Supply Chain Optimisation in the Paper Industry

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Abstract

We describe the formulation and development of a supply-chain optimisation model for Fletcher Challenge Paper Australasia (FCPA). This model, known as Paper Industry Value Optimisation Tool (PIVOT), is a large mixed integer program that finds an optimal allocation of supplier to mill, product to paper machine, and paper machine to customer, while at the same time modelling many of the supply chain details and nuances which are peculiar to FCPA. PIVOT has assisted FCPA in solving a number strategic and tactical decision problems, and provided significant economic benefits for the company.

1 Introduction

In late 1997 Fletcher Challenge Paper increased its share holding in Australian Newsprint Mills (ANM) from 50% to 100%. This led to the formation of a new entity called Fletcher Challenge Paper Australasia (FCPA), with paper mills in Kawerau-New Zealand, Boyer-Tasmania and Albury-New South Wales. These three mills have a combined paper capacity of around 945,000 tonnes per year. Combined sales in the year to June 30, 1999 were $NZ 1,115 million [1].

The acquisition of extra production capacity and increased Australian market share raised the possibility of rationalising pulp and paper production in Australia and New Zealand to exploit possible synergies that might emerge from this acquisition. The objective of this rationalisation was to reduce the costs of paper production while ensuring high returns from the markets that were supplied. In order to understand the complicated tradeoffs between the costs of raw materials procurement, production costs of pulp and paper products, and delivery and supply of finished products, FCPA undertook the development of a supply chain optimisation model.

The resulting model is known in Fletcher Challenge as Paper Industry Value Optimisation Tool (PIVOT). It is a large mixed integer program that has been created using AMPL and Cplex 6.5. Using budget sales and manufacturing data as inputs, PIVOT finds an optimal allocation of supplier to mill, product to paper machine, and paper machine to customer, while at the same time modelling all necessary supply chain details and nuances. In this paper we will describe the formulation and development of PIVOT, and give an overview of some of the strategic and tactical decision problems that it has helped to solve. We also shall comment on the cultural changes that it has brought to the FCPA organisation, and the significant economic benefits that it has provided.

In the next section we describe the paper-making process, and outline the structure of PIVOT. In section 3 we formulate the model as a mixed integer programming problem. Section 4 describes how the model is used in FCPA, and some concluding remarks are made in section 5.

2 Making Paper

Manufacturing paper is a capital intensive business, and the scale of operations are large. Paper machines generally run 24 hours a day, 365 days a year, shutting down only for routine maintenance. Hundreds of millions of dollars are spent each year on raw materials and their transportation, pulp and paper production and storage, and distribution of finished products to customers. This process is often called the paper industry supply chain.

A simplified schematic of the paper making process is shown in Figure 1. This diagram represents the processes and plant specific to the Tasman mill at Kawerau.

