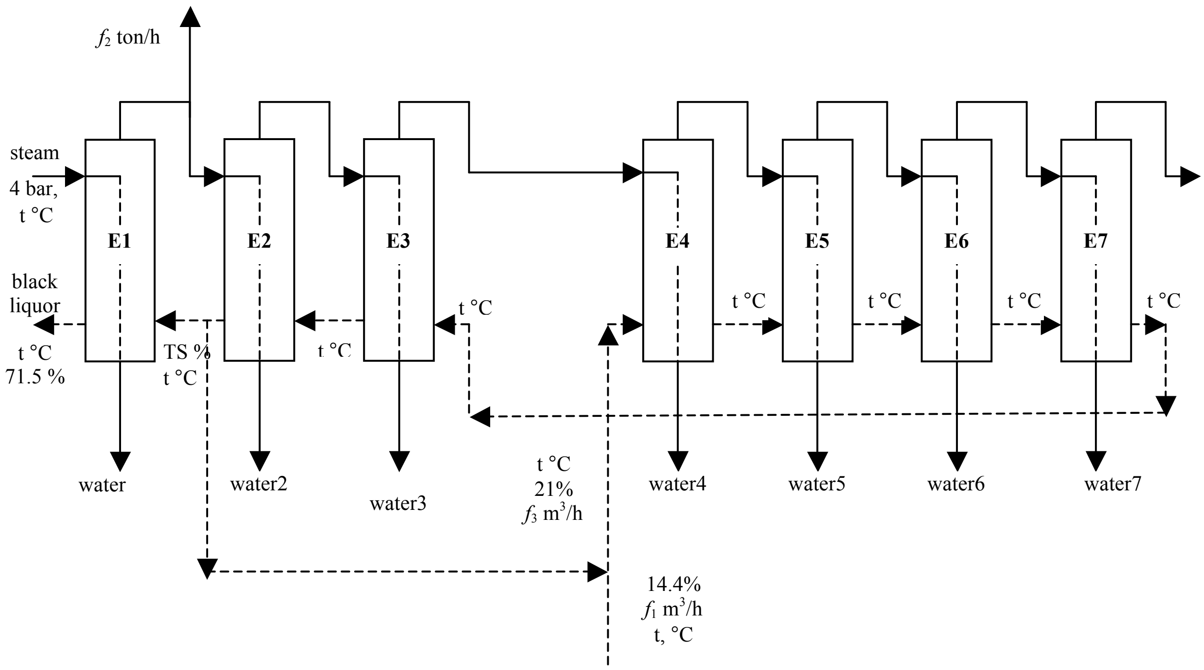

Figure 2: Schematic description of the evaporation plant

Because of the internal cycle of the liquor (part of the liquor out of effect 2 is supplied to effect 4), the boiling point rise, the counter-current/parallel flow of the liquor and the steam, and the heat capacity dependence on the dry content of the liquor, two iterations are needed to obtain the steam consumption of the evaporation plant. The iteration procedure is shown in Figure 3.

To simplify the model in reMIND, a rigorous Excel model was developed. Then an equation that depends on the main operation conditions was obtained by running the Excel model and was put into the equation editor in reMIND.

