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# Mill steam and power optimization in a real-time pricing environment

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## ABSTRACT

*Real-time electricity pricing gives the mill utility manager greater freedom in determining the balance of purchased vs. internally generated power. At the same time, it complicates the problem of determining the minimum-cost operation for the powerhouse. This paper describes an optimization formulation that can help pulp and paper mills optimize their steam and power production in a real-time pricing environment. Several parametric studies on a mill powerhouse are presented along with a methodology for developing rules of thumb for optimal powerhouse operation.*

***Application:***

*A model-based strategy for optimizing steam and power production when the cost of power from the local utility varies with the time of day.*


PULP AND PAPER PRODUCTION IS A highly energy-intensive operation, and small changes in the cost of steam and power can have a large impact on overall economics. These changes can be driven either by variations in the price of fuel or electricity. Recent innovations in the utility industry have resulted in real-time pricing (RTP) schemes for electricity, where the marginal price can vary on an hourly basis *(1)*. Time-varying prices for electricity provide a greater degree of freedom in the operation of the mill while adding complexity to the problem of determining minimum-cost operation. A mill operating under an RTP tariff can experience large swings in optimal plant set-points. These swings in optimal operation occur when the marginal price of electricity moves above or below a breakpoint value where the cost of internal generation equals this marginal price.

Optimal powerhouse operation is a complex decision because of the large number of manipulated inputs. **Figure 1** illustrates the equipment layout of a typical mill powerhouse. The layout consists of a variety of boilers, turbine generators, and pressure-reducing valves (PRVs) that generate and utilize process steam. A large proportion of the steam consumed by paper processes is low to medium pressure, so the high-pressure steam must be throttled to a usable level. Because mill operation is a highly power-intensive process, it is sensible, under normal circumstances, to throttle the steam through turbine generators, which extract power out of the pressure drop. The other alternative is to throttle steam through several PRVs that are part of a desuperheating unit where boiler feedwater can be injected to create additional steam.

Because steam is a necessary component of operation, the power that is produced by throttling it through turbines cannot be economically weighed in the decision to produce power internally or purchase it externally *(2)*. This operating scenario must be balanced against the occasions when a mill on the RTP pricing scheme is forced to purchase power at a high enough cost that it is economically feasible to generate steam for the sole purpose of power production. During the summer months, the RTP signal to the mill can be quite variable, and the marginal price of electricity can increase manyfold from one hour to the next. A mill must be able to respond to this by curtailing the amount of external electricity purchased. This can be accomplished by venting steam to the atmosphere and thus being able to extract additional power from the backpressure portion of the turbine. Similarly, steam can be sent to the turbine generator's condenser, producing "condensing power."

The powerhouse operation can be viewed as a process where economic inputs (fuel and electricity) are regulated in an optimal fashion to generate the desired outputs (steam and power), as shown in **Fig. 2**. One of the major challenges for the utility manager is to determine the balance between internally generated power and purchased electricity. These decisions are then translated to utility and plant set-points.

The aim of this paper is to present a method of determining optimal plant operation over a large variety of operating conditions using an optimization framework.

## POWERHOUSE MODELING AND VERIFICATION

Models that accurately predict mill performance are necessary to obtain reliable optimization results. Our models are based on thermodynamic principles and minimize the use of ad hoc empirical efficiencies *(3)*. The strength in this approach is that these models have (a) elements that can be verified against previous models of such systems and (b) well-defined extrapolations beyond the data range over which they have been observed.

Each piece of powerhouse equipment was modeled using the same approach. The models were verified with PRO/II, a comprehensive computer simulation package for process engineers in the chemical industry *(4)*. The PRO/II software served as a tool to verify that thermodynamic principles were being obeyed. Next, the models were entered into GAMS, a high-level computer language for mathematical programming problems *(5)*. Finally, several mills served as the final validation of the optimization framework. These mills were chosen because they were equipped with state-of-the-art distributed control systems (DCS) and thus could provide most of the necessary data for validation.

### *Powerhouse equipment models*

This section presents each major piece of equipment and the relevant modeling equations.

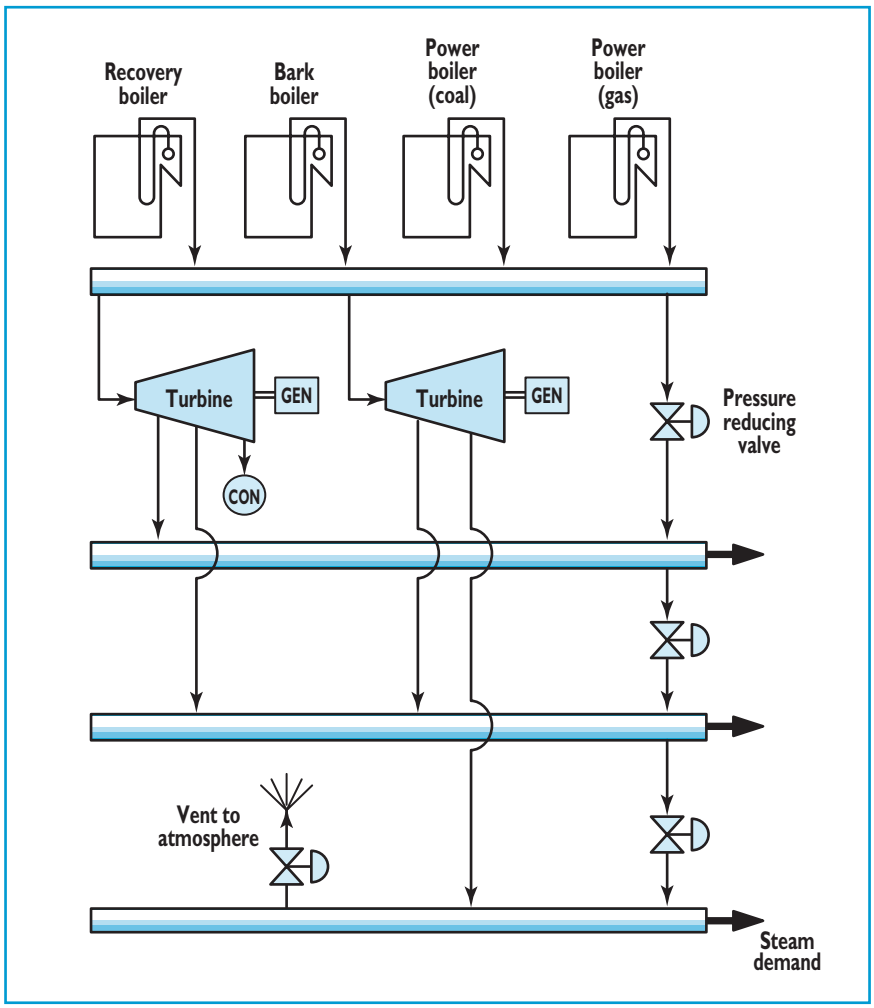
***Steam generator.*** Steam generators use heat produced by combusting fuels to generate high-pressure steam from boiler feedwater. The current boiler model computes the heat of reaction with the simple equation:

$$Q_b = \sum_{j \in c} \eta_{b,j} F_{b,j} H_j^{\circ} \qquad \forall b \in B \quad (1)$$

