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ENERGY MODEL FOR AN INDUSTRIAL PLANT USING GEOTHERMAL STEAM IN NEW ZEALAND

G.W. Hotson[1] and G. Everett[2]
[1] Project Engineer, Fletcher Challenge Paper Australasia Ltd, Private Bag, Kawerau, New Zealand
[2] Operations Research Specialist, Fletcher Challenge Paper Ltd, Private Bag 92114, Auckland, New Zealand

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ABSTRACT.

Fletcher Challenge Paper Australasia Ltd operates a kraft pulp and newsprint paper mill at Kawerau, New Zealand. The energy requirements for the mill's operation are large, complex and varied. The process itself produces energy sources ("fuels") in the form of wood waste and spent cooking liquors where both are burnt in power boilers (for wood waste) and chemical recovery boilers (liquors) to produce 400 ^{o}C steam at 45 barg. This amounts to 75% of the process steam requirement. Geothermal steam provides the remainder. Electrical energy is produced from this steam amounting to 15-20% of the mill's needs of 180 MW.

Steam Plant operators are required to manage the process of supplying the pulp and paper mills with steam and generating power internally. They have a number of options for doing this and substantial savings are available if the lowest cost options can be determined at any time, and then followed.

A model of the mill's energy system has been developed utilising mixed integer linear programming techniques and real time data from the mill's information system to provide operations staff the lowest cost option in meeting the mill's energy requirements from the available "fuels".

PROCESS DETAIL

A diagram of the Steam Plant is shown in Fig. 1. The two Chemical Recovery Boilers and two Power Boilers generate steam at 45 barg, and deliver it to a common header. The 45 barg steam is then reduced in pressure to provide process steam at 10.3 barg and 3.4 barg for the pulp and paper mills. The balance of 3.4 barg steam is produced in heat exchangers, utilising geothermal steam.

Pressure reduction can take place in the mill's two turbo alternators whilst producing power, or passing through pressure reducing valves, or a combination of both depending on the process steam demand.

The turbine control system incorporates two pressure controllers. One to control the passout pressure (10.3 barg) the other to control the exhaust pressure (3.4 barg). The outputs from the pressure controllers are interlinked to provide turbine stability when there is a change in demand in either process steam main.

The final process steam temperature is controlled by adding water through de-superheating stations at selected points in the steam mains. This process also adds to the total mass of steam produced.

Approximately 270 tonnes/hour of geothermal steam is imported from the Kawerau borefield through two pipelines. The steam is utilised in five heat exchangers, which produce 3.4 barg process steam, direct in the process (Recovery Boiler area) and boiler feedwater heaters.

The remaining steam is passed through a turbine which has a number of functions:

1. Electrical power generation (8 MW max.)
2. The exhaust is utilised in a liquor pre-evaporator, water heater and foul condensate stripper.
3. The turbine has control systems which stabilise the pressure of the incoming geothermal steam to the mill.

The two power boilers are primarily fired with waste wood (hog) as fuel. Provision to fire fuel oil is provided for boiler start-ups, and in the event of insufficient wood waste being available due to supply problems. Also, if the moisture content of the wood waste is high then auxiliary fuel is burnt to stabilise the combustion process.

The operating range of Turbo Alternator Two is shown in Figure 2. TA1 has a similar performance curve. The turbines can operate anywhere within the highlighted portion of the curve and therefore are solely dependent on the mill's steam demand for the amount of electrical power that can be produced.

2. FORMULATION OF LINEAR PROGRAM

The problem of supplying steam and electricity to meet the mill's requirements at the lowest cost option has been formulated as a linear program, which forms the "engine room" of the model. The detail of this formulation is outlined in this section.

Many variables make it difficult to know which option is preferable. These variables include:

- process demand for steam
- availability of recovery boiler steam
- availability of geothermal steam
- cost of fuel oil
- moisture content of the waste wood fuel, which is stored in open to the weather
- the spot price of purchased electricity at any time (NZ has a deregulated electricity market)
- cost of imported hog fuel

These variables have been defined. Constraints, which impose certain limits on these variables, are also defined. The model is able to alter the values of these variables within the limits defined by the constraints in such a way as to minimise the overall cost of running the plant.

