Pulp Mill Electricity Demand Management

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Abstract

We describe a mixed integer programming model for scheduling mechanical pulp production with uncertain electricity prices.

1 Introduction

Norske Skög owns and operates a newsprint mill at Kawerau in New Zealand's Bay of Plenty. Energy comprises about one third of variable costs with wholesale electricity purchases in the mechanical pulp mill comprising the bulk of this. The mechanical pulp mill (MPM) at Norske Skög Tasman consists of several pulp refiner lines and grinders, and can be thought of as distinct pulp production units, or plants. When running, the pulp plants operate at full capacity. Pulp production from individual pulp plants is mixed in buffer tanks and delivered to the three paper machines. Limited storage is provided by the buffer tanks allowing for temporary cessation of production at one or more pulp plant.

A simplified flow diagram of the MPM is shown in Figure 1. The MPM has two stone grinders (SGW1 and SGW2), two Refiner Mechanical Pulp Plants (RMPA and RMPB) and two Thermo-Mechanical Pulp Plants (TMP1 and TMP2). These plants break down wood into pulp and deliver it to three intermediary storage tanks: the Holding, Rejects and Blend tanks. Pulp is then pumped to two storage tanks: the RMP-SGW and TMP tanks. Pulp is pumped from these two tanks into a single Mixed Tank before being delivered to the paper machines, and converted into newsprint. Note that it is possible to supply each paper machine directly from the RMP-SGW tank.

In this paper we describe a mixed integer optimization model called ROME (Real-time Optimization Model for Electricity), that has been developed to provide advice regarding production schedules. The model utilises pulp storage tanks so

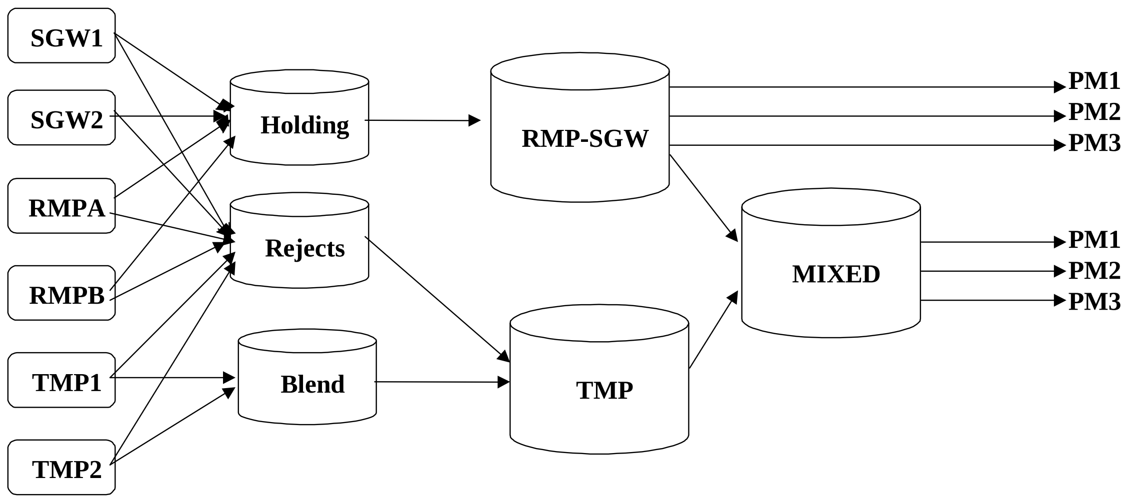

Figure 1: Mechanical Pulp Mill Flow Diagram

that production in the mechanical pulp mill can be scheduled to avoid incurring high wholesale electricity prices, whilst still meeting paper machine demand. Costs associated with load shedding and rules encapsulating pulp-quality requirements are important considerations. Uncertainty in electricity prices is considered by way of price scenarios.

The problem of deciding which plants to use at each trading period in a planning horizon, is very similar to the electricity generation unit commitment problem (see for example[1][2]). Lagrangian relaxation techniques have proved to be very successful in attacking large instances of these problems, particularly when there is uncertainty in some of the problem data. While Lagrangian relaxation models at Norske Skog are being considered, ROME provides a useful pilot model to provide guidance to the mill operators, and enable benchmarking of any more comprehensive models that might be developed.

In the next section, we describe the model formulation in detail. Section 4 outlines the extension of ROME to accommodate uncertain prices and in section 5 we illustrate the results of ROME by considering a simple example.

