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Operational Flexibility in Pulp Mill Steam Production at Off-design Heat Loads

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This paper focuses on the steam production in a chemical pulp mill that is retrofitted to reduce its process heating demand. A multi-period optimization model for design decisions is proposed that takes into account the operational limits of the steam production units as well as the heat load variations over the year. Large variations in combination with the retrofit that causes off-design loads in the steam production system will influence the flexibility of the steam system. Minimum boiler load limits will then be a greater constraint on operation since the average load of boilers is moved closer to the minimum for longer periods of time. A conventional approach that considers fixed annual averages of process parameters therefore risks leading to sub-optimal solutions because of neglecting the variations in heat demand and the operational limits. The multi-period approach suggested in this paper considers this operational flexibility associated with different design choices. A case study based on a Kraft pulp mill with a recovery boiler and a bark boiler shows the benefit of properly modelling the varying heat demand. Numerical results are presented that compares the results of the multi-period model with that of a conventional annual average approach. Differences in design decisions, energy balances and economic performance are demonstrated and discussed.

1. Introduction

When making decisions about process retrofits for energy savings at an industrial plant, potential operational flexibility towards variations in, for example, heat loads and energy prices should be considered. When process variations cause the load of certain process equipment to approach their minimum and/or maximum operational limits valuable operational flexibility might be lost. The risk of being constrained by such operational limits might increase in a retrofit situation leading to deviations from the original design conditions. Retrofit energy savings will, for example, lead to a reduction in heat load of the steam production units at the plant, causing their average load to approach their minimum load limits.

This paper focuses on variations in process parameters. Variations in energy prices or, for example, carbon prices can also be essential to consider if processes that are flexible in operation with regard to such changes are considered (see e.g. Manca and Grana (2010)). Siitonen and Ahtila (2010) studied the effect of operational flexibility towards fluctuating carbon prices for energy savings in a pulp and paper mill and showed that its economic value can be significant. Nemet et al. (2012) optimized the process design of a distillation column sequence integrated with a heat exchanger network over the full lifetime by considering future utility price variations in a multi-period approach.

This study analyses a retrofit project in an existing pulp mill. The purpose of the retrofit project is to reduce the heat demand of the plant. However, in order to assess the value of the steam savings, it is necessary to determine how the steam production is most profitably adjusted in response to the savings.

Methodologies for the design optimization of utility systems with varying demands need to simultaneously consider both design and operational decisions. Several such methodologies have been published in literature. Maia and Qassim (1997) used a simulated annealing algorithm to solve the synthesis problem with time-varying demands. However, most published methods rely on a multi-period, mixed-integer linear programming (MILP) formulation. Hui and Natori (1996) suggested a model for the optimization of the utility system operation including design decisions by considering both existing and new power generation

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equipment. Iyer and Grossmann (1998) formulated a MILP model for the multi-period synthesis and operational planning of the utility system and proposed a bi-level decomposition algorithm for effective solution of the problem. Marechal and Kalitventzeff (2003) used a genetic algorithm to identify the minimum number of operating periods needed to describe the yearly demand variations with sufficient detail and then optimized the synthesis and operation of the utility system using a multi-period MILP model. More recently, the focus has been increasingly directed towards improved modelling of energy equipment performance. Varbanov et al. (2004) proposed improved models for steam and gas turbines in part-load operation. Shang and Kokossis (2005) considered the performance of turbines and boilers to depend on size, load and operating conditions in their approach to synthesis of utility systems with varying demands, in which they rely on thermodynamic targeting models to reduce the problem to a reasonably sized MILP formulation. Aguilar et al. (2007) also considered part-load operations and varying energy demands in their generic modelling framework for utility systems, in which they obtain linearity by starting from the development of linear models for boilers and turbines. Recent advances also include the modelling of variations in steam header properties, either as predetermined parameters (Aguilar et al., 2007) or as variables to be optimized (Chen and Lin, 2010). Common for the cited studies are their general applicability for optimization of complex networks of a wide range of heat and power production units.

In contrast, the present work suggests a simplified, but nonetheless multi-period approach for the specific application to a chemical pulp mill retrofit. A MILP model is suggested for the optimization of design and operating decisions in the steam production system at an existing pulp mill in response to a process heat savings retrofit. The model is deliberately kept simple with regard to, for example, part-load efficiency, linearized investment cost functions and pre-determined steam header properties. The intent is to help enable its integration with more complex, strategic decision-making models that cover not only decisions related to the utility system, but also decisions about the level of energy savings and decisions about integration of new technology and processes at the plant. It should, for example, be possible to integrate it with a model for strategic decision-making under uncertainty (Svensson et al., 2011). Nonetheless, a multi-period modelling approach has been chosen in order to account for variations in process heat demand. Explicit modelling of operational constraints of the boilers has also been included.