The units of all costs and consumptions in the model are per hour of plant operation.

1.1 Objective Function

Minimise Cost =

*Hog Fuel Cost * Amount of hog fuel burnt*
*+ Oil Cost * Amount of oil burnt*
*+ Geothermal steam cost * Amount of Geothermal steam used*
*+ Purchased electricity cost * Amount of purchased electricity*

The fixed costs of running the steam plant are included in the model. Recovery Boiler steam is available at zero cost due to the need to operate the process.

3. CONSTRAINTS

A number of equations, or constraints, are included in the model that are necessary to accurately define the plant operations. The main constraints are described here.

3.1 Steam Demands Must Be Met

Steam is required for the paper machines mainly at 3.4 barg, and mainly at 10.3 barg for the pulp mill. The overall demand for 10.3 and 3.4 barg steam is available to the model from the Plant Information system (PI). It also treats the operations of the turbo alternators, Pressure Reducing Valves and Geothermal Heat Exchangers as processes which can be varied. Therefore the amounts of steam at each process are defined as variables in the model.

A number of constraints ensure that the steam demands are met, whilst allowing the model the freedom to alter each variable (i.e. the processes which generate steam).

(i) Demand of 3.4 barg steam =

Exhaust from TA2
+ 3.4 barg ex Pressure Reducing Valves
+ 3.4 barg ex Geothermal Heat Exchangers
+ Enthalpy control steam.

(ii) Demand for 10.3 barg steam =

Passout from TA2
+ 10.3 barg ex Pressure Reducing Valves
- Enthalpy control steam

Enthalpy control steam is used to heat the process steam outlet from the heat exchangers.

3.2 Electricity Demand Must Be Met

The mill electricity demand at any time is also available from the PI. The model treats the MW generated through each turbo alternator, and the amount of electricity purchased, as variables.

A simple constraint ensures that the electricity demand is met.

Mill Electricity Demand =
Electricity generated in TA1
+ Electricity generated in TA2
+ Electricity generated in TA3
+ Electricity purchased

3.3 Power Boiler Operations

Both boilers can utilise hog (wood waste) and oil as fuel, either separately or concurrently. When burning hog, the hog moisture content affects the combustion rate.

Several equations define the steam which can be generated through the Power Boilers. The model is able to manipulate the variables of the amount of oil and hog burnt in both boilers.

45 barg Steam from Power Boiler 2 =

$$\frac{HogBurnt*MaxsteamwithHog}{MaxRateofHogSupply} + \frac{OilBurnt*MaxsteamwithOil}{MaxRateofOilSupply}$$

where the Maximum Steam available with Hog also varies with the moisture content.

3.4 Geothermal Steam

The maximum amount of geothermal steam which is available from the nearby steam bores is available from PI.

The model is able to determine how much of this should be used through TA3, and how much should be passed through the geothermal heat exchangers.

Geo steam to TA3 + Geo steam to Heat Exchangers

<= Max available geothermal steam

Whenever TA3 is operating there is a requirement in the plant for 95 tonnes per hour of exhaust to be used for the hot water heaters, foul condensate system and liquor pre-evaporators. This requirement is handled in the model by allowing the first 95 tonnes per hour of steam through TA3 to be at zero cost. Two equations define this.

(i) Geo Steam to TA3 =
Free geothermal steam
+ purchased geothermal steam

(ii) Free geothermal steam <= 95 tonnes per hour

3.5 Geothermal Heat Exchangers

The heat exchangers essentially convert raw geothermal steam from the steam bores at 7 barg into clean 3.4 barg process steam.

The efficiency of the heat exchangers is not linear, but it is sufficient for modelling purposes to approximate the efficiency as a two-stepped function.