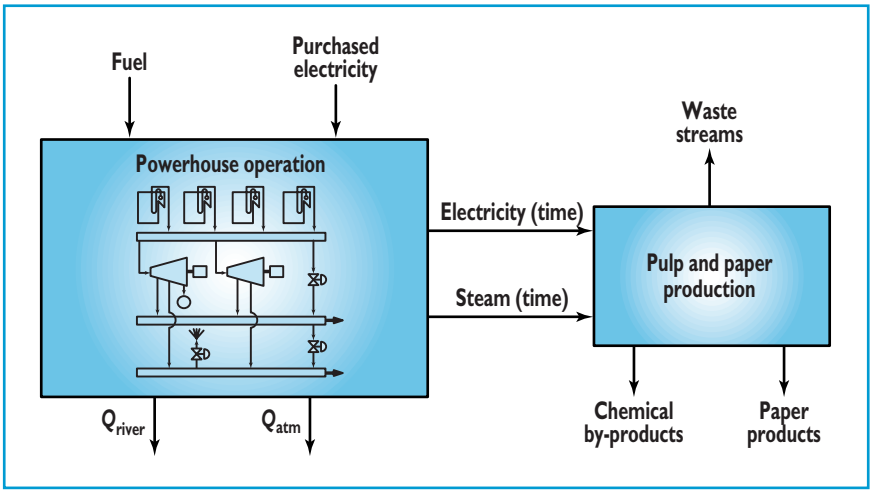
[Note: Definitions for the variables in Eq. 1 (and all other equations) appear in the Nomenclature section at the end of this work.]

The model in this form can easily deal with the simultaneous burning of different fuels. This is a situation that often occurs in mill powerhouses because of the need to satisfy varying steam loads and minimize boiler setpoint shifts. The boiler efficiencies represent losses from such factors as radiation and unburned combustibles. These efficiencies are typically nonlinear and vary with a boiler's steaming rate.

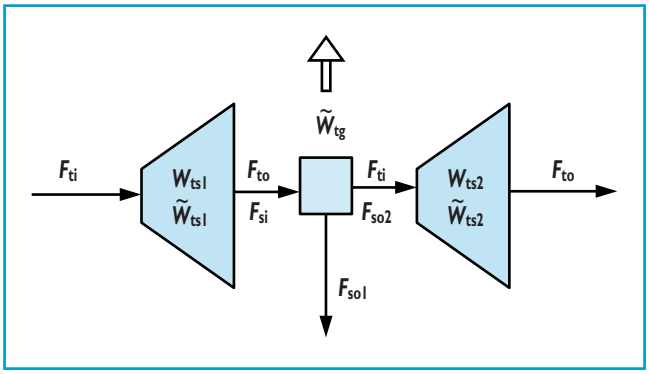
Steam generators are very large, expensive pieces of equipment with elaborate shutdown procedures. The heating and cooling from startups and shutdowns causes thermal stress on the equipment. Consequently, boilers are always running, even if that means producing steam and then venting it at the boiler outlet to avoid shutdown. Continuous operation is included in the formulation given in Eq. 2. Every boiler also has a



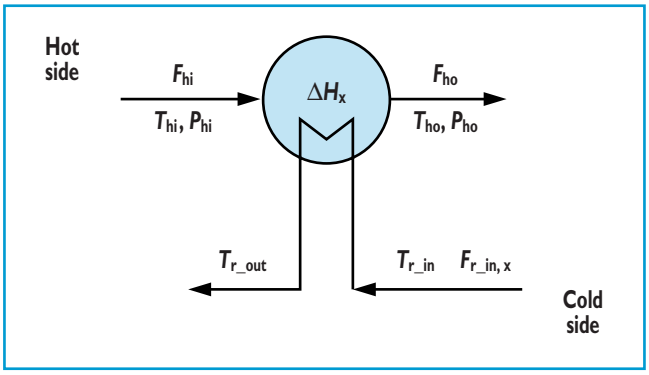

*1. Typical powerhouse layout*




*2. Overview of mill operation*




*3. Turbine generator*




*4. Condensing heat exchanger*

maximum capacity $\overline{F}_b$ as seen in Eq. 3.

$$F_{bo(b)} \geq \underline{F}_b \qquad \forall b \in B \quad (2)$$

$$F_{bo(b)} \leq \overline{F}_b \qquad \forall b \in B \quad (3)$$

Boiler output can also be constrained by the boiler's maximum rate of fuel consumption, as expressed in Eq. 4,

$$\sum_{j \in b} F_{j,c} \leq \overline{F}_c \qquad \forall c \in C \quad (4)$$

where $\overline{F}_c$ is the maximum rate at which fuel c can be consumed by the powerhouse boilers. This constraint is particularly relevant when discussing the consumption of black liquor. Often a mill is capable of operating a recovery boiler at a higher capacity but is limited by the supply of by-product fuel available from another operation.

***Turbine generator.*** The mathematical equations related to the turbine generator are at the heart of the powerhouse formulation. Most turbine generators found in mills consist of at least two turbine stages with extractions to multiple pressures, as shown in **Fig. 3**. The ideal power produced by each turbine stage is represented by the following:

$$W_{ts} = -\Delta H_{ts} F_{ti(ts)} \qquad \forall ts \in TS \quad (5)$$

where $\Delta H_{ts}$ is the enthalpy change of the steam undergoing an isentropic expansion. This ideal expansion is then corrected by the following constraint:

$$\tilde{W}_{ts} = \eta_{ts} W_{ts} \qquad \forall ts \in TS \quad (6)$$

where the real power $\tilde{W}_{ts}$ produced by each turbine stage ts is corrected by an efficiency $\eta_{ts}$. Finally, the power produced by each stage is summed and corrected to produce the actual power output of the turbine generator, $\tilde{W}_{tg}$. This is expressed by the following constraints:

$$\psi_{tg} = \alpha_{tg} F_{ti(ts(tg))} + \beta_{tg} \qquad \forall tg \in TG \quad (7)$$

$$\tilde{W}_{tg} = \psi_{tg} \sum_{j \in ts(tg)} \tilde{W}_j \qquad \forall tg \in TG \quad (8)$$

The overall turbine coefficient $\psi_{tg}$ is a function of the flow entering the first stage of the turbine generator. Values for $\alpha_{tg}$ and $\beta_{tg}$ are determined by regression of mill data, and the value of $\psi_{tg}$ is typically close to one (0.95 to 1.10).

