Pulp Mill Power Tool

A.B. Philpott and G.R. Everett
Department of Engineering Science
University of Auckland
and
Norske Skog Tasman Limited
a.philpott@auckland.ac.nz
graeme.everett@norskeskog.com

Abstract

In [2] we presented a mixed integer programming model for scheduling mechanical pulp production with uncertain electricity prices, that was being used at the Norske Skog newsprint mill in Kawerau. Since then there have been a number of machinery closures at the mill, reducing plant capacity but increasing the flexbility of operations. In this paper we describe a new version of the mixed integer programming model that utilises a value of pulp storage function to provide advice for short, and medium term production decisions.

1 Introduction

Norske Skog owns and operates a newsprint mill at Kawerau in New Zealand's Bay of Plenty. Newspaper publishers are experiencing large and rapid reduction in newspaper copies and pagination, generally attributed to the rise of electronic media. This has resulted in a very large reduction in demand for newsprint throughout the western world and closure of many newsprint mills worldwide. New Zealand has not been spared this attrition, firstly the number 1 paper machine closed in 2006 and then in 2013 the number 2 machine also closed. Site capacity has reduced from 365,000 Tonnes in 2005 to 155,000 Tonnes today. The site has also simplified considerably - only one pulp mill (the Thermo Mechanical Pulp (TMP) Mill) remains in operation and that mill has just two lines of refiners for converting wood chips into pulp. The pulp is firstly sent to a number of storage tanks before being mixed with water to the desired consistency and delivered to the paper machine.

Converting the Tasman plant into an alternative paper grade is infeasible due to the excessive capital costs involved. Tasman's only strategy for survival in the newsprint industry is to maintain a very low cost operation. Almost half of the variable production costs of newsprint are spent on electricity, and most of this electric power is used to drive the TMP mill. Substantial savings can be made by shutting off this plant during periods of high electricity prices. A mixed-integer programming decison model (ROME) for optimizing the savings by scheduling these shutdowns was described in [2].

ROME is driven by forecasts of electricity prices. New Zealand has an ex-post electricity market where prices are published every half hour, signalling the marginal cost to meet demand. One might expect prices to be correlated with demand; low overnight and high during the day. However for a multitude of reasons, prices do not always reflect what might be considered logical outcomes. Market participants have access to a number of price forecasts, and must make their own judgement about what the final prices will be.

The reduction in worldwide demand for newsprint has led to a decreased capacity of the paper mill, and allowed some simplifications in ROME to form a new model we call PowerTool. The use of a single pulp mill means that there is now no need to separate different types of pulp. PowerTool also exploits pulp storage more aggressively. The combined pulp mill capacity of 700 Tonnes per day exceeds the paper machine capacity of about 450 Tonnes (depending on the paper grade being produced). The combined storage capacity is about 640 Tonnes. Thus the pulp mill is required to operate about 15 hours per day on average to meet the paper machine demand for pulp. This buffer provides more flexibility in operation and allows operators to use PowerTool to minimize electricity procurement costs by using pulp storage to smooth peaks.

The use of pulp storage to improve mill operations is not new. Philpott and Pritchard [1] describe a dynamic programming model for electrity load shedding for a pulp mill that stores pulp for later shipment. Their model is used to compute a function $\Psi(L)$ that defines the future value of stored pulp as a function of storage level L. The dynamic programming model used in [1] to compute Ψ approximates the inter-stage scheduling of the pulp mill. In this paper we assume that $\Psi(L)$ is known and focus on the mixed integer programming model for scheduling pulp production within each stage. PowerTool has been implemented in the newsprint mill at Kawerau and is used by pulp mill operators to minimize the cost of pulp production by using storage as a buffer between the pulp mill and the paper machine.

The paper is laid out as follows. In the next section we describe the formulation of PowerTool. In section 3 we describe the user interface of PowerTool and show how it is used in practice. We conclude with some suggestions for improving the model.