The utility system studied here is different from earlier studies also in its application to a chemical pulp mill. The pulp mill steam production is centred on the recovery boiler, which does not only fill the purpose of utility production, but also the recovery of process chemicals. It is therefore an important part of the actual process, not only the utility system, and its operational flexibility is more strongly constrained than of a conventional boiler. The recovery boiler does therefore not straightforwardly fit into generic boiler models. Furthermore, this study includes the possibility of investing in lignin separation (see e.g. Olsson et al. (2006)), an emerging technology for the pulping industry, for which operating performance data is not yet readily available. However, it provides a great opportunity for indirectly increasing the flexibility of the pulp mill utility production as will be shown in this paper.

The aim of this paper is to illustrate the importance of modelling the process variations and operating load limits instead of taking the simplifications one step too far by modelling a single-period, fixed-value problem. The results demonstrate the potentially large errors in unit sizes, energy balances and economic results that can arise if a problem is inadequately simplified to average values.

2. Studied system – Pulp mill

The main steam producer in a chemical pulp mill is the recovery boiler, which purpose is twofold: Recovery of energy and chemicals from the black liquor, which consists of the wood by-products that are not used for the pulp production and the used cooking chemicals. The load of the recovery boiler is determined by the demand for chemical recovery set by the pulp production rate. Seasonal variations in steam demand are therefore normally controlled by varying the steam production in a supplementary boiler, typically fired with bark or other wood residues.

The bark boiler is therefore important for the flexibility of the mill’s steam system. The highest flexibility is achieved when the varying load is never constrained by the maximum and minimum operating limits of the boiler. The value of having a high flexibility in bark boiler operation must be considered when evaluating the economic consequences of steam savings at the mill, as is shown below.

For this study, a heat-load variation curve has been constructed that represents a typical steam demand of a pulp mill that is the dominant heat supplier in a district heating network (see Figure 1a). The heat-load chosen is approximately the average steam demand of the mill studied in (Persson and Berntsson, 2009) with the relation between maximum and minimum district heating demand being approximately the same as for a typical medium-sized district heating system as defined in Jönsson et al. (2008). The few days with top-load demand are, however, assumed to be covered by alternative heat supply.

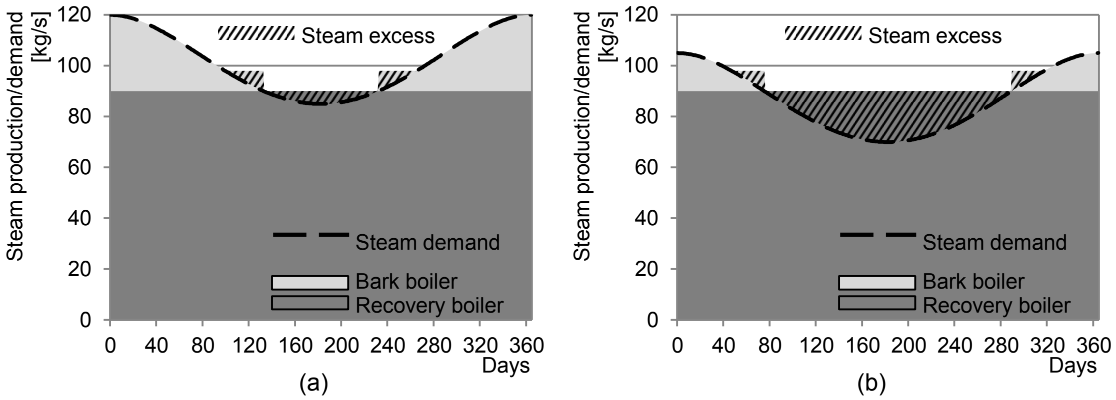

Figure 1: Steam demand of the pulp mill (incl. district heating) covered by steam produced in the bark boiler and the recovery boiler. (a) Current situation. (b) Situation after steam and bark savings retrofit

Figure 1a shows how the steam demand is currently covered by the steam production in the recovery boiler and bark boiler. Because of the minimum load limitation on the bark boiler and the constant steam production in the recovery boiler, there will be an excess of steam during parts of the year. There is clearly a lack in the flexibility of precisely controlling the steam balance of the mill. However, the amount of steam that is vented to the atmosphere is currently fairly small. Figure 1b, on the other hand, shows the situation after a steam saving retrofit. Here, the amount of excess steam becomes significant and the limited flexibility becomes obvious. In a situation like the one illustrated in Figure 1b, there is a very small gain of implementing the steam savings, simply because the existing utility system is not flexible enough to meet such a change. Flexibility can, however, be achieved by extracting lignin from the black liquor and thereby controlling the steam production also in the recovery boiler. As shown below, the value of this flexibility provided by lignin extraction would not be captured in a single-period, average-value model.