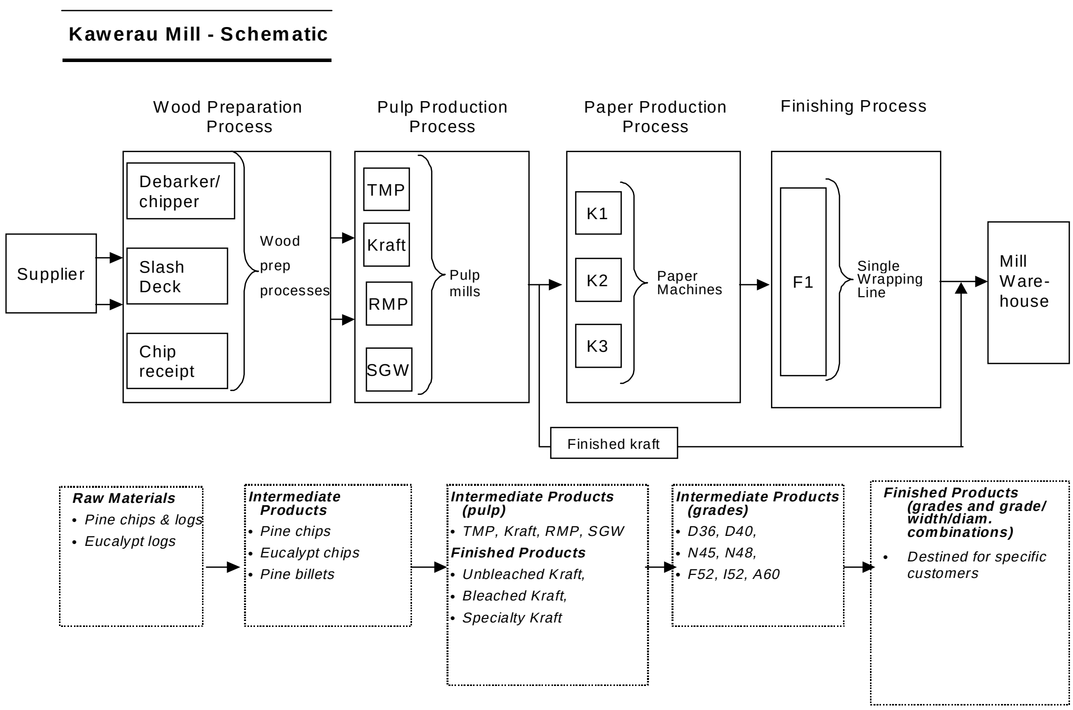

Figure1: Paper Making Process at Kawerau Mill

2.1 Paper Machine Operations

In order to understand the paper industry supply chain, it is necessary to understand how pulp and paper is manufactured. Fundamentally a paper machine converts cellulose fibres into paper. Equipment in the paper mill takes different pulp streams with different properties, and blends them in varying proportions to produce a mix of pulp, known as furnish. This furnish is supplied to the paper machine, which sprays it onto a wide mesh (or in between two wide meshes) to form a sheet of paper. From here on the paper machine removes water from the paper sheet. Water is drained out of the paper in the former section, squeezed out in the press section, and then evaporated in the dryer section. The paper is then smoothed by passing it through high pressure rollers in the calender stack. It is then taken off the paper machine in large jumbo reels, and wound onto solid cores to the width and diameter required by the customer.

2.2 Pulp Manufacturing Operations

Newsprint is currently the main grade produced at each of FCPA's mills. Telephone directory paper, and higher brightness newsprint are also manufactured. Different paper grades have different properties, and therefore require different blends of pulp in the furnish. Pulp types are characterised by wood type, and pulping process.

The *kraft pulping process* basically cooks chips under high temperature and pressure, utilising chemicals to dissolve the lignin which binds the wood fibres, producing pulp. The *Thermo Mechanical* (TMP) and *Refiner Mechanical* (RMP) processes are similar to each other, basically grinding wood chips between plate refiners. The *Cold Caustic Soda* (CCS) process is also a mechanical process, but utilises some chemicals to aid the wood decomposition. The *Stone Groundwood* (SGW) process involves using large abrasive stones to grind logs into pulp. Different pulping processes are available at each mill. All mills have the ability to manufacture TMP. In addition Albury produces recycled fibre (RCF) from waste paper, and Boyer has a CCS pulping process. The Tasman mill at Kawerau has neither of these but has a SGW and a RMP process.

Each of the pulping processes have different costs. There are also limits on each pulp mill's capacity. Currently the Tasman mill supplies kraft pulp to both Albury and Boyer, and the Albury mill supplies RCF to the Boyer mill. It is possible for other cross-supply arrangements to proceed, if required.

Other processes bleach pulp and defibrillate, or refine, the fibres until the pulp stream has the desired brightness, strength and drainage properties. Additional raw materials (such as clay fillers) are needed in small percentages to achieve the optical and printing properties required of each paper grade.

2.3 Raw Material Procurement

FCPA's three mills have many similarities, and all produce similar paper products. However each mill uses different fibre sources, and different pulping processes. The result is a number of raw material supply options. Upstream of the pulp process wood preparation at all three mills and waste paper collection for the Albury mill are required. Wood, in the form of pine and eucalyptus logs, is brought to the mills from a number of wood suppliers. It is debarked and chipped for the kraft, TMP, RMP and CCS processes. Wood is debarked and cut into 1.2 metre long billets for the SGW process. Wood is also purchased in the form of chips, normally from sawmills. Finally, old magazines and newspapers are collected throughout Australia and transported to the Albury mill.