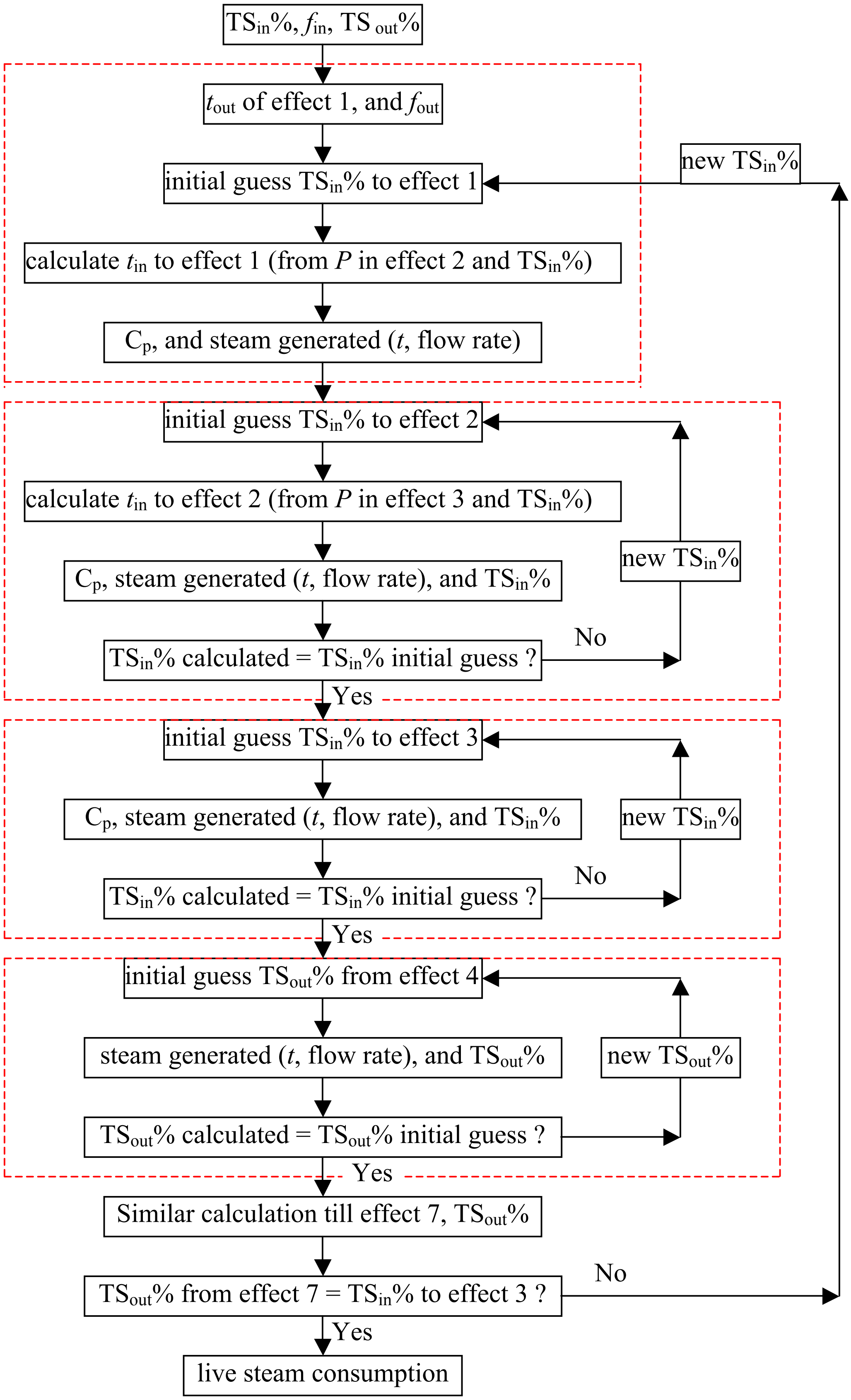

Figure 3: Schematic illustration of the calculation for evaporation plant in Excel model

In the evaporation plant, there are mainly six parameters affecting the live steam consumption, i.e. the dry content of the liquor to the evaporation plant (*TS%*$_{in}$), the temperature of the liquor to the evaporation plant (t_{in}), the flow rate of the liquor to the evaporation plant (f_{in}), the dry content of the liquor out of the evaporation plant ($TS\%_{out}$), the liquor steam leaving from effect 1 in the evaporation plant for stripping ($f_{liquorsteam}$), and the temperature of liquor enters to effect 3 after heat exchanger (t_3). These six key parameters were used as variables in the equation representing the steam consumption of the evaporation plant.

The Excel model was established on the basis of material and energy balances for each effect. To illustrate the material and energy balances in detail, effect 1 as illustrated in Figure 4 was used as a sample.