2 Model Formulation

Denote by P the set of pulp plants indexed by p, K the set of storage tanks indexed by k, and T the set of planning periods indexed by t. We let $C[k]$ be the set of pulp types that feed into tank k and $M[k]$ the set of paper machines that are fed from tank k. Apart from these index definitions, we adopt the convention throughout this paper of using lower case Roman letters to denote parameters, upper case Roman letters to denote continuous variables, and lower case Greek letters to denote binary variables. The central decision variables in this model are the nonnegative variables:

$$X_{kt} = \text{the number of tonnes of pulp delivered to tank } k \text{ in time period } t$$

and the binary decision variables

$$\sigma_{pt} = \begin{cases} 1, & \text{if pulp plant } p \text{ is running in period } t \\ 0, & \text{otherwise.} \end{cases}$$

We define the following parameters

s_t	=	Spot electricity price in trading period t
r_t	=	Spot reserve price in trading period t
d_t	=	Paper machine pulp demand in trading period t
a_p	=	Production capacity of plant p
e_p	=	Power load of plant p
i_p	=	Reserve available from plant p
u_k	=	Maximum storage capacity in tank k
l_k	=	Minimum storage capacity in tank k
$\widehat{l}_k$	=	Initial storage level of tank k
b_{pk}	=	Proportion of pulp from plant p delivered to tank k
n_p	=	Number of permitted plant shut downs
y_p	=	Penalty incurred for additional plant shut downs
q_j	=	Production short-fall penalty for paper machine j
$\widehat{d}_p$	=	Number of periods required for a reversal in plant p
z_p	=	Penalty if a reversal in plant p is required but not performed
t_0	=	First trading period in the model planning horizon
t_∞	=	Final trading period in the model planning horizon

and the following variables

E_{pt}	=	Power consumed in plant p during trading period t
I_{pt}	=	Reserve sold from plant p during trading period t
L_{kt}	=	Storage level of tank k during trading period t
F_{jkt}	=	Flow of pulp from tank j to tank k during trading period t
Q_{jt}	=	Paper production shortfall on machine j in trading period t
A_t	=	Pulp shortfall penalty
J_p	=	Plant shut down penalty
B_t, C_t, G_t	=	Plant combination penalties
γ_{pt}	=	Binary variable indicating reversal in plant p has commenced in trading period t
C_{pt}	=	Reversal indicator
H_p	=	Reversal violation penalty

2.1 Pulp Production

We are primarily interested in the total amount of pulp delivered into each tank defined by

$$X_{kt} = \sum_{p \in C[k]} b_{pk} a_p \sigma_{pt} \quad k \in K, \quad t \in T. \tag{1}$$

Observe that b_{pk} is a fixed parameter defined by production recipes.

2.2 Paper Machine Pulp Demand

We allow paper machine j to reduce pulp demand by including a paper production short-fall, Q_{jt}. This trade-off of lost paper sales opportunities would make sense if the costs of pulp production were sufficiently high. The opportunity cost is represented by a penalty q_j incurred for each tonne of pulp that is not supplied to paper machine j. Therefore

$$\sum_{k \in K} \sum_{j \in M[k]} F_{kjt} = d_t - Q_{jt}, \quad t \in T,$$

ensures that the flow of pulp to the paper machines meets the paper machine demand less any shortfall. We define

$$A_t = \sum_{j \in M[k]} Q_{jt} q_j, \quad t \in T.$$

to be the pulp-shortfall penalty in each time period, to be deducted from the objective function.

2.3 Pulp Storage and Flow Balance

Storage tank levels must be kept within upper and lower bounds. This gives

$$l_k \leq L_{kt} \leq u_k, \quad t \in T.$$

The level in tank k in time period t is equal to the level in the previous period plus incoming production and incoming flow from other tanks, minus outgoing flow to other tanks. Recall $C[k]$ is the set of pulp types that feed into tank k. Let us also define $J[k]$ to be the set of tanks that receive pulp from tank k. Then

$$L_{kt} = L_{kt-1} + \sum_{p \in C[k]} X_{pt} b_{pk} + \sum_{j \in J[k]} (F_{jkt} - F_{kjt}), \quad k \in K, \quad t \in T \setminus \{t_0\}.$$

and

$$L_{kt} = \widehat{l}_k + \sum_{p \in C[k]} X_{pt} b_{pk} + \sum_{j \in J[k]} (F_{jkt} - F_{kjt}), \quad k \in K, \quad t = t_0.$$

Finally we require that pulp inventory can not be run down at the end of the planning period. This means that at the end of the planning horizon (at $t = t_\infty$) the pulp tanks must be at least as full as they were at the beginning, so

$$L_{kt} \geq \widehat{l}_k, \quad k \in K, \quad t = t_\infty.$$

2.4 Pulp Switching Constraints

Each time a pulp plant is shut down and started up again, costs are incurred due to impacts on quality and risk of plant damage. We introduce a number of penalties that have the effect of encouraging ROME to produce production schedules that do not compromise quality unless it makes economic sense to do so.