Each turbine stage contains large blades that spin at very rapid speeds, generating frictional heat. As a result, every turbine stage must have a certain amount of steam flow to cool the blades. This aspect of operating is represented by the following constraint:

$$F_{to(ts)} \geq \underline{F}_{tg} \quad to \in k \quad \forall ts \in TS, \forall tg \in TG \quad (9)$$

where $\underline{F}_{tg}$ represents the lowest outlet flow that must enter through the last turbine stage *k*.

Turbine generators produce power within some minimum and maximum operating limit. These constraints are as follows:

$$\tilde{W}_{tg} \geq \underline{W}_{tg} \qquad \forall tg \in TG \quad (10)$$

$$\tilde{W}_{tg} \leq \overline{W}_{tg} \qquad \forall tg \in TG \quad (11)$$

Startups and shutdowns of the turbine generators are minimized to avoid the mechanical stress associated with these procedures. Vibrational stress occurs when blades are spun below a certain frequency. Shutdowns are prevented by operating in accordance with Eq. 10. Also, the maximum amount of power produced by a turbine generator is limited by the equipment, as expressed in Eq. 11.

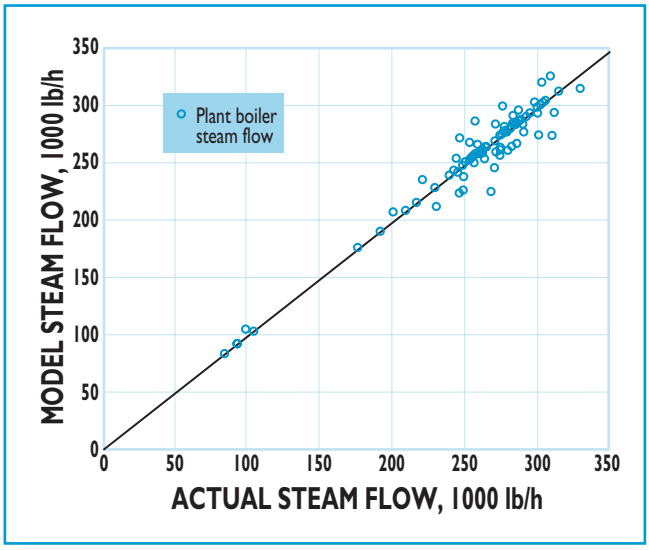
***Condensing heat exchangers.*** The operation of the condensing heat exchanger is modeled as a simple transfer of heat from a hot stream to a cold stream, as seen in **Fig. 4**. This can be expressed by the following constraints:

$$\Delta H_x = F_{hi(x)} (\hat{H}_{hi(x)} - \hat{H}_{ho(x)}) \qquad \forall x \in X \quad (12)$$

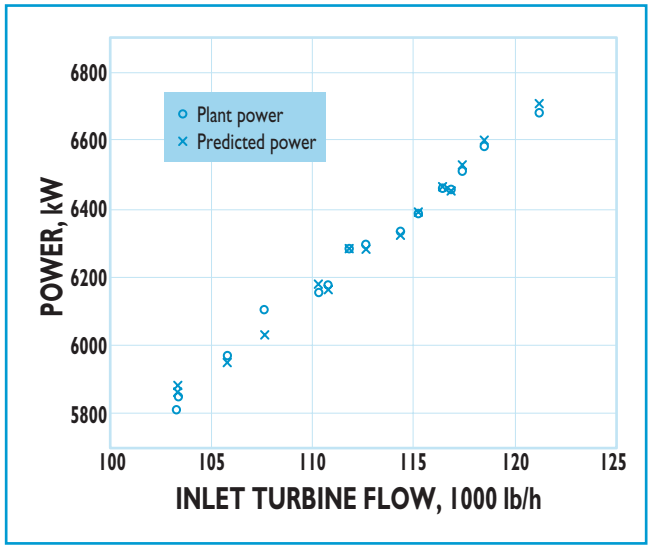
$$\Delta H_x = F_{r_in,x} (\hat{H}_{r_out} - \hat{H}_{r_in}) \qquad \forall x \in X \quad (13)$$

The heat exchanger's duty is represented by $\Delta H_x$. These equations state that the amount of heat required to condense steam is the same as the heat absorbed by the river or cooling water. We assume that the steam condenses at a temperature $T_{r_out} + \Delta T$. Thus the outlet pressure of the turbine, and hence the work extracted, is a function of this outlet temperature.

The optimization is performed with the actual temperatures of the river water, $T_{hi(x)}$, and $T_{r_out}$. The con-




*5. Validation of steam generator models with mill operating data*




*6. Validation of turbine models with mill operating data*

densers can have an important impact on mill operation, with the following constraint:

$$\sum_{j \in x} F_{r_in,j} \le \overline{F}_r \qquad (14)$$

This equation has the capability of limiting the amount of steam the mill can condense. Environmental constraints are imposed upon a mill to ensure that only a reasonable amount of water is processed through the mill. Similarly, a limit on the outlet temperature $T_{r_out}$ can be accommodated.

### *Model verification*

Model accuracy is an essential part of instilling confidence in an optimization framework. An operator's confidence in a program is one of the most important issues when dealing with an advisory tool *(6)*.

We were able to successfully model the equipment in an actual mill powerhouse, including steam generators, turbine generators, condensing heat exchangers, steam headers, and pressure-reducing valves. For example, the boiler models were able to predict generated steam within 3% of actual mill data. **Figure 5** shows typical modeling results for three months of boiler operation, with each data point representing a day. The straight line represents the results for a model with a perfect fit.