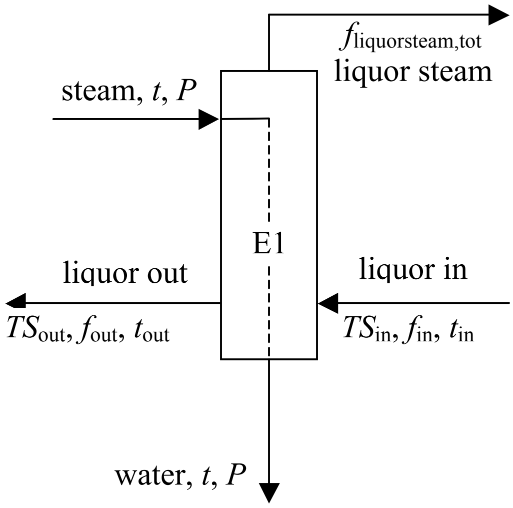

Figure 4: Schematic representation of the effect 1 in the evaporation plant

The material balances were expressed according to Equations (1) to (3).

$$f_{liquorin} = f_{liquorout} + f_{liquorsteam,tot} \quad (1)$$

$$f_{liquorin} \cdot TS_{in} = f_{liquorout} \cdot TS_{out} \quad (2)$$

$$f_{water} = f_{steam} \quad (3)$$

The energy balance was expressed as according to Equation (4).

$$f_{water} \cdot \left(h_{steam} - h_{water}\right) = f_{liquorin} \cdot C_p \cdot \left(t_{out} - t_{in}\right) + f_{liquorsteam,tot}\left(h_{steam} - h_{water}\right)\Big|_{t_{out},P_{effect}} \quad (4)$$

where h was calculated with steam-table [24], and C_p depends on temperature as well as the dry content of the liquor and was calculated according to Equation (5).

$$C_p = 4.216 \cdot (1 - TS) + (1.675 + 3.31 \cdot t/1000) \cdot TS + (4.87 - 20t/1000) \cdot (1 - TS) \cdot TS^3 \quad (5)$$

Because of the existence of solid substances, the boiling temperature of the liquor increases. In this work, the boiling point rise (Δt) was calculated according to Equations (6) and (7).

$$\Delta t = 1.3 \times 10^{-6} TS^4 - 0.00013 \cdot TS^3 + 0.0046 \cdot TS^2 - 0.011 \cdot TS + 5.2 \quad \text{(effect 1)} \quad (6)$$

$$\Delta t = \left(6.173 \cdot TS - 7.48 \cdot TS^{1.5} + 32.747 \cdot TS^2\right)\left(1 + 0.006\left(T_{sat,P} - 373.16\right)\right) \quad \text{(other effects)} \quad (7)$$

The temperature t_{out} was calculated according to Equation (8).

$$t_{out} = t_{sat}(P) + \Delta t \quad (8)$$

where t_{sat} is the saturation temperature of pure water at pressure P and was calculated with steam-table [24].

For other effects, the principle is the same but the condensate was assumed to be the saturated water at pressure P.

The Excel model was developed based on the principle shown in Figure 3. By executing the Excel model, the steam consumption was calculated according to Equation (9).

$$f_{steam} = -0.6897TS\%_{in} - 0.552t_{in} + 0.8655f_{liquorsteam} - 0.4288t_3 + 0.2445TS\%_{out} + 0.1182f_{in} \quad (9)$$

Detailed modelling of digester

The digester is operated batch-wise in several steps, i.e. wood-chips filling, steaming, liquor filling, heating, cooking, displacement, and emptying (blowing). 4 bar steam is used for wood-chips filling, 4 bar as well as 10 bar steam are used for the wood-chips steaming up to a temperature of 108 °C (t_{end1}), the white liquor is preheated with 10 bar steam from 90 to 122 °C and added into digester together with the black liquor (16%), and 10 bar steam is used for the heating step up to 168 °C (t_{end2}). The displacement liquor (black liquor, 11%) is preheated from 125 to 168 °C using 10 bar steam.