2.4.1 Plant Shut Downs

We apply restrictions on the number of plant shut downs permitted in the planning horizon. We introduce a non-negative variable S_{pt} that represents a change in production state:

$$S_{pt} = \begin{cases} 1, & \text{if pulp plant } p \text{ shuts down in period } t \\ 0, & \text{otherwise.} \end{cases}$$

Then

$$\begin{aligned} S_{pt} &\geq \sigma_{pt-1} - \sigma_{pt}, \quad t \in T \setminus \{t_0\} \\ S_{pt} &= 0, \quad t = t_0 \end{aligned}$$

We note that S_{pt} takes on binary values naturally as it is equal to the difference between two binary variables. We allow n_p shut downs for plant p to reflect maintenance schedules. Each additional time a pulp plant is shut down a penalty y_p is incurred and the total shut down penalty for plant p is given by J_p, which must satisfy

$$\begin{aligned} &J_p \geq (\sum_{t \in T} S_{pt} - n_p) y_p, \\ &J_p \geq 0. \end{aligned}$$

2.4.2 Pulp Plant Combinations

In practice there are pulp quality considerations involved with shutting down combinations of lines of refiners. Pulp strength and drainage properties are adversely affected each time the mix of pulps being used is altered. It is important to control pulp properties between tight limits so that the mixed pulp furnish sent to the paper machines allows paper production to progress satisfactorily. ROME allows any combination of pulp lines to be shut down concurrently, but applies significant penalties for some combinations. Table 1 shows the combinations that incur penalties. Penalty variables B_t, C_t and G_t are defined and three constraints are included in ROME to ensure that penalties are incurred if the combinations of plants running at any trading period warrant it.

Plant	RMPA	RMPB	TMP1	TMP2	Penalty
Plant Index	3	4	5	6	
	on	on	off	on	h_1
	on	on	on	off	h_1
	on or off	on or off	off	off	h_2

Table 1: Plant Combinations Incurring Penalties

$$\begin{aligned} B_t &\geqslant (\sigma_{3t} + \sigma_{4t} - \sigma_{6t} - 1) h_1, \quad t \in T. \\ C_t &\geqslant (\sigma_{3t} + \sigma_{4t} - \sigma_{5t} - 1) h_1, \quad t \in T. \\ G_t &\geqslant (1 - \sigma_{5t} - \sigma_{6t}) h_2, \qquad\quad t \in T. \end{aligned}$$

2.4.3 Reversals

TMP and RMP refiner plates must be run in the reverse direction regularly, approximately every 100 hours in order to reduce burring of the plates. If a reversal is required during the model planning horizon we set $\widehat{r}_p = 1$. We restrict the scheduling of reversals to be within a subset of T that varies by pulp plant. This set is defined as $W[p]$, and reflects the availability of tradesmen required to affect the reversal. We define binary variables

$$\gamma_{pt} = \begin{cases} 1, & \text{if a reversal is commenced in period } t \\ 0, & \text{otherwise.} \end{cases}$$

Recall that $\widehat{d}_p$ periods are required to perform the reversal in pulp plant p and a penalty of z_p is incurred if a reversal is required, but is not scheduled by ROME. The penalty variable H_p is added to the objective function, where

$$H_p \geq (\widehat{r}_p - \sum_{t \in W[p]} \gamma_{pt}) z_p \tag{2}$$

To relate reversals to production we now impose the constraint

$$\sum_{t_1 \in W[p], t_1 \leqslant t \leqslant t + \widehat{d}_p} \sigma_{pt_1} \leqslant \widehat{d}_p (1 - \gamma_{pt}), \quad p \in P, \quad t \in T. \tag{3}$$

To see how the constraint works, observe that if there are $\widehat{d}_p$ consecutive periods in which plant p is not operating then it is possible to perform a reversal. This is reflected in the summation term of (3), which will only equal 0 if a reversal can be commenced in trading period t. In this case the binary variable γ_{pt} will take on the value 1, as the optimiser will attempt to avoid the reversal penalty incurred in (2).