A number of equations are required to achieve this:

(i) 3.4 barg Steam from Geothermal Heat Exchangers =

Geothermal Steam at the first efficiency
+ Geothermal Steam at the second efficiency

(ii) Geothermal Steam at the first efficiency = $(Amount\ of\ Raw\ Geo)_1 / Efficiency_1$

(iii) Geothermal Steam at the second efficiency = $(Amount\ of\ Raw\ Geo)_2 / Efficiency_2$

(iv) $(Amount\ of\ Raw\ Geo)_1$ *<= Limit of geothermal steam available at the first efficiency*

(v) Total Raw Geothermal Steam Supplied to the Heat Exchangers =

$(Amount\ of\ Raw\ Geo)_1 +$
$(Amount\ of\ Raw\ Geo)_2$

Note: $Efficiency_1 > Efficiency_2$

A small amount of 10.3 barg steam is injected into the outlet stream of steam from the heat exchangers in order to maintain sufficient enthalpy of the process steam.

The equation which defines this is:

*Enthalpy Control Steam = constant * steam from heat exchangers*

3.6 Marginal Cost of Hog Fuel

A certain amount of hog fuel is generated on site in the woodyard. Additional hog fuel is brought in from surrounding saw mills. With higher volumes needed the hog must be transported from sawmills which are further away, thus increasing the cost. This marginal cost of hog fuel is included in model as a series of constraints:

(i) *Amount of Hog Fuel used =*

$$\textit{Amount of free hog fuel} + \sum_{i=1}^{n} hogsawmill(i)$$

Where n= No. of Sawmills

$$hogsawmill(i) \; <= \; \textit{hog available at sawmill i}$$

(ii) *Cost of Hog Fuel =*

$$\sum_{i=1}^{n} hogsawmill(i) \; * \; \textit{cost of hog at sawmill i}$$

where $hogsawmill(i)$ = amount of hog fuel purchased from sawmill i

3.7 Turbo Alternator Operations

Equations have been included which define the operating region of the three turbo alternators. For instance, in the case of TA2 (Fig. 2) the equations are:

(i) Supply of 45 barg steam to TA2 =

*Windage + PassOut *0.4 + MW generated * 6.06*

Furthermore practical experience has shown that the operating region is somewhat different from the original specifications in figure one and additional constraints are required to reflect the range of exhaust which is actually achievable. These are shown as the bold outlines in figure one.

(ii) Supply of 45 barg steam to TA2 <=

$MW * m_{upper} + c_{upper}$

m_{upper} *and* c_{upper} *being straight line constants which define the maximum exhaust from TA2.*

(iii) Supply of 45 barg steam to TA2 >=

$MW * m_{lower} + c_{lower}$

m_{lower} *and* c_{lower} *being straight-line constants which define the minimum exhaust from TA2.*

3.8 Pressure Reducing Valves

Steam can be converted from higher pressure to lower pressure through de-super heating pressure reducing stations. The first reduction is from 45 barg to 10.3 barg, the second from 10.3 barg to 3.4 barg. The equations that define these are:

(i) 10.3 barg steam from PRV = $constant_1$ ** 45 barg steam supplied to the PRV*

(ii) 3.4 barg steam from PRV = $constant_2$ ** 10.3 barg steam supplied to the PRV*

Note: These constants include the effect of adding water to the steam.

3.9 Additional Constraints

Further constraints, that will not be listed here, are included in the model to provide:

- Additional process detail
- Ability to switch on and off various sections of plant
- Alter some process parameters

4. SOFTWARE PLATFORM

Initially the model was developed using the AMPL mathematical programming environment, and the CPLEX linear solver, both available from ILOG Corporation. However, a critical component of the model is the ability to incorporate real-time process data such as:

- Steam Demands
- Plant Availability
- Recovery Boiler Steam Availability
- Geothermal Steam Availability
- Spot electricity price

These parameters are available on the mill PI system. A real-time interface to Microsoft Excel is also available. Therefore it was thought to be appropriate to convert the model into a spreadsheet based linear program, and make use of the standard Excel solver.

5. RESULTS

Prior to implementation in the Steam Plant Control Room an in-depth verification programme was initiated to ensure the results from the model were correct. The model was run automatically every half-hour for some weeks. Actual plant operating data was logged with the corresponding model data. The average difference between the actual plant operating costs and the model operating costs was determined. The results have shown an opportunity for significant reductions in operating costs.