Material and energy balances for the steps of filling and steaming as illustrated in Figure 5 (a) were calculated according to Equations (10) to (12).

$$w_{chips,dry} = w_{chips,wet} \cdot TS \quad (10)$$

$$w_{water} = w_{chips,wet} \cdot (1 - TS) + w_{4bar,steam} + w_{10bar,steam} \quad (11)$$

$$w_{chips,dry} C_{p,chips,dry}(t_{end1} - t_{ini1}) + w_{chips,wet}(1 - TS)C_{p,water}(t_{end1} - t_{ini1}) + h_{loss} = w_{4bar,steam} \cdot \left(h_{4bar,steam} - h_{watter}\big|_{t_{end1}}\right) + w_{10bar,steam} \cdot \left(h_{10bar,steam} - h_{watter}\big|_{t_{end1}}\right) \quad (12)$$

where w is the amount (mass) of wood-chips, water or steam supplied into the digester. It should be mentioned that the input temperature of the wood-chips is generally higher than 0 °C. In the modelling, only the sensible heat has been considered for the wood-chips warming up. h_{loss} is the estimated heat loss, and h is the enthalpy of steam or water. Enthalpy of steam or water was primarily calculated from the NIST online database [25] and then fitted to an equation that is a function of temperature and pressure by assuming that the pressure effect is linear. The fitted equation for 10 bar steam, 4 bar steam, and water is shown in Equations (13), (14), and (15), respectively, and were input in the equation editor in reMIND.

$$h = (2400.1 + 2.1856t) + (2.910 \times 10^{-2} t - 11.00)(P - 9) \quad \text{(10 bar steam)} \quad (13)$$

$$h = (2443.9 + 2.1157t) + (8.06 \times 10^{-2} t - 20.5)(P - 3) \quad \text{(4 bar steam)} \quad (14)$$

$$h = 4.256998t - 4.4463 \quad \text{(water)} \quad (15)$$

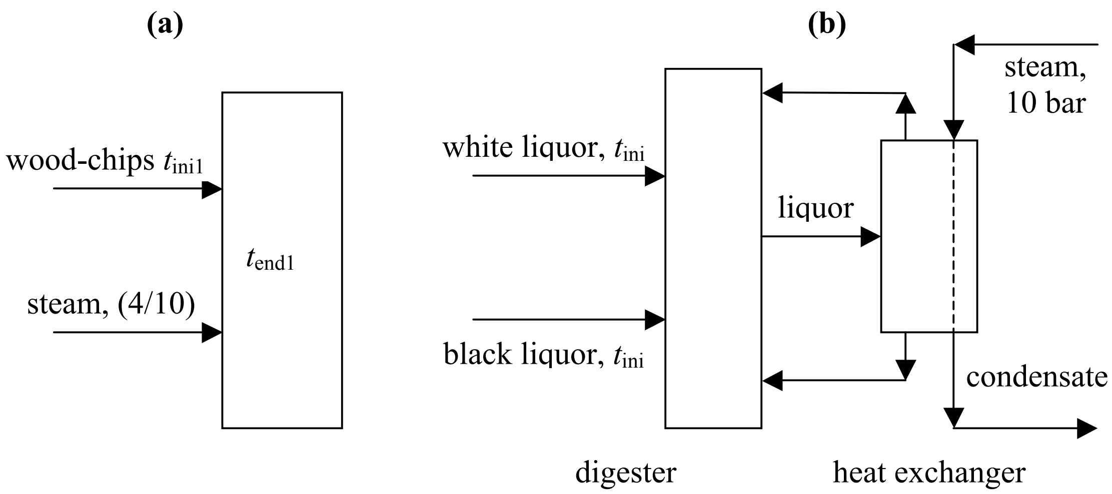

Figure 5: Schematic representation of steps of filling and steaming (a) and steps of liquor filing and heating (b) for the digester

Table 1: heat capacities (kJ/kg·K)

material	heat capacity	material	heat capacity
wood-chips, dry	1.47	black liquor (16%)	3.74
water	4.20	displacement liquor (11%)	3.74
white liquor	3.81		

The energy balance for the steps of liquor filling and heating as shown in Figure 5(b) is established according to Equation (16).