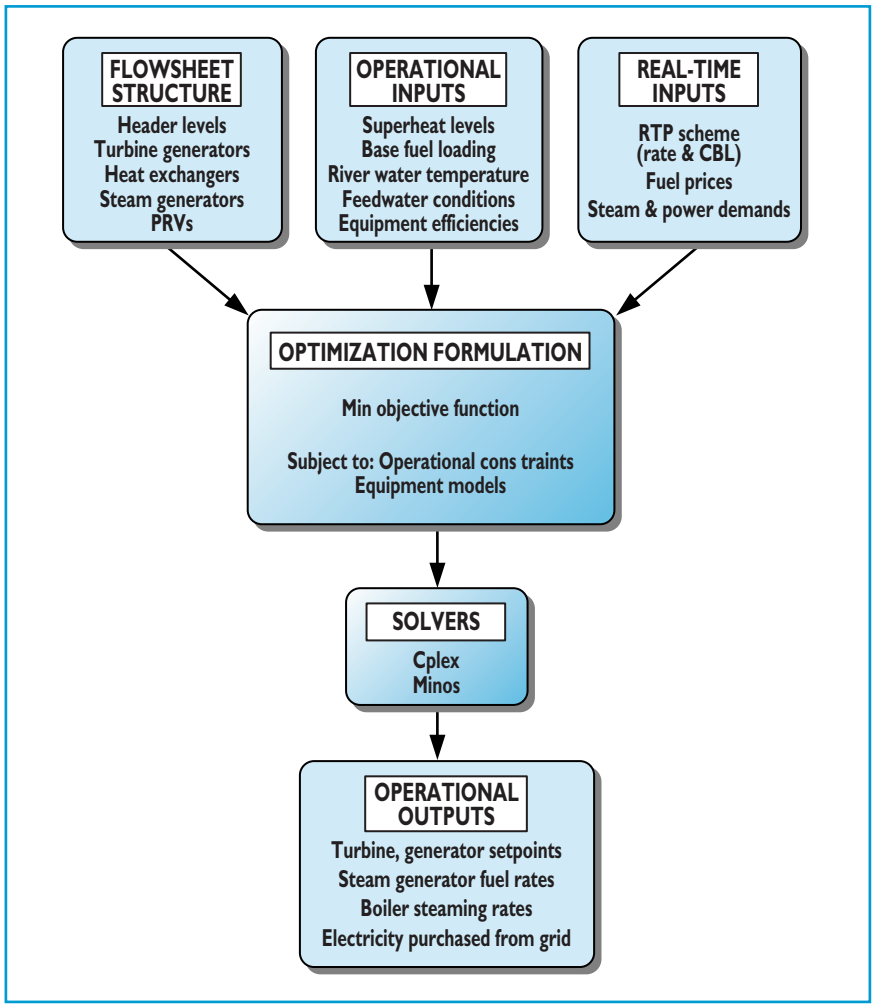
The turbine generators are governed by similar empirical efficiencies that correct for nonideal deviations of an isenthalpic expansion. The turbine empirical efficiencies are also load varying, although they tend to be more linear than the efficiencies that describe boiler behavior *(7)*. **Figure 6** is representative of verification comparisons made on four actual mill turbines. (Results have been scaled to protect confidential information.) The turbine models were able to predict power output within a 2% margin of error. Further attempts to refine the model could not be justified on the basis of the available plant data.

The nonlinear efficiencies of the equipment models become important when these models are embedded within an optimization framework. Consider the example of a boiler efficiency with a downward parabolic shape *(8)*. If a mill's boiler is loaded such that it is operating to the left of the curve's maximum, it will exhibit inherently different operating characteristics than if the boiler were loaded so as to operate on the right of the maximum. An optimization algorithm will treat these two cases in a different manner. A linear formulation of such a problem could thus yield misleading results if one linearizes around an operating point on one side of the efficiency curve and then operates on the other.

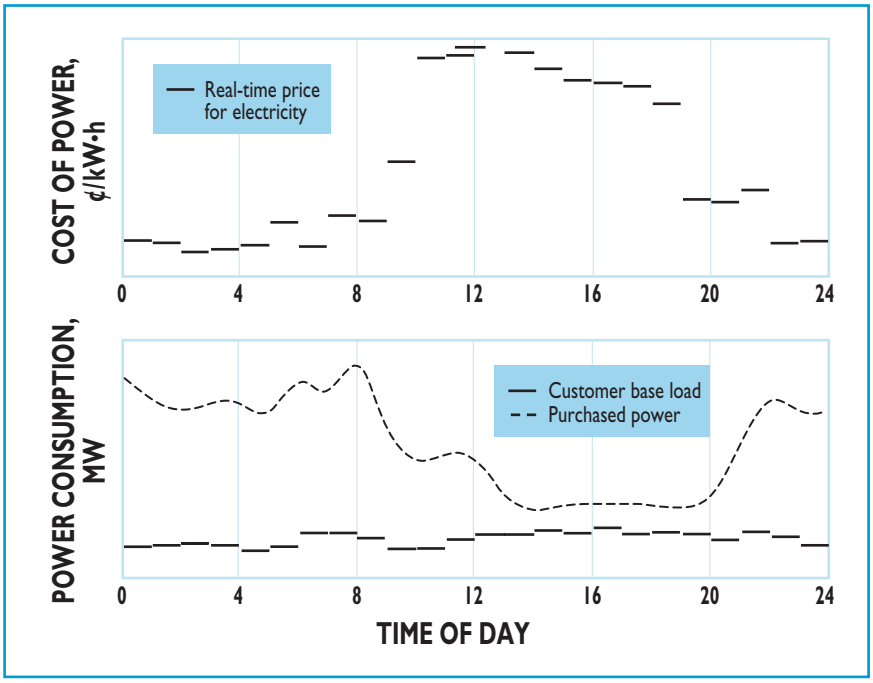
## OPTIMIZATION FORMULATION

The operating decisions that must be made by the powerhouse are time dependent. The price of purchased power changes every hour, which can have a large influence on the powerhouse's balance of internally generated and externally purchased power. The mill demands for steam can change even more rapidly, and the optimal routing of steam to meet these changing demands must be made relatively quickly. Thus determining the exact balance of internal vs. external power consumption involves the calculation of marginal costs, evaluating load-varying equipment efficiencies, and various other parameters and constraints. The complex nature of optimal powerhouse operation can be addressed effectively with the use of computer optimization. This has spurred significant efforts to develop computer applications for devising mill cost-saving measures *(6, 9–14)*.