3. Optimization model

The MILP model is used to identify how the steam production at the pulp mill should best be adapted to meet a reduction in process steam demand. A design decision (investment in lignin extraction) is optimized, considering the effect of varying operating conditions.

3.1 Assumptions and simplifications

The adaption of the steam production system of the mill is assumed to be made in connection to a retrofit for a given amount of heat savings in the process. The steam header data is assumed to be fixed. Heat savings are expressed as a reduced demand for high-pressure (HP) steam. Heat savings are, however, more commonly implemented for low-pressure (LP) steam. The LP steam savings have therefore been converted to an equivalent HP steam amount. The steam savings are assumed to not affect the electricity production in back-pressure turbines. This assumption is based on that the existing turbines are currently too small to accommodate all HP steam. Hence, a significant amount of steam is passed through let-down valves between the HP and LP steam headers. A reduction in steam use will lead to a reduction in let-down steam, and will therefore not affect the electricity production. Finally, all possible practical hinders or costs associated with daily variations in the operation of the studied processes and steam production units are neglected. Also, part-load efficiency effects are neglected.

3.2 Multi-period model

The objective of the optimization model is to maximize the net annual profit. Note that the actual profit of the retrofit also depends on the investment cost of the process steam savings, but since the amount of steam savings is assumed to be fixed, this cost does not affect the optimal decision.

Maximize $-\mathrm{r}\,Inv + Rev$ (1)

where r is the annuity factor and $Inv(X)$ is the cost of a possible lignin extraction investment, expressed by a piecewise linear function of the capacity, X, of the lignin extraction plant:

$$Inv = \begin{cases} 0, & X = 0 \\ C_{inv}(i) + k(i)\big(X - bp(i)\big), & bp(i) \le X < bp(i+1) \end{cases} \qquad (2)$$

$$z\,\mathrm{bp}(1) \le X \le z\,\mathrm{bp}(n) \tag{3}$$

Here, $\mathrm{C_{inv}}(i)$ is the investment cost at the breakpoints, $\mathrm{bp}(i)$, between the segments of the piecewise function and $\mathrm{k}(i)$ is the slope of the linear function between breakpoints $\mathrm{bp}(i)$ and $\mathrm{bp}(i+1)$. The variable z is a binary variable taking the value 1 if the investment is made, and 0 otherwise. Eq (3) thus represents the range in which the linearization is valid. $Rev(\Delta Prod)$ is the annual revenues from the fuel savings, as a function of the boiler fuel price, $\mathrm{p}(b)$, the steam production reduction $\Delta Prod(b,d)$, the boiler efficiency $\eta(b)$ and the enthalpies of high-pressure steam and feed water, $\mathrm{h_{HP}}$ and $\mathrm{h_{FW}}$.

$$Rev = 24(\mathrm{h_{HP}} - \mathrm{h_{FW}}) \sum_b \mathrm{p}(b) \left(\sum_{d=1}^{\mathrm{D}} \frac{\Delta Prod(b,d)}{\eta(b)} \right) \tag{4}$$

Note that this expression should be adjusted for lost back-pressure electricity production if relevant. The plant is assumed to be operated for 24 hours a day during D days of the year. The steam demand of the process is given by the demand before the retrofit, $\mathrm{RefDem}(d)$, minus the steam savings, $\Delta\mathrm{Dem}(d)$. The steam production in each boiler is the reference production before the retrofit, $\mathrm{RefProd}(b,d)$, minus the production reduction, $\Delta Prod(b,d)$. The sum of the steam production in all boilers should equal the process steam demand plus possible steam excess $Qxs(d)$ that is vented to atmosphere. Furthermore, the steam production in each boiler must be either zero, or between the minimum and maximum operating limits, $\mathrm{MinProd(b)}$ and $\mathrm{MaxProd}(b)$.

$$\sum_b \left(\mathrm{RefProd}(b,d) - \Delta Prod(b,d)\right) - Qxs(d) = \mathrm{RefDem}(d) - \Delta\mathrm{Dem}(d) \tag{5}$$

$$y(b,d)\,\mathrm{MinProd(b)} \le \mathrm{RefProd}(b,d) - \Delta Prod(b,d) \le y(b,d)\,\mathrm{MaxProd}(b) \tag{6}$$