$$\begin{aligned} & w_{chips,dry} C_{p,chips,dry} \left(t_{end2} - t_{end1}\right) + w_{water} C_{p,water} \left(t_{end2} - t_{end1}\right) \\ & + w_{whiteliquor} C_{p,whiteliquor} \left(t_{end2} - t_{ini2,whiteliquor}\right) + w_{blackliquor} C_{blackliquor} \left(t_{end2} - t_{ini2,balckliquor}\right) + h_{loss} \\ & = w_{10bar,steam} \left(h_{10bar,steam} - h_{condensate}\right) + h_{heat\ release,reaction} \end{aligned} \quad (16)$$

where $h_{\text{heat release, reaction}}$ is the heat release due to the chemical reaction before cooking. To take the heat release into account, the chemical reaction heat has been measured experimentally. The heat release will however be started after the liquor filling, and only a part of the heat is released till the end of the heating. It is estimated that the temperature of the digester may increase by 2-3 °C before cooking, corresponding to 1/3 of the total heat release. This estimation has been used to account for the heat release due to the chemical reactions before cooking.

The energy balance for the preheating of the white liquor or for the displacement liquor can be expressed according to Equation (17).

$$wC_p\left(t_{out} - t_{in}\right) = w_{10bar,steam}\left(h_{10bar,steam} - h_{condensate}\right) \quad (17)$$

where $h_{\text{condensate}}$ is the enthalpy of the condensate, assumed to be the saturated water, and was calculated with equation (15).

In addition, because of the batch operation, the steam consumption is time-dependent. However, in the process modelling, the average steam consumption of a certain period for a fixed consumption of dry wood-chips was used.

Model validation and process integration

Because of the detailed material and energy balances, the applied methodology is a combination of process simulation, optimization and integration. A model of a sub-process could either be validated individually or when implemented into a process model of the entire plant. Since the sub-processes will affect each other, the latter validation method has been chosen in this work.

Process integration model

The sub-models describing the evaporation plant and digester were implemented into a process model for the entire mill. For model optimization, the commercial software CPLEX was used as a solver. The objective function was to minimize the energy cost and can be expressed according to Equation (18).

$$\min f(x) = c_{oil} \cdot m_{oil} + c_{bark} \cdot m_{bark} + c_{el,purchased} \cdot q_{el,purchased} - C_{el,produced} \cdot q_{el,produced} \quad (18)$$

where c is the price of an energy carrier (oil, bark or electricity) in units of €/ton or €/MWh, m is flow rate in unit of ton/h for oil or bark, and q is electricity (el) flow rate in unit of MW. The price used in this work is the same as that in [23].

Validation

The model results of the evaporation plant and digester were obtained and compared to actual plant measurements. The steam consumption of the evaporation plant calculated is 72.9 ton/h assuming that the heat loss is 2%. According to plant measurement the steam consumption amounted to 72.5 ton/h during the studied operational conditions. For the digester, from measurements, the 10 bar steam consumption for (the steaming + the digester heating + the preheating of white liquor) is 42 ton/h, and the consumption of the 4 bar steam for (the wood-chips filling + steaming) is 16.92 ton/h. Assuming the same consumption of the 4 bar steam and 2% for the heat loss, the model results of the 10 bar steam consumption for (the steaming + the digester heating + the preheating of white liquor) is 41.9 ton/h.

Results and discussion on process integration

Evaporation plant

There are mainly six parameters that affect the performance of the evaporation plant. The effect of the dry content of the strong black liquor ($TS\%_{out}$) will also affect the mass and energy balances in RB and the discussion was excluded in this work. The effects of other parameters were discussed in this work.

The light liquor from the digester, with a temperature of around 87°C, is mixed with liquor from E2 resulting in a temperature increase to around 92°C before it enters E4. In practice, the temperature of the light liquor can be increased to the boiling temperature (around 102 °C at 1 bar). The effect of the temperature of the liquor to E4 is illustrated in Figure 6 (a). If the temperature of liquor to E4 increases from 85 to 105°C, the steam consumption of the evaporation plant decreases from 77 to 66 ton/h, the bark consumption decreases from 22 to 17 ton/h, and the electricity generation decreases slightly from 35 to 34 MW due to the decrease of the total high pressure steam production. The temperature of the liquor depends on the washing part, and an improved temperature control at the washing part can save energy.