It was recognised early on in the development that the model would require a dedicated PC to run it every few minutes. This would take the focus of the operator from the Distributed Control System (DCS) screens to another screen to update predicted to actual performance. This has been overcome by a specialist piece of equipment that can reference a cell in Excel and convert it to a 4-20 mA output signal which can be read by the DCS. The operator will now have a real time trend of optimised performance against actual. It should be noted that an incentive was deliberately provided for the operators to 'beat the model'. The maximum output from the turbo alternators are limited in the model. Under some conditions it is actually possible to generate more from these turbines. Also, the actual steam flows vary somewhat due to the inherent flow meter variations. The implications of this are that at times the model requires slightly more 45 barg steam than the actual values (from PI) to meet the Mill's steam demands.

6. CONCLUSIONS

The development and implementation of the model has been a very successful exercise. Operators now have a tool that allows them to make optimal decisions regarding the running of the Steam Plant. This has identified significant cost savings. The model is now known as SPOT (Steam Plant Optimisation Tool).

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APPENDIX - USER INTERFACE

A number of menus have been developed using Visual Basic for Applications in Microsoft Excel 5.0. These allow users of the model to update parameters with current real time values in PI, or override any of these parameters. This interface is shown below.

Main Menu
A customised menu titled Energy Use has been added to the standard Excel menus. These menus and their functions are:

- Run Automatically

  Calls the linear program solver, solves the problem and displays the Report based on current actual values.

- Solve

  Solves the problem with manual inputs as is.

- Enter Costs

  Allows changes to costs of fuel, steam and fixed operating costs

- Enter Demands

Downloads current real time values from the PI system for steam demands, electricity price, and plant status or manual inputs for what if scenarios.

- Enter Constants

  Allows changes to hog fuel quality (moisture level) and minimum steaming rates for the Power Boilers

- Alter Geothermal Parameters

  Allows changes to the operating parameters of TA3, the geothermal heat exchangers and Geothermal steam availability.

- Graph Last 24 Hours Data

  Plots calculated costs and the Actual Plant costs over the last 24 hours

- Graph All Data

  Plots calculated costs and the Actual Plant costs for the entire set of data.

- Control PI

  Enables or disables the PI connection

- Archive Data

  Allows archived data to be retrieved for analysis.

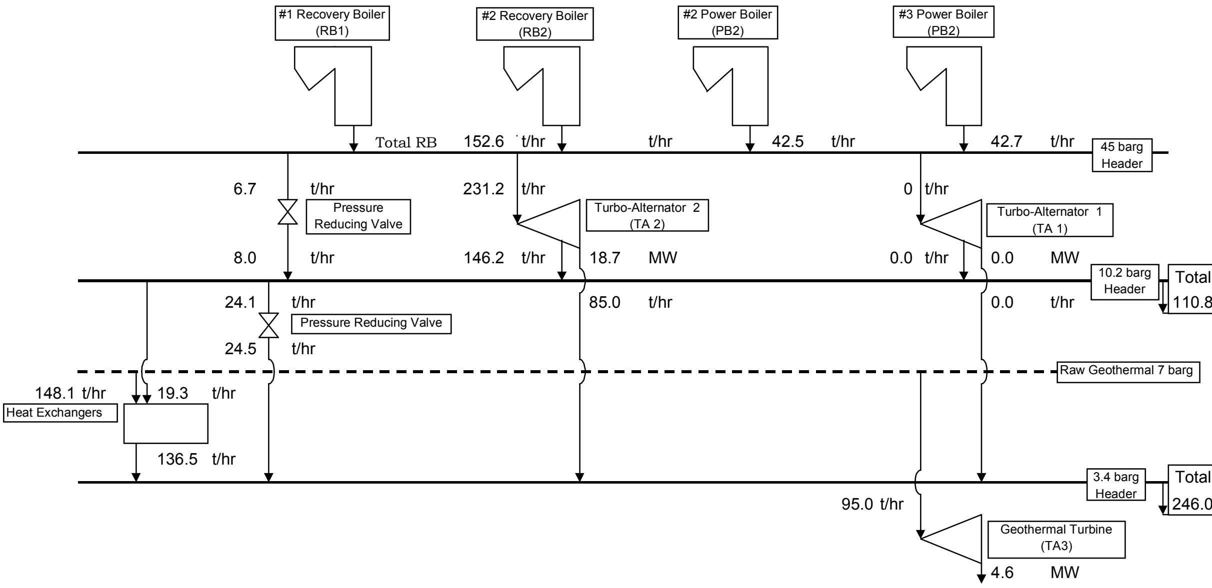

Figure 1.