The benefit of such an approach is that once a mill operation has been modeled, minimal effort is required to answer a set of related questions that could affect opera-




*7. Daily operational optimization framework*




*8. Real-time pricing scheme for electricity*

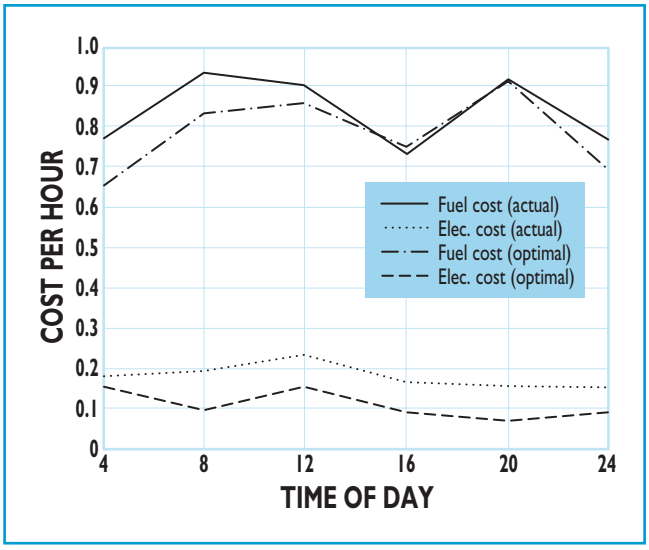
tion. For example, how would the powerhouse deal with an increase in steam demand? How would optimal operation have to shift to accommodate the addition of a turbine generator?

In the discussion of powerhouse modeling and verification in the previous section, we gave examples of models that would predict the behavior of powerhouse equipment. These thermodynamic models have been linked together into a comprehensive framework that can be used to optimize mill powerhouse operation as a whole. In this section, we present the mathematical formulation for daily powerhouse operation.

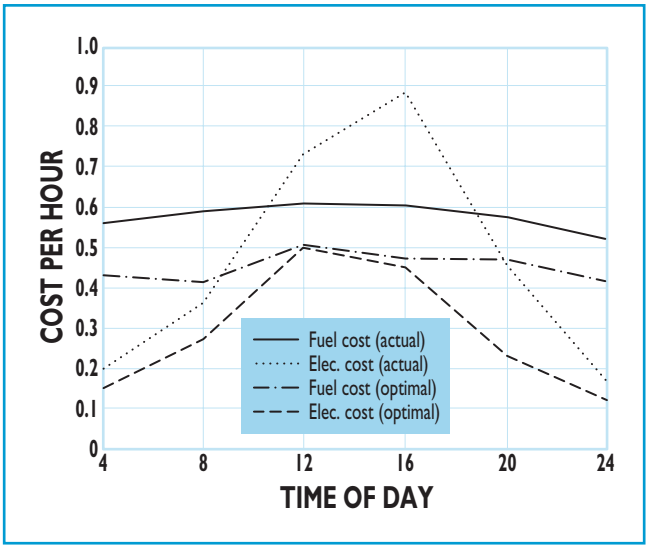
The formulation's general structure is illustrated in **Fig. 7**. Given the various model inputs—the process diagram of the plant, the physical properties of the streams, prices for fuel and purchased electricity, and steam and power demands—the lowest overall operating cost to meet the given steam and power demands (while satisfying the imposed constraints) will be computed. Mill data are used to specify the constraints that describe the unit models and the operating bounds. Once the algebraic form of the model is generated in GAMS *(5)*, it is passed to mathematical programming solvers—Minos for nonlinear programs *(15)* and Cplex for linear programs *(16)*—to find the optimal solution. The optimal solution is defined as the minimum overall energy cost, as given later in Eq. 18. The results yield:

- The optimal steam allocation for the entire powerhouse
- Optimal boiler loading and the combusted fuels
- Optimal loading of each turbine generator
- The amount of electricity to be purchased from the grid.

There are two essential elements




*9. Mill operation during a spring day*




*10. Mill operation during a summer day*

to the real-time pricing for electricity, the customer baseline load (CBL) for purchased electricity $E_{bl}$ and the hourly marginal price $\phi_e$. The mill is charged a fee for the customer base load, and then any deviation from the base is credited back to the plant and an increase above the CBL is charged to the plant. The cost of the electricity $\Phi_e$ depends on the duration of the powerhouse purchase $\delta t$. The pricing scheme is represented within our formulation by the following mathematical expressions:

$$\Delta = E_e - E_{bl} \qquad (15)$$

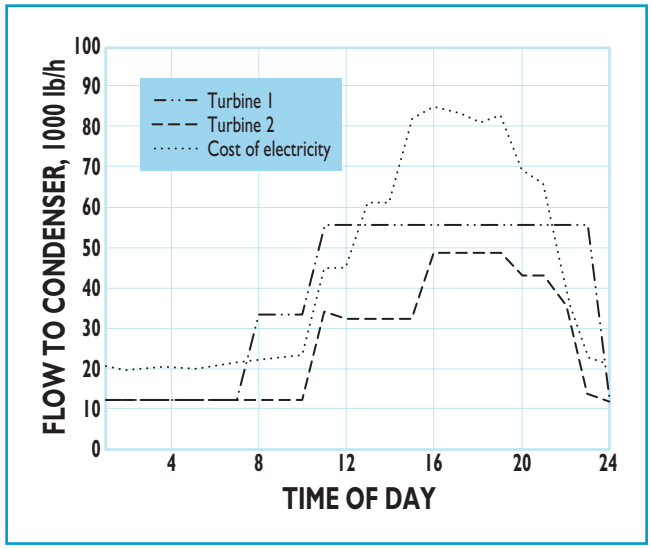
$$\Phi_e = \phi_e \times \Delta \times \delta t \qquad (16)$$

A fictitious example of mill operation has been created to illustrate how a real-time pricing scheme can influence operation. **Figure 8** shows a mill's daily electricity price. Price variations are rather consistent except during the summer months, when there can be considerable swings because of high demand from the local grid. This price can have an influence on how the mill decides to run operations. From Fig. 8 it can be seen that a mill might decide to cut back on turbine production, which lowers fuel costs, and purchase power from the external source during the night. During midday, when the electricity prices are at their peak, the mill's turbines run to maximum power and condensing, thus allowing the mill to operate while purchasing as little power as possible.