2 Model Formulation

Suppose there are P pulp plants indexed by p and T planning periods indexed by t. 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. Suppose also that we combine all storage tanks into one single tank for the purposes of this model. The central decision variables in this model are the nonnegative variables

$$L_t = \text{the number of tonnes of pulp held in storage in time period } t,$$

$$X_t = \text{the number of tonnes of pulp delivered to the storage tank in time period } t,$$

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	=	Maximum pulp storage capacity
l	=	Minimum pulp storage capacity
$\widehat{l}$	=	Initial storage level of tank
i_p	=	Reserve available from plant p
$\widehat{l}$	=	Initial storage level
n_p	=	Number of permitted plant shut downs
y_p	=	Penalty incurred with each plant shut down

and the following variables

Y_{pt}	=	Pulp produced in plant p during trading period t
E_{pt}	=	Power consumed in plant p during trading period t
I_{pt}	=	Instantaneous Reserve sold from plant p during trading period t
F_t	=	Flow of pulp from storage to the paper machine in trading period t
Q_t	=	Paper Production shortfall in trading period t

2.1 Pulp Production

Let us define the capacity of pulp plant p as a_p tonnes per time period, the MW of power consumed as e_p and the MW of interruptible load available for sale in the reserves market as i_p. Then production at each pulp plant is given by

$$Y_{pt} = \sigma_{pt} a_p, \quad p = 1, \ldots, P, t = 1, \ldots, T.$$

and power consumption is $\sigma_{pt} e_p$, $p = 1, \ldots, P$, $t = 1, \ldots, T$. Interruptible load can only earn revenue when the plant is running, so we represent this by $\sigma_{pt} i_p$, $p = 1, \ldots, P$, $t = 1, \ldots, T$.

2.2 Paper Machine Pulp Demand

We allow the paper machine to reduce pulp demand by including a paper production short-fall variable, Q_t. Reduction in paper sales makes sense if the costs of pulp production are sufficiently high. The cost of this reduction is represented by a penalty q incurred for each tonne of pulp that is not supplied. Therefore

$$F_t = d_t - Q_t, \quad t = 1, \ldots, T$$

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

$$A_t = Q_t q, \quad t = 1, \ldots, T,$$

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

2.3 Pulp Storage and Flow Balance

The pulp storage level L_t in time period t is equal to the level in the previous period plus incoming production minus outgoing flow to the paper machine, whence

$$L_1 = \widehat{l} + \sum_{p \in P} Y_{p1} - F_1,$$

and

$$L_t = L_{t-1} + \sum_{p \in P} Y_{pt} - F_t, \quad t = 2, \ldots, T.$$

The storage tank level must be kept within upper and lower bounds, so

$$l \leq L_t \leq u, \quad t = 1, \ldots, T.$$

2.4 Penalty Costs

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. It is important to control pulp strength and drainage between tight limits so that the mixed pulp furnish sent to the paper machines allows paper production to progress satisfactorily. Down time on the paper machines may result from poor and/or inconsistent pulp quality.

We introduce a number of penalties that have the effect of encouraging PowerTool 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. To enable this we introduce a non-negative variable S_{pt} that represents a change in production state:

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

We model S_{pt} by

$$\begin{aligned} S_{pt} &\geq \sigma_{pt-1} - \sigma_{pt}, \quad t = 2, \ldots, T. \\ S_{pt} &= 0, \quad t = 1. \end{aligned}$$

Observe 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. The plant shutdown penalty in period t is then modelled by

$$\begin{aligned} & B_t \geq \sum_{t \in T} \sum_{p \in P} (S_{pt} - n_p) y_p \\ & B_t \geq 0 \end{aligned}$$

2.4.2 Pulp Plant Combinations

In practice there are pulp quality considerations involved with shutting down combinations of lines of refiners. We denote the two lines of refiners by $p1$ for $TMP1$ and $p2$ for $TMP2$. The most consistent quality pulp is made when both TMP refiner lines operate at the same time, so

$$\sigma_{p1t} + \sigma_{p2t} = 2.$$

Pulp strength and drainage properties can be adversely affected each time

$$\sigma_{p1t} + \sigma_{p2t} = 1$$

We model this by imposing a penalty b on any time periods when only one TMP refiner is operating. To do this define two binary variables β_t and γ_t constrained by