2.4 Transportation of Finished Paper Products

Finished paper is transported by either truck, rail, or ship, or some combination of these. The mode of transport is dependent on the location of the mill and customer. Each mill can theoretically supply paper to any customer, but obviously mills located closer to customers than others will have lower freight costs. Considerable freight savings are attained if the same truck which brings waste paper to Albury is used to transport finished paper back to customers from the same city.

2.5 Cost and Efficiency

Not only do the three mills have different raw material and pulp production costs, but each of the six paper machines have different manufacturing costs for different grades. There are variations in capacity between the paper machines, which result from variations in machine width and speed. Also some machines are more efficient at manufacturing certain grades of paper than other machines, due to a number of design differences.

A further complication is the effect of manufacturing a variety of paper grades on one paper machine. Every time the machine changes grade, there are losses of finished product and increases in manufacturing costs. These effects on machine capacity and manufacturing costs vary by machine, and also vary with the additional grades required.

3 The PIVOT model

PIVOT is a mixed integer programming model. In this section we give a general mathematical description of PIVOT. We begin by looking at the paper production constraints.

3.1 Production

Suppose there are M machines indexed by m, and J paper products indexed by j. For each machine m we must choose a set of products to produce on that machine. We call this set of products a *cluster*. The choice of the cluster for any machine affects the throughput of the machine, as well as its variable cost. (The current throughput of machine m when making product j is a_{mj} tonnes per year.) For example, making two products on a machine throughout a year incurs some downtime associated with switching products. Reducing the allocation to one product avoids this downtime, effectively increasing the capacity of the machine, and any excess costs in running two products throughout the year are saved. For each machine there is also a capital cost for each cluster that represents the fixed cost of enabling the machine to make new products.

We define a collection of L clusters indexed by l. For simplicity we assume that these are the same for each machine, though in practice they will vary with machine. It is useful to define a parameter

$$b_{jl} = \begin{cases} 1 & , \quad \text{if cluster } l \text{ makes product } j, \\ 0 & , \quad \text{otherwise.} \end{cases}$$

To determine an allocation of clusters to machines we use binary variables

$$\delta_{ml} = \begin{cases} 1 & , \quad \text{if we allocate the cluster } l \text{ to machine } m, \\ 0 & , \quad \text{otherwise.} \end{cases}$$

Thus the term $\sum_{l=1}^{L} b_{jl}\delta_{ml}$ is equal to 1 if and only if machine m makes product j. To ensure that each machine makes a unique cluster of products we add the constraint

$$\sum_{l=1}^{L} \delta_{ml} = 1, \qquad m = 1, \ldots, M. \tag{1}$$

(We ensure that production on any machine is limited to products in its allocated cluster using the constraint (2) below.)

The first five production constraints in the model relate to the capacity utilisation of each machine as compared with the status quo. Allocating cluster l to machine m gives different production efficiencies for each product. To model this we define the following variables.

$x_{mj} =$ tonnes of product j made on machine m,
$e_{mlj} =$ years production of product j lost from producing cluster l on machine m,
$f_{mlj} =$ years production of product j gained from producing cluster l on machine m.

(All variables are assumed to be nonnegative unless stated otherwise). Suppose allocating cluster l to machine m decreases the time to make each tonne of product j by S_{mlj} years, or increases the time to make each tonne of product j by T_{mlj} years. Then the time f_{mlj} saved in making product j on machine m using cluster l satisfies

$$f_{mlj} \leq b_{jl}\delta_{ml}, \qquad m = 1, \ldots, M, \; l = 1, \ldots, L, \; j = 1, \ldots, J,$$

$$f_{mlj} \leq -b_{jl}\delta_{ml} + 1 + S_{mlj}x_{mj}, \qquad m = 1, \ldots, M, \; l = 1, \ldots, L, \; j = 1, \ldots, J.$$

The time e_{mlj} lost in making product j on machine m using cluster l satisfies

$$e_{mlj} \geq b_{jl}\delta_{ml} - 1 + T_{mlj}x_{mj}, \qquad m = 1, \ldots, M, \; l = 1, \ldots, L, \; j = 1, \ldots, J,$$

$$e_{mlj} \leq b_{jl}\delta_{ml}, \qquad m = 1, \ldots, M, \; l = 1, \ldots, L, \; j = 1, \ldots, J.$$

