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Flexibility to seasonal demand variations in pulp mill steam production: The effect of steam savings leading to off-design heat loads

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HIGHLIGHTS

- A multi-period model for optimization of pulp mill steam production is proposed.
- The model accounts for boiler minimum load limits and variations in steam demand.
- Steam savings combined with seasonal variations reduce the flexibility of the utility system.
- Results of the multi-period and a conventional annual-average model are compared.
- The importance of using the multi-period approach is demonstrated.

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ABSTRACT

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 operational limits of the boilers and variations in heat demand. Large variations in combination with the retrofit cause off-design loads that affect the flexibility of the steam system. The minimum boiler load limits will be a greater constraint on operation when the average load of the boilers is moved closer to the minimum for longer periods of time. As shown in this paper, 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 inaccurately modeling the operational limits. The multi-period approach suggested in this paper considers operational flexibility associated with different designs. A case study based on a Kraft pulp mill with a recovery boiler and a bark boiler shows the benefit of this approach. Four scenarios for heat savings and lignin prices are analyzed. Numerical results are presented that compares the solution of the multi-period model with that of a conventional annual-average approach. Differences in designs, energy balances and economic performance are demonstrated.

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. Ref. [1]). Siitonen and Ahtila [2] 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.

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Nomenclature

bp(i)	breakpoint i between the segments of the piecewise linear function Inv(X) [MW]
$C_{inv}(i)$	investment cost for a lignin extraction plant of size bp(i) [€]
D	number of days of the year [days/yr]
ΔDem(d)	steam savings day d (expressed as HP steam) [kg/s]
$\Delta\overline{\text{Dem}}$	annual-average steam savings (expressed as HP steam) [kg/s]
h_{FW}	enthalpy of feed water [MJ/kg]
h_{HP}	enthalpy of high-pressure steam [MJ/kg]
Inv(X)	piecewise linear function for the investment cost of lignin extraction process with capacity X [€]
$k(i)$	slope of the piecewise linear function Inv(X) between breakpoints bp(i) and bp($i+1$) [€/MW]
MinProd(b)	minimum steam production of boiler b [kg/s]
$\overline{\text{MinProd}}(b)$	minimum steam production of boiler b, annual-average model [kg/s]
MaxProd(b)	maximum steam production of boiler b [kg/s]
$p(b)$	net value of the fuel savings in boiler b [€/MWh]
ΔProd(b,d)	reduced steam production in boiler b, day d [kg/s]
$\Delta\overline{\text{Prod}}(b)$	annual-average reduction of steam production in boiler b [kg/s]
Qxs(d)	steam excess day d (expressed as HP steam) [kg/s]
$\overline{\text{Qxs}}$	annual-average steam excess (expressed as HP steam) [kg/s]
r	annuity factor [1/yr]
RefDem(d)	process steam demand before the heat savings retrofit (expressed as HP steam), day d [kg/s]
RefProd(b,d)	steam production before the retrofit in boiler b, day d [kg/s]
$\overline{\text{RefProd}}(b)$	annual-average steam production before the retrofit in boiler b [kg/s]
Rev	function for the annual revenues from the fuel savings [€/yr]
X	capacity of the lignin extraction plant [MW lignin extracted]
$y(b,d)$	binary variable, taking the value one if boiler b is in operation day d, and the value zero otherwise.
$\bar{y}(b)$	binary variable, taking the value one if boiler b is in operation during the year, and the value zero otherwise.
z	binary variable taking the value 1 if the investment in lignin extraction is made, and 0 otherwise.
$\eta(b)$	marginal efficiency of boiler b defined as the ratio between steam production reduction and enabled fuel export [MW steam/MW fuel]

[3] optimized the design of a heat exchanger network over its 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.

The pulping process is continuous and typically designed for maximization of quality and throughput of one core product. The operational objective is to maintain the production as close to the design capacity as possible. Consequently, pulp mill energy systems are traditionally modeled using annual averages representing values very close to design conditions. However, recent and expected future changes in wood, pulp and energy market conditions motivate a shift towards producing a larger variety of products including traditional pulp mill energy by-products such as electricity and heat, and emerging lignocellulosic biorefinery products such as different kinds of materials and chemicals (see e.g. Ref. [4]). This transition from the traditional pulp mill to a biorefinery will connect the pulp mills to an increased number of external markets. Also for the traditional by-products of heat and electricity, an increased implementation and production rate can be expected when, for example, energy prices rise. Consequently, mills are likely to become affected by more sources of variations. In combination with the opportunities connected to the diversified product portfolio of a pulp mill biorefinery, this should provide a higher value to technological options that provide flexibility in process operation than what would be seen for the typical pulp mill today.

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 [5] 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 [6] suggested a model for the optimization of the utility system operation including design decisions by considering both existing and new power generation equipment. Iyer and Grossmann [7] 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 [8] 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 modeling of energy equipment performance. Varbanov et al. [9] proposed improved models for steam and gas turbines in part-load operation. Shang and Kokossis [10] 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. [11] also considered part-load operations and varying energy demands in their generic modeling 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 modeling of variations in steam header properties, either as pre-determined parameters [11] or as variables to be optimized [12]. 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

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