Here, $y(b,d)$ is a binary variable, taking the value one if the boiler is in operation, and the value zero otherwise. Finally, the lignin extraction capacity, X, expressed as the maximum reduction in recovery boiler input, gives a constraint for the reduced steam production in the recovery boiler $\Delta Prod(\mathrm{RB},d)$:

$$(\mathrm{h_{HP}} - \mathrm{h_{FW}}) \frac{\Delta Prod(\mathrm{RB},d)}{\eta(\mathrm{RB})} \le X \tag{7}$$

3.3 Annual-average model

Realizing that on average, the yearly production might well be between 0 and the minimum operating load, and introducing $\overline{}$ for the annual average value, the corresponding single-period, annual-average, model is obtained by replacing Eqs (4)-(7) from the multi-period model by Eqs (8)-(11) below.

$$Rev = 24\mathrm{D}(\mathrm{h_{HP}} - \mathrm{h_{FW}}) \sum_b \mathrm{p}(b) \frac{\Delta\overline{Prod}(b)}{\eta(b)} \tag{8}$$

$$\sum_b \left(\overline{\mathrm{RefProd}}(b) - \Delta\overline{Prod}(b)\right) - \overline{Qxs} = \overline{\mathrm{RefDem}} - \Delta\mathrm{Dem} \tag{9}$$

$$0 \le \overline{\mathrm{RefProd}}(b) - \Delta\overline{Prod}(b) \le \mathrm{MaxProd}(b) \tag{10}$$

$$(\mathrm{h_{HP}} - \mathrm{h_{FW}}) \frac{\Delta\overline{Prod}(\mathrm{RB})}{\eta(\mathrm{RB})} \le X \tag{11}$$

3.4 Input data and assumptions

Table 1 shows the investment cost data for lignin extraction and Table 2 shows data for the boilers.

Table 1: Investment cost data for the lignin extraction plant.

Investment cost parameter	
Annuity factor, r [1/y]	0.2
Breakpoints, $\mathrm{bp}(i)$[MW]	$10 + 8 * (i-1), \quad i = 1..9$
Investment cost at breakpoints, $\mathrm{C_{inv}}(i)$ [€]	$1{,}020{,}000\ \mathrm{bp}(i)^{0.6}$
Slopes of investment cost function, $\mathrm{k}(i)$ [€/MW]	$(\mathrm{C_{inv}}(i+1) - \mathrm{C_{inv}}(i))/(\mathrm{bp}(i+1) - \mathrm{bp}(i))\left(X - \mathrm{bp}(i)\right)$

Table 2: Performance and operating data for the boilers

	Recovery boiler	Bark boiler
Efficiency, $\eta(b)$	0.96[a]	0.88
Minimum production, $\mathrm{MinProd}(b)$ [kg/s]	65[b]	8
Reference production, $\mathrm{RefProd}(d)$ [kg/s]	90	See Figure 1
Maximum production, $\mathrm{MaxProd}(b)$ [kg/s]	90	40
Enthalpy, HP-steam, h_{HP} [MJ/kg]	3.3	
Enthalpy, feed water, h_{FW} [MJ/kg]	0.5	

[a] Ratio between boiler production decrease and heat content of extracted lignin (accounting for the change in energy demand of the evaporation plant due to lignin extraction)
[b] Corresponding to the assumed maximum lignin extraction rate of 74MW to not risk the operation of the recovery boiler.

A constant saving, $\Delta\mathrm{Dem}(d)$, of 15 kg/s HP steam is investigated. The price of bark, $\mathrm{p(BB)}$, is set to 20 €/MWh and the price of lignin, $\mathrm{p(RB)}$, to either 20 €/MWh or 30 €/MWh, representing lignin being valued relative to the wood fuel price, or to the oil price. The lignin price has been adjusted for operating costs of lignin extraction. No alternative use of excess steam has been considered.

4. Results

Figure 2 illustrates the energy situation at the mill after the steam savings and optimally adjusted boiler operation, including investment in a lignin extraction plant. With a low lignin value (Figure 2a) the optimal solution implies an investment in lignin extraction despite the fact that bark savings are prioritized in operation. The capacity for lignin extraction is used to reduce the load on the recovery boiler and to reduce the steam excess that is vented to atmosphere after the point when the bark savings have been maximized. When lignin is assumed to have the higher price of 30 €/MWh (Figure 2b) its value is sufficiently high in relation to that of bark to make it optimal to maximize the lignin extraction rate. This will actually lead to increasing the use of bark to the maximum bark boiler capacity. The investment in lignin extraction provides flexibility to the steam production system at the mill, which otherwise was strongly constrained by the operating limit of the bark boiler and the fixed load of the recovery boiler.