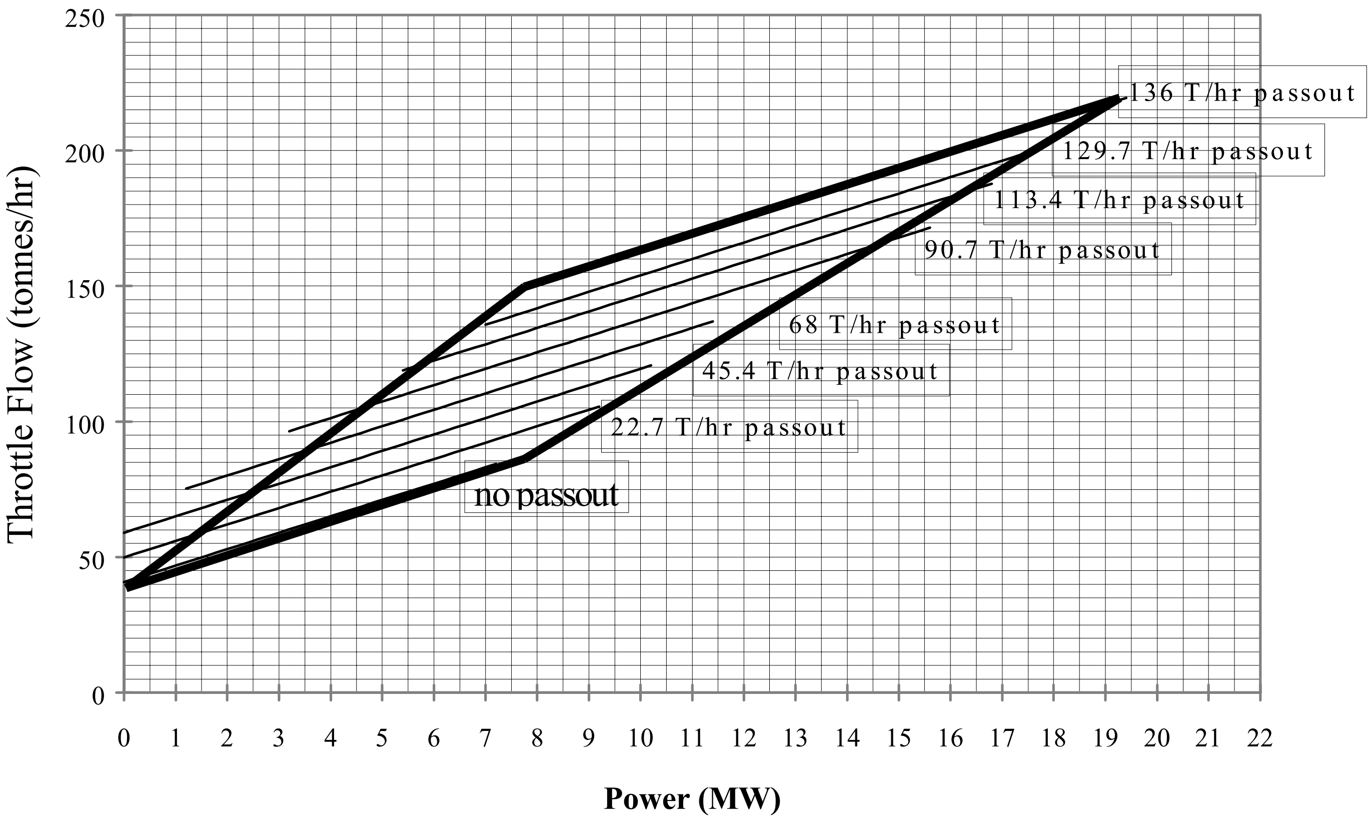

Figure 2: Operating Range of turbo-alternator 2. Range for TA1 is similar.