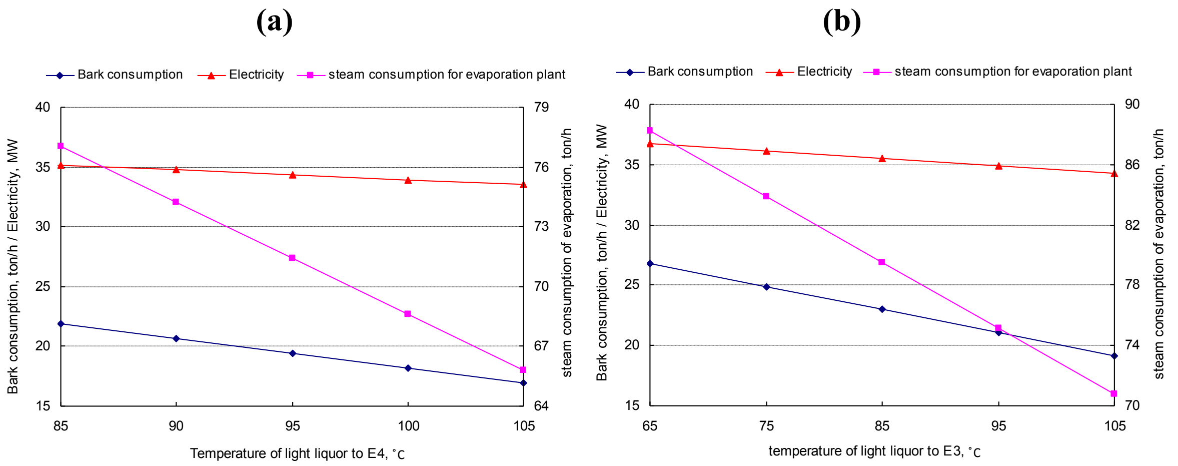

Figure 6: The effect of the temperature of liquor to E4 (a) / the liquor temperature to E3 (b) on the steam consumption of the evaporation plant and the performance of BB

The temperature of the liquor from E7 is normally in the range of 60 to 70 °C depending on the dry content of liquor. From energy point of view, it would be desirable if the liquor to E3 would be around 100 °C (near the boiling point) in order to use less live steam for evaporation. One way to accomplish that could be to use a heat exchanger to pre-heat the liquor before it enters to E3. Therefore, the effect of the temperature of the liquor to E3 on the steam consumption was studied to find how much live steam that can be saved by using a heat exchanger. The results are shown in Figure 6 (b). If the temperature of liquor to E3 increases from 65 to 105 °C, the steam consumption of the evaporation plant decreases from 88 to 70 ton/h leading to reduced bark consumption from 27 to 19 ton/h. At the same time the electricity generation decreases from 37 to 34 MW.

The dry content of the light liquor depends on the degree of washing. Meanwhile, it also affects the steam consumption considerably as shown in Figure 7 (a). If the dry content of the light liquor increases from 13 to 16%, the steam consumption of the evaporation plant decreases from 79.5 to 66.6 ton/h, the bark consumption decreases from 23 to 17 ton/h, while the electricity generation decreases slightly from 35.6 to 33.6 MW. However, exactly how the overall operation of the washing changes with a modified dry content has not been investigated, but the optimization potential has been illustrated.