$$\beta_t \geqslant \frac{\sigma_{p1t} + \sigma_{p2t}}{2},$$

$$\gamma_t \leq \frac{\sigma_{p1t} + \sigma_{p2t}}{2},$$

and let

$$C_t = (\beta_t - \gamma_t) b.$$

Since C_t is included in the objective as a penalty cost, the optimal solution will seek to make β_t as small as possible and γ_t as large as possible. If $\sigma_{p1t} + \sigma_{p2t} = 0$, then $\beta_t = \gamma_t = 0$. If $\sigma_{p1t} + \sigma_{p2t} = 2$ then $\beta_t = \gamma_t = 1$. Thus $C_t > 0$ only when

$\sigma_{p1t} + \sigma_{p2t} = 1$, when $C_t = b$. This is summarised by Table 1.

Plant/Variable				
p_1	off	off	on	on
p_2	off	on	off	on
β_t	0	1	1	1
γ_t	0	0	0	1
C_t	0	b	b	0

Table 1: variable states given pulp mill operating configuration.

2.4.3 Objective Function

The objective function is the value of stored pulp Ψ less the cost of production (which is the purchased power less the cost of reserve market sales) and any model penalty costs incurred.

$$\max \Psi - \sum_{p \in P} \sum_{t \in T} (\sigma_{pt} e_p s_t - \sigma_{pt} i_p r_t) - A_t - B_t - C_t$$

The value Ψ of residual pulp storage L_T is modelled as a concave polyhedral function using cutting planes. Thus we add constraints

$$\Psi \leq a_k + b_k L_T,\ k = 1, 2, \ldots, K.$$

2.5 Example 1

Typical values for the future value of pulp are shown in Figure 1. When pulp storage is low, the pulp is valued highly. When storage is high the value of pulp is very low. The solution from PowerTool with these pulp values is shown in 2. The red bars indicate trading periods that the TMP refiner lines should be off, whereas green indicates when they should be on. The forecast spot electricity price is shown in blue, the reserve price is shown in green and the effective energy price forecast is shown in the red line. The pulp storage levels that would arise if this solution is implemented is shown at the bottom of the graphic. It can be observed that the final storage position is slightly over 500 Tonnes. The marginal value of storage is equivalent to \$30/MWh. The PowerTool solution has identified the trading periods in which to operate to deliver a marginal cost of less than \$30/MWh (also taking into account penalties B_t for excess refiner line shut-downs).

2.6 Example 2

Using the same pulp storage values from Figure 1, but different electricity prices, produces a different solution as shown in Figure 3