Finally, it is necessary to account for the cost of producing steam with the following expression:

$$\Phi_c = \left(\sum_b \sum_c \phi_c \times F_{b,c}\right)\delta t \qquad (17)$$

The cost of fuel $\phi_c$ is attached to each fuel flow for




*11. Condensing power during a summer day*

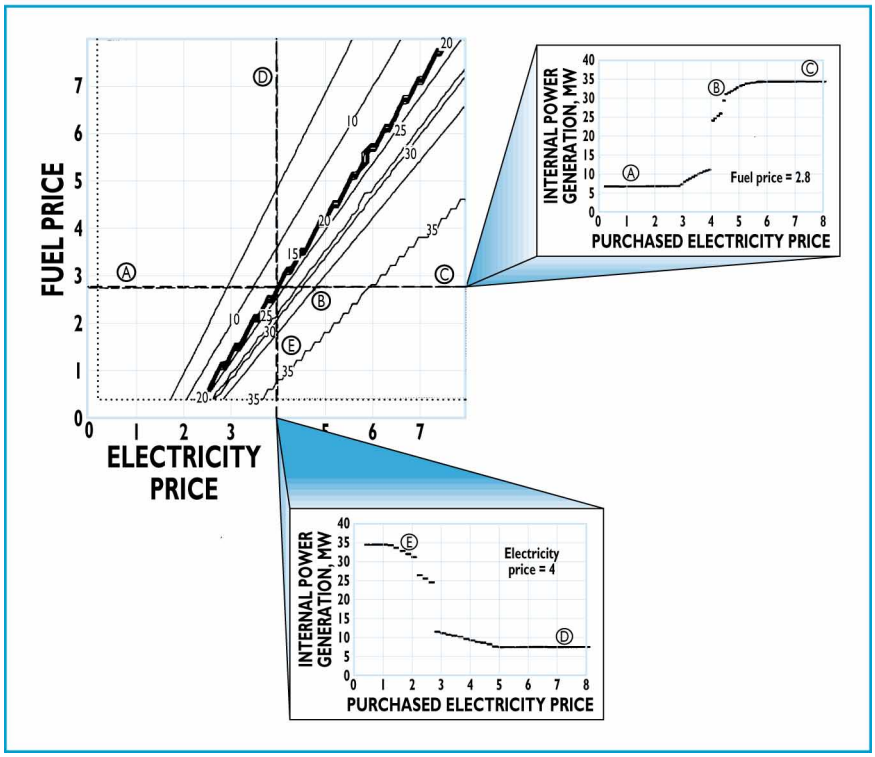
the duration of the operation $\delta t$. The objective function $\Phi$—the total cost of operation for the mill's powerhouse—includes the contributions of both steam production and electricity purchase:

$$\Phi = \Phi_e + \Phi_c \qquad (18)$$

It is clear from this expression that the major optimization decision is to determine the exact balance between the amount of power produced internally and that purchased externally.

## RESULTS AND DISCUSSION

Energy costs can be a significant component of the overall product cost. In 1987, Tabucanon and Raja *(17)* estimated a value of 30% for one particular mill, although




*12. Contours of equal internal power generation as functions of fuel and electricity prices*

this reference is somewhat dated. Given the high volume of paper production, even a slight reduction in operational costs can generate substantial annual savings. We now will illustrate the possible benefits of the optimization formulation presented in this work. We compare our predicted optimal operation with a mill's actual operation and show the effects of various operating parameters.

### Seasonal variables

***A spring day.*** A typical day of operation during the month of March was chosen to investigate the possible savings from a change in current operations. **Figure 9** shows a comparison of the actual and optimal costs of powerhouse operation. (Some operational aspects are not shown in this figure.) In the case of optimal operation, the turbine generators were operated at maximum capacity, and the condensing sections of the generators were operated at their minimum allowable level. The predicted optimal operation resulted in a total savings of 12% of the total operating cost for the selected day. Substantial savings also resulted from efficient boiler operation and optimally determining how the time-varying steam demands should be met.

***A summer day.*** A day's operation in July was chosen as a representative day for summer operation. This day was chosen because of its high and variable RTP rates. The comparisons between actual and optimal operation for this summer day are very different from those for an operating day in spring. The results of our summer comparison are summarized in **Fig. 10**.

The largest contrast between the operating days in March (Fig. 9) and July (Fig. 10) is the variation in electricity costs. It is apparent from Fig. 10 that the price of electricity is varying substantially with the time of day. In contrast to the case study taken in March, the optimal operation in July resulted in a savings of 29% for the day. This savings is largely attributed to the economic purchase of electricity.

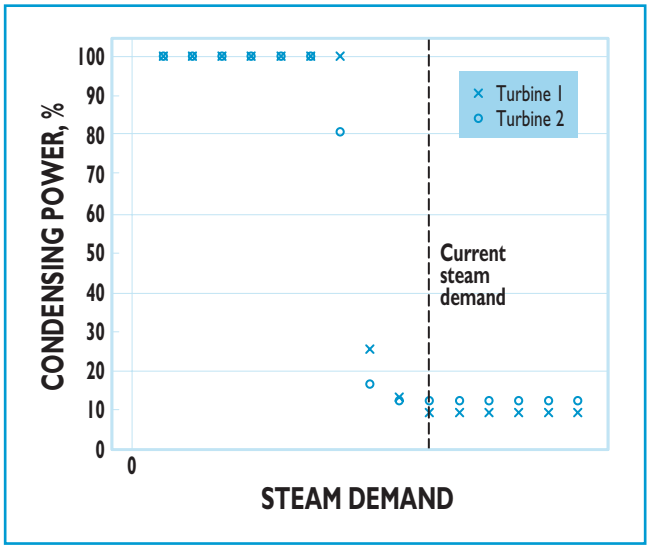
The actual fuel costs did not vary from the optimal by the same degree as the electricity purchase. This can be explained by the fact that a steam demand must be met and, therefore, this steam must be generated regardless. Electricity, on the other hand, can be generated internally *or* purchased from the grid.

The optimal turbine setpoints responded to changes in the hourly electricity rates. During the middle of the day, the turbines were operated at full capacity. During the night, however, the turbines were cut back to approximately 85% of their maximum value. Also, power was produced by condensing during the day. **Figure 11** illustrates the operation of the condensing turbines in response to electricity prices. The electricity price has been scaled and included in the figure to show its influence on condensing power. Note that once the condensers have switched to "condensing mode," the small variations in condenser flow occur because of changing steam demands. For example, an increased steam demand may allow one to generate more power out of the backpressure portion of the turbine and thus condense less steam.