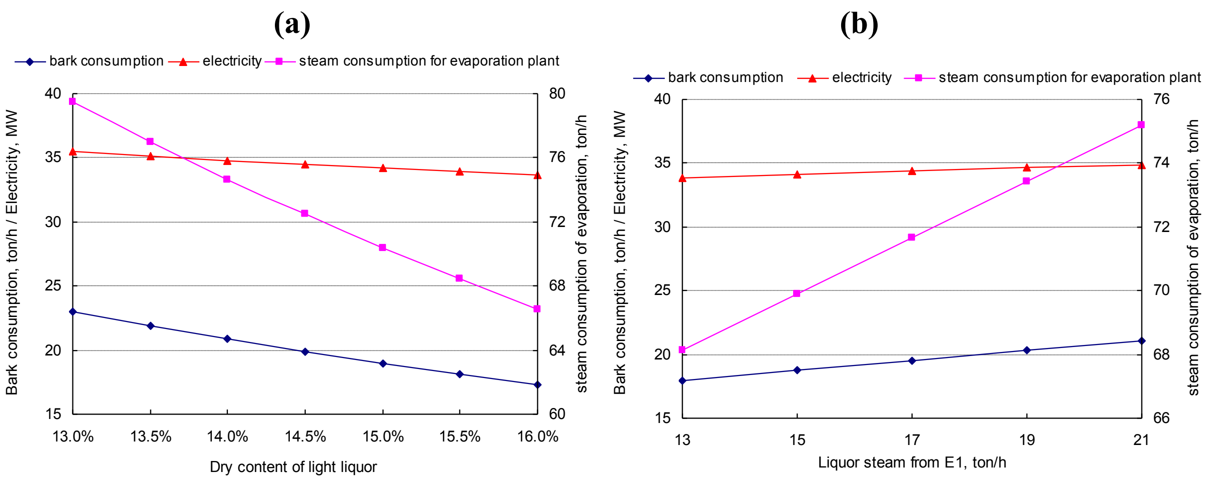

Figure 7: The effect of the dry content of the light liquor (a) / the steam liquor to stripping (b) on the steam consumption of the evaporation plant and the performance of BB

One part of steam generated from E1 is used for stripping and the rest part is used in E2. The distribution between the stripping and E2 affects the performance of the entire plant as shown in Figure 7 (b). If the utilization of the liquor steam to the stripping increases from 13 to 21 ton/h, the steam consumption of the evaporation plant increases from 68 to 75 ton/h, the bark consumption increases from 18 to 21 ton/h, and the electricity generation increases from 33.9 to 34.9 MW.

Digester

The influence of the supply ratio between 4 and 10 bar steam for steaming has been described in previous work [23]. In this work, the influence of the initial temperature of the wood-chips and the preheating temperature of the white liquor were investigated.

The temperature of the wood-chips supplied to the digester depends on the outdoor temperatures, and in winter, the wood-chips can be frozen. To investigate the effect of the initial temperature of the wood-chips on the steam consumption and the performance of BB, process integration model was run at different initial temperatures of the wood-chips but with the same ratio of 4 and 10 bar steam for steaming. The results are shown in Figure 8. With increasing initial temperature of the wood-chips, the steam consumption decreases considerably. Because of the amount of steam for filling will affect the water content in the digester, and the steam consumption for the later step (steaming and heating) decreases with increasing temperature of wood-chips. Subsequently, the bark consumption and the electricity generation are reduced as shown in Figure 8. This underlines the importance to use waste heat to preheat the wood-chips.

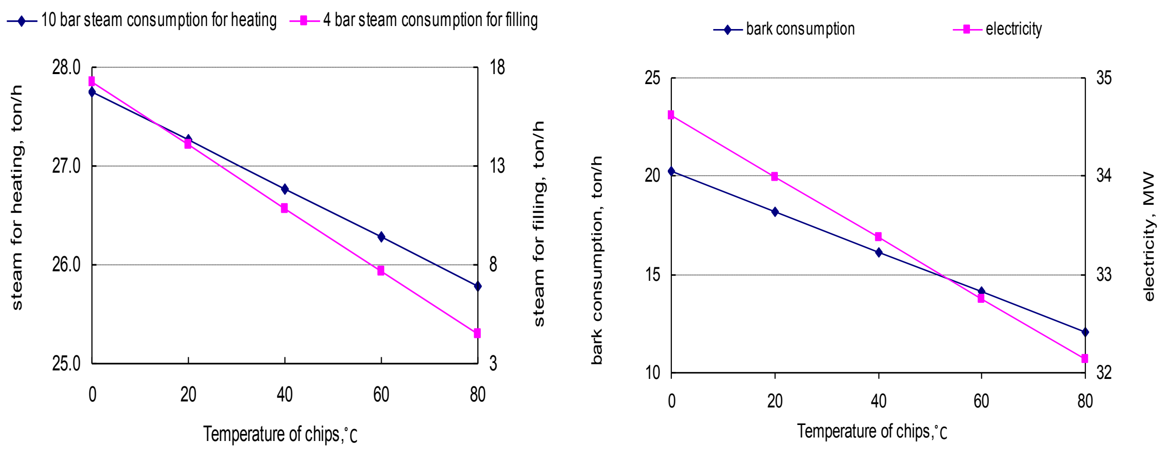

Figure 8: The effect of the temperature of wood-chips on the team consumption of digester and performance of BB