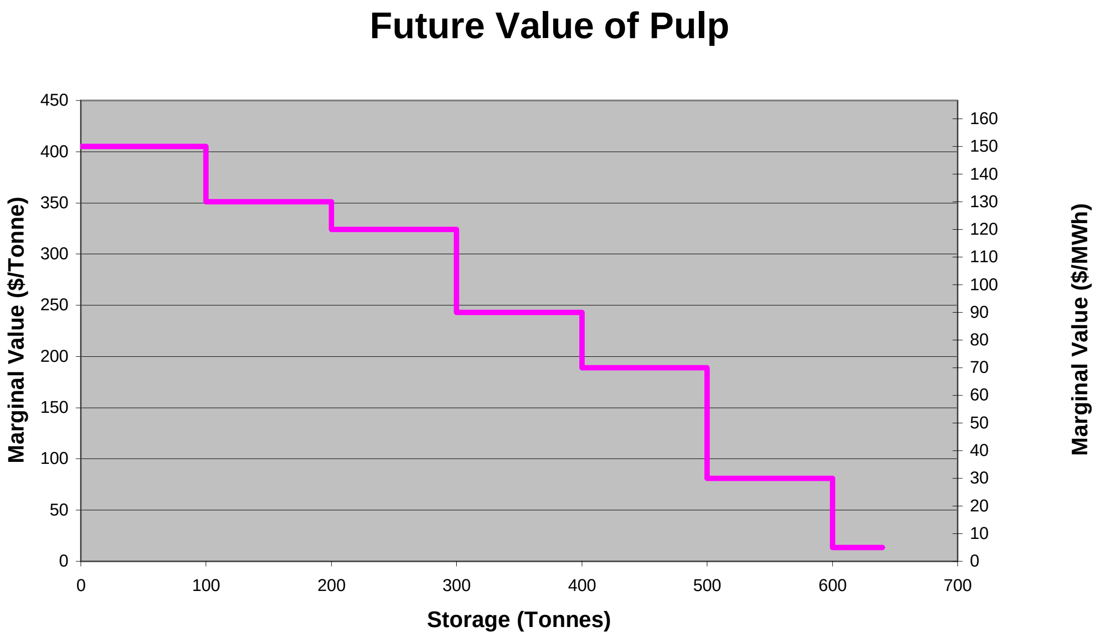

Figure 1: Future Value of Pulp in $/Tonne and $/MWh

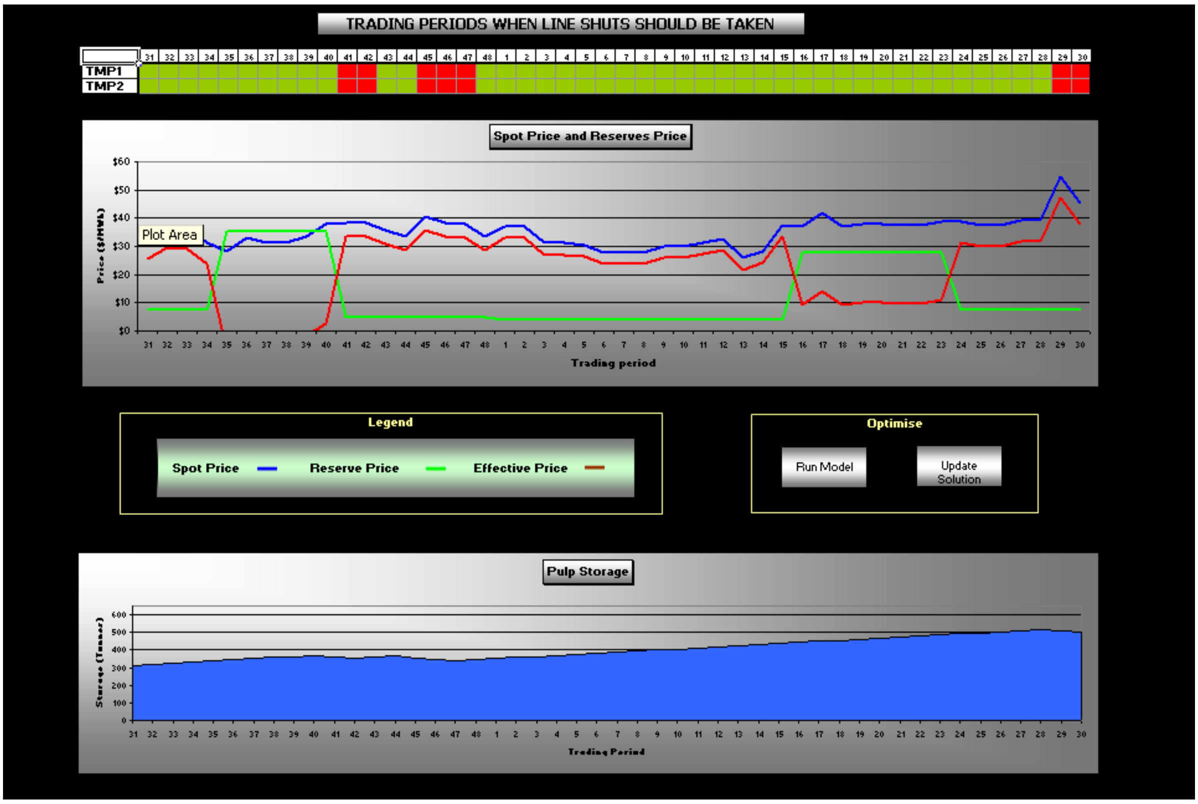

Figure 2: Example 1 Solution from Power Tool

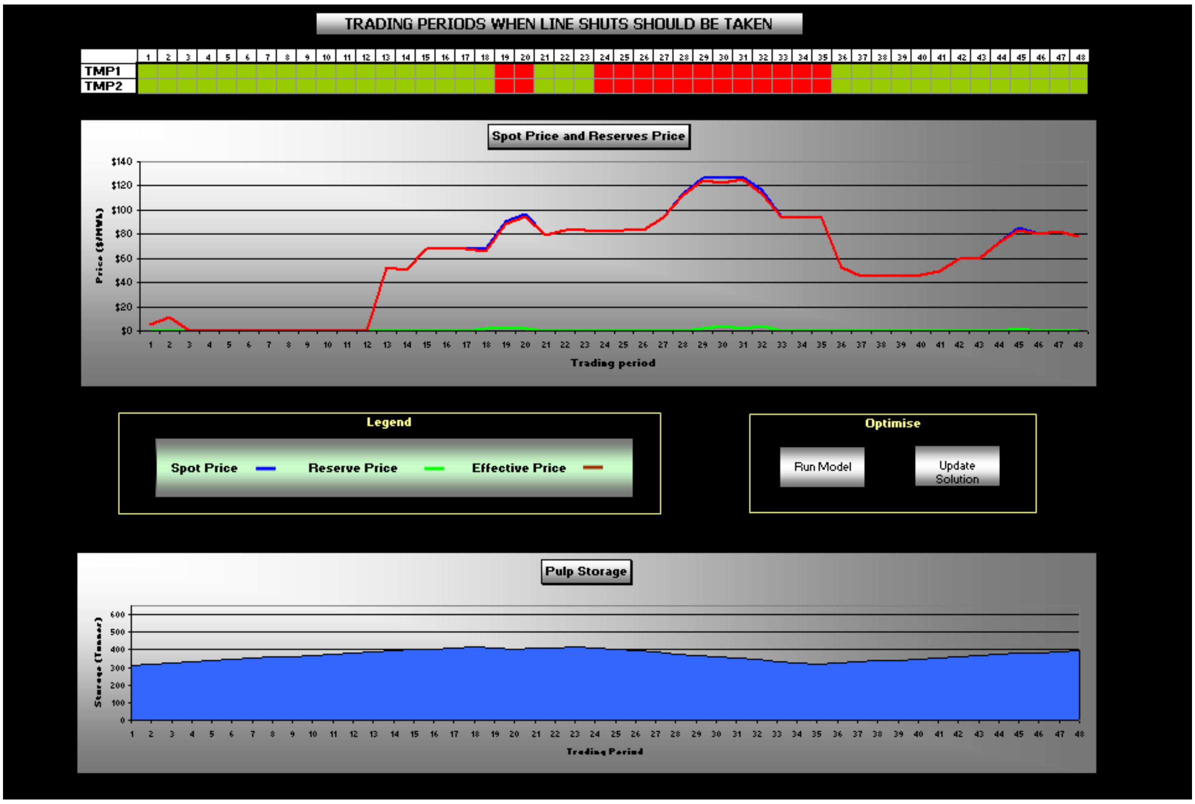

Figure 3: Example 2 Solution from PowerTool

2.7 Conclusion

The PowerTool model is used every day by operators to make shutdown decisions at the newsprint mill in Kawerau. Before each daily run of PowerTool the cutting planes that define the default value function Ψ are altered to reflect current operating conditions, and the operator's informed view of future electricity prices. For example if it is known that a planned transmission outage might increase prices in certain periods in the following day then the values of a_k and b_k are increased. Currently this operator intervention is essential, but the opportunity exists for an automated system based on improved short-term price analytics.

References

[1] Philpott A.B and G. Pritchard. An electricity procurement model with energy and peak charges. In H.I. Gassman and W.T. Ziemba, editors, *Stochastic Programming: Applications in Finance, Energy, Planning and Logistics*. World Scientific, 2013.

[2] A.B. Philpott and G.R. Everett. Pulp mill electricity demand management. In *Proceedings of the 37th Annual Conference of ORSNZ*, pages 55–63, 2002.