The solutions to the multi-period model and the single-period, annual-average model have been compared with regard to optimized lignin extraction capacity, boiler loads and economic results (see Table 3). As shown, the single-period model arrives at a solution with a drastically under-dimensioned lignin extraction plant. This kind of inadequate estimation of the optimal design capacity provides poor guidance for investment decisions. The results also show significant errors for the single-period model in how the fuel reductions are divided between the boilers, which instead lead to poor estimations of expected cash flows, possibly leading to unfair comparisons with alternative investment options. The comparison between the constant-load model and the model accounting for variations shows that the effect of the variations is not just that a greater capacity is needed for a certain average load, but in fact, it is profitable to extract more lignin in the presence of variations. This shows that there is a value of the flexibility itself that is provided by the lignin extraction. The results thus show that the economic value of a heat-saving project can only be correctly determined by properly including variations in heat-load data. This is true, especially, when there are strong constraints on the operation of the heat production units.

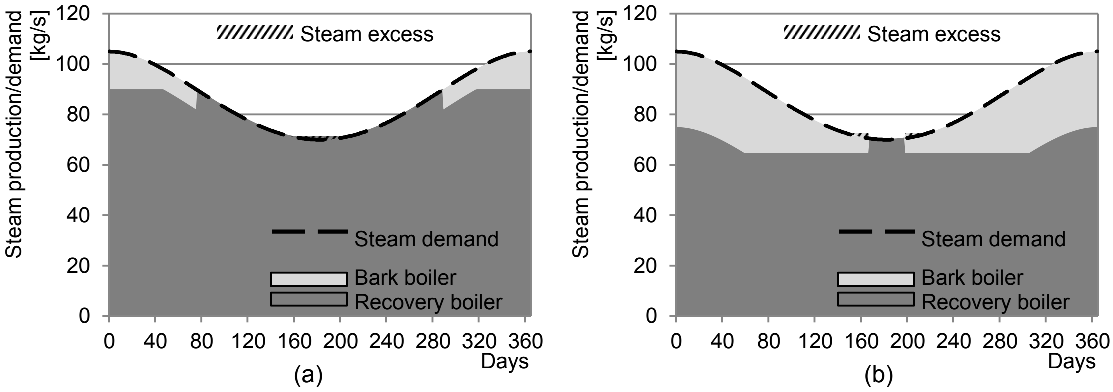

Figure 2: Steam production adjusted for the educed steam demand of the mill and district heating system after steam savings. (a) Lignin price 20 €/MWh. (b) Lignin price 30 €/MWh

Table 3: Comparison of results for the multi-period and the average-value model. Lignin price: 20 €/MWh.

	Multi-period	Average-value	Error
Lignin extraction capacity (MW)	54.3	10.6	−81 %
Recovery boiler reduction[a] (kg/s)	8	3.6	−55 %
Bark boiler reduction[a] (kg/s)	8.6	13.1	+53 %
Annualized investment for lignin extraction (M€/y)	2.2	0.83	−62 %
Revenues from lignin sales (M€/y)	4.1	1.9	−53 %
Revenues from bark exports (M€/y)	4.8	7.3	+52 %

[a] Annual average reduction in high-pressure steam production

The pronounced effect of the variations in this case study is partly explained by the magnitude of the variations in relation to the average load, that is, the district heating network is small in relation to the excess heat deliveries from the pulp mill. In a larger district heating grid, the industrial excess heat would constitute a constant base load instead of, as in this case, the dominant heat production source covering almost all the variations in district heating demand.
Note that transition costs, duration times and operability issues associated with load changes and on/off switches in process operation have not been considered, but could be important to evaluate. Also note that no alternative use of the heat savings, such as electricity production, has been considered.

5. Conclusions

When assessing the economic value of an industrial heat saving retrofit projects, in the presence of significant heat-load variations, these should be explicitly modelled in order to properly value flexibility to such variations. This paper shows that failing to do so can lead to errors above 50% in equipment load changes and economic results. If investments can be made that will enable more efficient ways of adjusting the operation of the mill's energy system to the varying conditions, then this can provide a valuable flexibility to the plant operation. The value of this flexibility can be captured in the model only if the seasonal variations are properly modelled.

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