Four case studies have been carried out, in which the white liquor temperature has been varied to investigate the influence on the energy consumption of the digester. As a reference case (Case 1), the white liquor is, as presently, preheated to a certain temperature before it is supplied to the digester by using 10 bar steam. From the energy point of view, it is better to use 4 bar steam, which represents Case 2. In Case 3, the white liquor is not preheated at all. In Case 4, the white liquor is preheated by using 10 bar steam to the final temperature of digester, 168 °C. The results are shown in Table 2.

Table 2: Energy consumption of the digester for different cases regarding the preheating the white liquor

substance	Case 1	Case 2	Case 3	Case 4
bark consumption, ton/h	20.08	20.23	20.36	19.68
steam generation from BB, ton/h	46.43	46.78	47.08	45.50
electricity from turbine, MW	34.55	34.95	34.62	34.46
10 bar steam consumption for preheating white liquor, ton/h	8.25	-	-	20.11
4 bar steam consumption for preheating white liquor, ton/h	0	8.59	-	-
10 bar steam consumption for heating, ton/h	27.70	27.70	36.59	14.93

As the case studies show, using 4 bar steam for preheating (Case 2) increases the required bark supply slightly compared to the reference case (Case 1) due to the required higher total mass flow of steam. On the other hand, the electricity generation also becomes higher. From practical point of view, it is however more convenient to use 10 bar steam for the preheating. As the temperature of white liquor will affect the amount of water in digester and then affect the steam consumption for the subsequent steps, therefore, it is better to preheat the white liquor to a higher temperature, for example, to the final temperature of the digester (Case 4). As shown in Table 2, the bark consumption (19.68 ton/h) is lower than that in Case 1 (20.08 ton/h) and consequently also the electricity generation becomes slightly reduced. In Case 3, the bark consumption becomes higher due to the higher amount of water in digester, leading to an increased electricity generation.

The calculations show that the energy consumption is lowest in Case 4 and highest in Case 3. This implies that it is better to preheat the white liquor to a higher temperature. However, investments in new or modified existing heat exchangers have not been taken into account. The best option depends on the price of the fuel, the price of the electricity, the investment and the operational cost of the heat exchangers.

Conclusions

A mathematical process integration model of a pulp and paper mill in the Northern Sweden was developed. In this work, detailed material and energy balances for the evaporation plant and digester are described. The models of these two sub-processes were implemented into a complete plant model and validated with the operational data.

Case studies regarding how various operational parameters influence the steam demand, electricity production and biomass fuel consumption have been carried out. As a result, several options to save steam and fuel have been identified. For example, if the wood-chips supplied to the digester is preheated from a temperature of 0°C to say 60°C by the use of low grade residual heat, approximately 5 ton/h of biomass can theoretically be saved. Another case study shows that if the inlet liquor temperature to effect 4 of the evaporation plant increases from 85 to 105°C, the steam consumption of the evaporation plant decreases from 77 to 66 ton/h at the same time as the bark consumption decreases from 22 to 17 ton/h. However, the electricity production decreases consequently from 35 to 34 MW due to a reduced production of the total high pressure steam.

Acknowledgements

The authors gratefully acknowledge the Swedish Energy Agency, Billerud Karlsborg AB and Bio4Energy for funding and support of this work.

Nomenclature

c: Price of an energy carrier [€/ton or €/MWh]
C_p: Heat capacity [kJ/(kg·°C)]
f: Flow rate [ton/h]
h: Enthalpy [kJ/kg]
m: Energy carrier flow rate [ton/h]
P: Pressure [bar]
q: Eectricity (el) flow rate [MWh/h]
t: Temperature [°C]
TS: Dry content, mass fraction
w: the amount of component [ton]
Δt: Boiling point rise [°C]

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