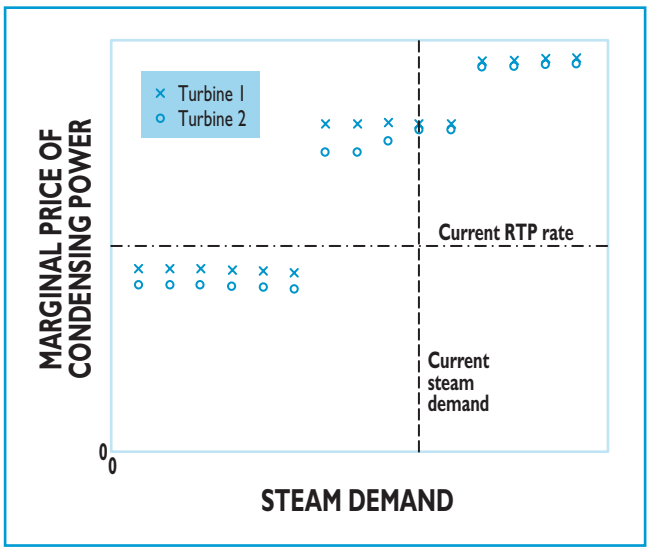
### A parametric study

***Effect of electricity and fuel prices.*** The marginal price of purchased electricity and fuel prices are two of the most important factors in powerhouse economics. **Figure 12** plots the contours of equal internal power generation as functions of the fuel and electricity prices. The contour lines run from the lower left to the upper right. They are labeled with the optimal internal power level for the combination of electricity price and fuel price. As would be expected, at constant fuel price, higher electricity prices lead to higher internal generation. This corresponds to the contours increasing from left to right, labeled A → C. Similarly the contours increase from top to bottom as the fuel price decreases D → E at constant electricity price.

There are several observations




*13. Effect of steam demand on condensing power*




*14. Marginal cost of condensing power*

that can be made from Fig. 12. The transition between maximum and minimum generation takes place in a series of steps. The large changes in the optimal level of internal power generation occur within a relatively short range of fuel and electricity prices and reflect individual turbines "flipping" from minimum to maximum power generation. If the fuel and electricity prices lie within this region, then the optimal operation will be hard to determine, but the cost associated with making the wrong decision will be small.

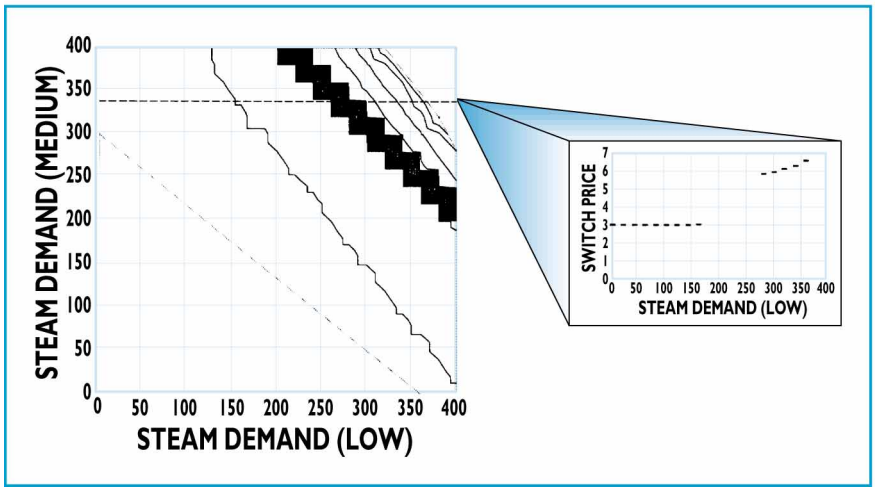
Figure 12 illustrates that when the price of electricity is very low (essentially free), the turbines idle at their lower limit and additional power is purchased from the grid to meet the mill's power demand. The only steam produced is that needed to keep the turbines operational while meeting the paper mill's steam demand.

As the price of electricity increases, the internal power generation is abruptly increased to its maximum capacity. The final plateau of Fig. 12 corresponds to all turbines operating at their maximum limit. Internally generated power is radically increased when the marginal price of electricity is such that it becomes more economical to generate power rather than generate steam through the PRVs. From the slice at constant electricity price, it can be seen that when fuel is inexpensive, enough steam can be economically generated to operate the turbine generators at their maximum capacity. However, when fuel prices are increased beyond a certain point, steam is generated only to meet the process demands and internal generation is curtailed.

***Effect of steam demand.*** The effect of changes in steam demand on various levels of process steam is illustrated in **Fig. 13**. The incremented steam demand shown on the *x*-axis consists of three process-steam pressure levels that are increased by a constant amount based on a certain percentage of its current level. The *y*-axis shows the percentage of the inlet stream that is fed to the condenser. A value of 100% corresponds to a turbine operating in "condensing mode." The vertical line indicates current steam demands.

When demand for steam is low, boilers are required to operate at a minimum level, with the surplus steam being condensed and the remaining amount vented to the atmosphere. However, there is a point where the steam demand becomes too high to allow for the production of condensing power. In this instance, only the minimum amount of steam is routed to the last stage. Any increase in steam demands beyond that shown in Fig. 13 results in an infeasible solution where the boilers cannot meet the demands imposed by the mill's paper production. Note that the point where a dramatic change in condensing power occurs is slightly below the current steam demands for the mill.

The decision to cut back on condensing power is made when the marginal cost to produce the steam *solely* for generating power is larger than the marginal price at which power can be purchased from the grid. This decision process for the results shown in Fig. 13 is illustrated in **Fig. 14**. The vertical line represents current steam demand, while the horizontal line is the current real-time price for electricity. Notice that when the turbines are at 100% condensing (Fig. 13, upper left), the price of fuel is below that of externally purchased electricity. As the steam demands increase, another boiler (more costly) is required for operation. As a result, the marginal price of condensing power jumps above the price of electricity and thus triggers a reduction in condensing. At this point, it is more economical to cut back on condensing power and purchase power from the grid. A third jump in the cost of fuel is caused by




*15. Condensing "switch price" of a turbine generator*

yet another boiler usage being increased from its minimal value.

***"Switch prices"***

The observation that a particular price of purchased electricity would trigger a radical change in optimal powerhouse operation leads to the concept of a "switch price." This concept is already a popular rule of thumb used by utility managers to determine their generating strategy, so it is not surprising to find it embedded in the results of the optimization. The key difference is that the "switch prices" found by our approach reflect optimal distributions of load to boilers and turbines, which are rapidly calculated as fuel prices and steam loads change. The advantage of using switch points is that the optimal generation need not be recalculated every time the RTP rate changes. The rate can be compared with the "switch price" and the decision made, depending on which side of the price it falls.