2.5 Objective Function

The objective function is simply the cost of purchased power less the cost of reserve market sales plus any model penalty costs incurred. Formally this is

$$\sum_{p \in P} \sum_{t \in T} (\sigma_{pt} e_p s_t - \sigma_{pt} i_p r_t) + \sum_{p \in P} (J_p + H_p) + \sum_{t \in T} (A_t + B_t + C_t + G_t).$$

3 Uncertainty in Prices

The New Zealand Electricity Market publishes final prices the next day. Leading up to real time, three different price forecasts are published. Price predictions are not the subject of this paper, nevertheless it is important to recognise that final prices are quite uncertain and that it is possible to form views of what those prices will be.

Appreciating this point we have altered ROME so that it incorporates a set of price scenarios Ω indexed by ω, rather than using merely the expected price.

Now electricity and reserve prices and all variables are indexed over both tranding period and scenario. We define Π_ω, the probability of each scenario, and ensure that $\sum_{\omega\in\Omega}\Pi_\omega = 1$. We also introduce indexed subsets of Ω as required to allow us to construct branching scenarios for non-anticipative constraints. For example we define Ω_i, $i = 1,\ldots,7$, and T_i, $i = 1,\ldots,7$, (as shown in Table 2) that allow us to construct branching price scenarios in the fashion depicted in Figure 2.

Scenario Set Name	Branch	Scenarios Included	Trading Period Set Name	Trading Periods Included
Ω_1	Bundle 1	1 2 3 4 5 6 7 8	T_1	1,2,3,4,5
Ω_2	Bundle 2	1 2 3 4	T_2	6
Ω_3	Bundle 3	5 6 7 8	T_3	6
Ω_4	Bundle 4	1 2	T_4	7
Ω_5	Bundle 5	3 4	T_5	7
Ω_6	Bundle 6	5 6	T_6	7
Ω_7	Bundle 7	7 8	T_7	7

Table 2: Branching Scenarios

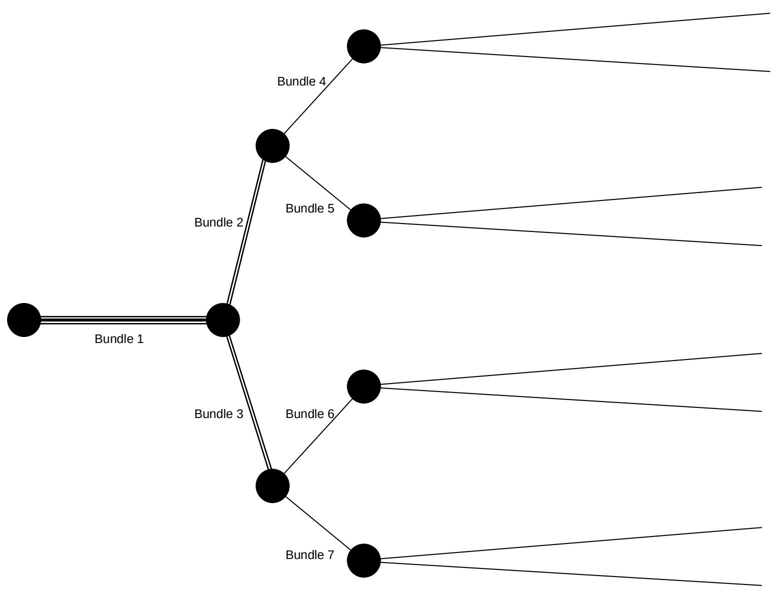

Figure 2: Branching Scenario Tree

With a scenario index, the objective function becomes

$$\sum_{\omega\in\Omega}\Pi_\omega\sum_{p\in P}\sum_{t\in T}(\sigma_{\omega pt}e_p s_t - \sigma_{\omega pt}i_p r_t) + \sum_{\omega\in\Omega}\Pi_\omega\sum_{p\in P}(J_{\omega p} + H_{\omega p})$$
$$+\sum_{\omega\in\Omega}\Pi_\omega\sum_{t\in T}(A_{\omega t} + B_{\omega t} + C_{\omega t} + G_{\omega t}),$$

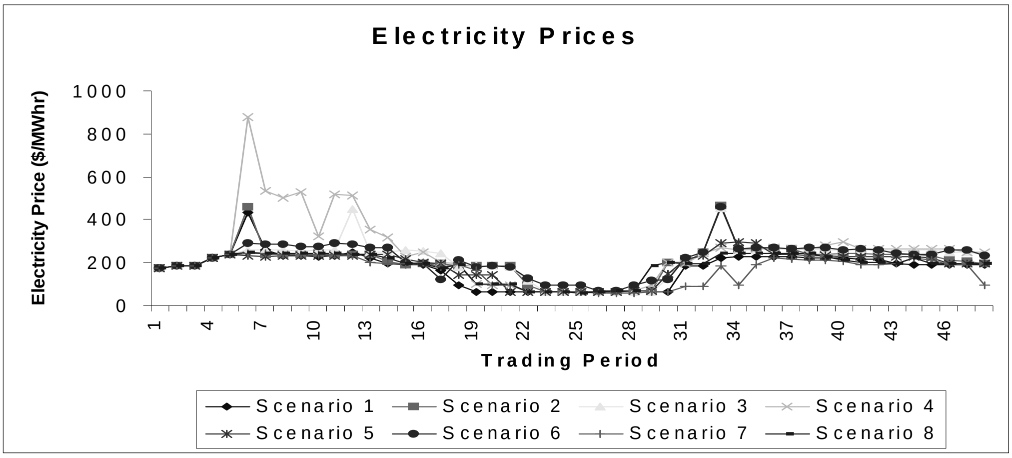

Figure 3: Price Scenarios

and to ensure that scenarios that share the same price-histories have identical decisions, we add non-anticipative constraints of the form

$$\begin{aligned} \sigma_{\omega pt} &= \bar{\sigma}_i, \quad \omega \in \Omega_i, \quad p \in P, \quad t \in T_i, \\ \gamma_{\omega pt} &= \bar{\gamma}_i, \quad \omega \in \Omega_i \quad p \in P, \quad t \in T_i, \end{aligned}$$

where $\bar{\sigma}_i$ and $\bar{\gamma}_i$ are additional binary variables chosen for each scenario bundle.

4 Example

To illustrate the results from ROME we consider an example of planning for a single day (48 trading periods) in which dispatch prices for the next five trading periods are available and represent forecasts of final electricity prices. We construct eight price scenarios as shown in Figure 3. These are based on the distribution of prices from the previous two weeks.

In the New Zealand Electricity Market two hours notice must be provided before demand bids can be altered. This means that decisions for the next four trading periods have previously been made and the only decision that must be made now is for the fifth trading period. We consider a decision required immediately prior to the evening demand peak (6 pm), and define trading period 1 to be equivalent to 3.30 pm. All scenario prices equal the dispatch price for the first five trading periods and then vary. For simplicity we ignore the effect of reserve prices by setting $r_{\omega t} = 0, \quad \omega \in \Omega, \quad t \in T.$

We apply non-anticipative constraints as defined in Table 2 and Figure 2. We also stipulate that a reversal lasting two trading periods must be performed on $TMP1$ at some time in the planning horizon. High penalty costs have been set for production shortfall, pulp plant combinations and failure to perform the reversal, and we assume that paper machine demand will be constant throughout the day at 90% of the combined pulp mill capacity, enabling up to 10% of pulping capacity to be curtailed.

Scenario\Period	1	2	3	4	5	6	7	8	9	10	11	12	13	32	33	34	35	36	37	38	39
1	1	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1
3	1	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	1	1
7	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	1

Figure 4: Rome Production Schedule for TMP1

We show in Figure 4 the results for the $TMP1$ plant. A state of 1 indicates that the plant is running. Reversals occur when the plant is shut down for two consecutive periods. The optimal decision is to run this plant in trading period 5, and as one would expect the scheduling of the reversal varies depending on the scenario. Reversals are scheduled in period 6 for Scenarios 1 to 4 whilst they are delayed until price peaks are observed for scenarios 5 to 8. Scheduling of plant shut-downs are restricted by the requirement to observe pulp supply feasibility. Rome avoids reversal and pulp shortfall penalties and coordinates the shut down of various plants to avoid plant combination penalties.

5 Discussion

ROME has been developed using AMPL and CPLEX 8.0, both available from ILOG [3]. Although ROME is useful as a planning tool, its solution time grows very quickly with the number of price scenarios chosen. In a practical setting, where we would like to use many more scenarios, possibly in the hundreds, ROME is too slow to to be used as a real-time tool for pulp mill operators. We are in the process of developing a Lagrangian relaxation model (see for example [4]), which decouples the problem by relaxing the pulp production constraints (1) and attacks the switching of plants using dynamic programming. It is hoped that this alternative formulation will provide good solutions in an acceptable amount of time.

References

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