Several operations have been identified as being controlled by switch prices. As the marginal price is altered via real-time pricing, so the mode of plant operation should shift. We have observed four different "modes" of operation:

1. *The electricity price is so low that one does not generate any electricity*. All of the available steam is sent through the PRVs to minimize the fuel needed to generate steam needed for the mill processes.
2. *The electricity price is above the condensing price*. In this case, the formulation will tend to send steam to condensing at maximal achievable rate, which may be less than the turbine generator's power rating because of other constraints such as available cooling. This operating mode could consist of multiple switches that are all very close in value and signify turbines with different efficiencies. The switch level is also dependent on which fuel is consumed. The fuel type for which the analysis is performed is directly dependent on the overall plant steam load.
3. *The electricity price is above the venting price*. This switch will tend to be very close to the condensing switch but should account for water treatment costs and possible environmental issues.
4. *The electricity price is above equipment marginal profit of operation*. This is the case when load shedding takes place. Equipment production rates are cut back as the electricity price rises above the sum of marginal profits of equipment lying between inventories that can be run down or built up.

Under an RTP scheme, an effective powerhouse operating strategy can thus be captured by a concise rule of thumb. The rule can be summarized as: Find the highest switch price that is below the prevailing RTP rate and operate in that mode. For example, if the RTP rate is above the condensing price but below the venting price, then operate in condensing mode.

The optimization framework has the ability to compute the switch price for a particular set of operating conditions. **Figure 15** illustrates the variation of a turbine generator's condensing switch price as a function of steam demands. The contour lines run from the top left to bottom right and indicate a constant switch price. When overall steam demands are low, the switch price is relatively constant. However, there is quite a bit more variability when the steam demands increase. There is a particular point when the steam demands become high enough that another, more expensive boiler must come on-line to satisfy the demand. This result is an increased marginal cost to condense, as described previously under the heading "Effect of steam demand." This is shown in Fig. 15 by the very dense set of contour lines in the upper right corner of the plot. Note that for one particular overall steam demand there can be multiple switch prices. Depending on the distribution of the demand among the various pressures, the optimal routing of steam will differ, which will affect the load-varying equipment efficiencies. These changes in efficiency will slightly alter the optimal switch price. In most cases, the changes will be within the model error and thus a single "switch price" is an appropriate approximation. This is why the previously identified operating strategy was described as a rule of thumb.

## CONCLUSIONS

The proposed optimization formulation was able to capture the important characteristics of daily mill powerhouse operation. This was accomplished by embedding thermodynamic equations (corrected with empirical efficiencies) into an optimization framework. The equipment models were used to compare optimum and actual daily powerhouse operation, and the resulting savings were potentially significant.

The optimization models were an invaluable tool for performing parametric studies on powerhouse operation. It is easy to investigate the effects of various operating factors on operation. The studies revealed that electricity prices can have a large effect on optimal operation of a mill's powerhouse. The effect is particularly relevant when the price for electricity is high and steam demands are low. Numerous perturbations in powerhouse operation can be captured by parametric studies similar to those described in this paper. The described formulation can also be used as an aid for feasibility studies concerning things such as shutting down old, inefficient boilers or adding additional steam or power-generating capabilities such as with a gas turbine cycle.

The calculation of optimal "switch prices" was shown to be a quick and effective means by of optimizing plant operations. The concept of a "switch price" is commonly used by utility managers. The proposed model systematizes such rules of thumb and allows numerous variations in powerhouse operation to be accounted for in the development of optimal strategies. The "switch price" concept is useful because it eliminates the need to continually recompute optimal operating points and because it provides inherently more stable measures of the boilerhouse operation. We conclude that such frameworks will gain increasing popularity within the paper industry and that systematic computer-based strategies for powerhouse operation are increasingly viable. **TJ**

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## NOMENCLATURE

### *Variables*

$\alpha_{tg}$ = factor for the overall turbine coefficient of turbine generator tg

$\beta_{tg}$ = factor for the overall turbine coefficient of turbine generator tg

$\Delta$ = deviation from $E_{bl}$

$\eta_{b,c}$ = efficiency of boiler b and fuel c

$\eta_{ts}$ = efficiency of turbine stage ts

$\Phi_c$ = total cost of fuel for the mill's powerhouse (the objective)

$\Phi_e$ = total cost of purchasing electricity from the grid

$\Phi$ = total cost of operation for the mill's powerhouse (the objective)

$\phi_c$ = marginal price of fuel

$\phi_e$ = marginal price (per kW·h) of electricity during the hour of operation

$\psi_{tg}$ = overall coefficient for turbine generator tg

$E_{bl}$ = customer base load for purchased electricity

$E_e$ = total amount of electricity purchased from the utility

$F_{b,c}$ = flow of fuel c in boiler b

$\underline{F}_b$ = lower limit of steam output in boiler b

$\overline{F}_b$ = upper limit of steam output in boiler b

$\overline{F}_c$ = maximum rate of fuel c that can be consumed by the boilers

$F_j$ = flow of each stream j

$\overline{F}_r$ = maximum flow of river water pulled from all condensers

$F_{r,x}$ = river water flow through heat exchanger x

$\underline{F}_{tg}$ = amount of inlet flow of turbine generator tg that is condensed

$H^\circ_j$ = heat of combustion

$\hat{H}$ = specific enthalpy

$\Delta H_{ts}$ = enthalpy change from a pressure drop in turbine stage ts

$\Delta H_x$ = duty of heat exchanger x

$k$ = last stage contained in turbine generator tg

$P$ = pressure

$Q_b$ = heat generated as steam

$\delta t$ = time length (hours) between optimization runs

$\Delta T$ = approach temperature difference used for heat-exchanger analysis

$T_r$ = temperature of each river stream

$\underline{W}_{tg}$ = minimum power that can be generated by turbine generator tg

$\overline{W}_{tg}$ = maximum power that can be generated by turbine generator tg

$\tilde{W}_{tg}$ = real power produced by turbine generator tg

$W_{ts}$ = ideal power produced by turbine stage ts

$\tilde{W}_{ts}$ = real power produced by turbine stage ts

### *Subscripts*

b = individual boiler

B = set of all boilers

bi(b) = set of boiler inlets

bo(b) = set of boiler outlets

bl = baseline load

c = combustible fuel

C = set of all combustible fuels c

e = electricity

hi(x) = set of heat-exchanger (condenser) inlets

ho(x) = set of heat-exchanger (condenser) outlets

r_in = river inlet stream

r_out = river outlet stream

r = individual river stream

R = set of all river streams

si = splitter inlet

so = splitter outlet

tg = individual turbine generator

TG = set of all turbine generators consisting of turbine stages ts

ts = individual turbine stage

TS = set of all turbine stages

ti(ts) = set of turbine stage inlets

to(ts) = set of turbine stage outlets

x = individual heat exchanger

X = set of all heat exchangers