The annual utilisation of machine m is then represented by

$$\sum_{j=1}^{J} \frac{x_{mj}}{a_{mj}} + \sum_{j=1}^{J}\sum_{l=1}^{L}(e_{mlj} - f_{mlj}) \leq 1, \qquad m = 1, \ldots, M.$$

The next three production constraints relate to the change in variable cost for each machine as compared with the status quo. Suppose allocating cluster l to machine m decreases the variable cost to make each tonne of product in l by a given amount q_{ml}, or increases the variable cost to make each tonne of product in l by given amount p_{ml}. We define the following variables:

$P_{ml} =$ extra annual variable cost when producing cluster l on machine m.
$Q_{ml} =$ annual variable cost saved when producing cluster l on machine m.

Then, setting G to be an upper bound on P_{ml}, and H to be an upper bound on Q_{ml} we obtain

$$P_{ml} - G\delta_{ml} \geq -G + p_{ml}\sum_{j=1}^{J} x_{mj}, \qquad m = 1, \ldots, M,\ l = 1, \ldots, L,$$

$$Q_{ml} \leq q_{ml}\sum_{j=1}^{J} x_{mj}, \qquad m = 1, \ldots, M,\ l = 1, \ldots, L,$$

$$Q_{ml} \leq H\delta_{ml}, \qquad m = 1, \ldots, M,\ l = 1, \ldots, L.$$

3.2 Raw material constraints

As mentioned above each plant has different production processes available, each requiring raw materials in different proportions. Suppose there are R different raw material sources indexed by r. Denote by c_{mjr} the given number of tonnes of raw material r required to make one tonne of product j on machine m. Then w_{mr}, the tonnes of raw material used by machine m is gven by

$$\sum_{j=1}^{J} c_{mjr}x_{mj} = w_{mr}, \qquad m = 1, \ldots, M, \qquad r = 1, \ldots, R.$$

3.3 Market constraints

Suppose that there are K markets indexed by k. The market inputs for PIVOT consist of demands d_{jk} and prices π_{jk} for product j in market k. We define

$y_{mjk} =$ tonnes of product j made on machine m and shipped to market k.

This gives the following constraints:

$$\sum_{k=1}^{K} y_{mjk} = x_{mj}, \qquad m = 1, \ldots, M, \qquad j = 1, \ldots, J,$$

$$\sum_{m=1}^{M} y_{mjk} \leq d_{jk}, \qquad k = 1, \ldots, K, \qquad j = 1, \ldots, J,$$

$$y_{mjk} \leq (\sum_{l=1}^{L} b_{jl}\delta_{ml})d_{jk}, \qquad m = 1, \ldots, M,\ k = 1, \ldots, K,\ j = 1, \ldots, J. \quad (2)$$

3.4 Objective function

The aim of PIVOT is to understand and improve the performance of the FCPA supply chain. By judiciously changing the objective function, the model can be used to seek improvements in different aspects of the company's operations. The objective function most commonly used was annual earnings. This is represented using the following parameters.

$\pi_{jk} =$	price for product j in market k,
$\sigma_{mjk} =$	shipping cost of product j from machine m to market j.
$\mu_{mj} =$	current variable cost of producing j on machine m
κ_{ml}	annual investment required to make cluster l on machine m
$\rho_{mr} =$	procurement and process cost of raw material r for machine m
$F_m =$	fixed costs of running machine m

The earnings for machine m can now be written down as

$$\sum_{j=1}^{J}\sum_{k=1}^{K}(\pi_{jk} - \sigma_{mjk})y_{mjk} - \sum_{j=1}^{J}\mu_{mj}x_{mj} - \sum_{l=1}^{L}(\kappa_{ml}\delta_{ml} + P_{ml} - Q_{ml}) - \sum_{r=1}^{R}\rho_{mr}w_{mr} - F_m.$$

We seek to maximise the sum of these earnings over $m = 1, 2, \ldots, M$.

3.5 Mill-specific constraints

The PIVOT model described above is close to a generic supply-chain model. In addition to the features above there were a number of constraints in the PIVOT model that required special attention. We look briefly at two instances of these.

3.5.1 Backhauling at Albury

In PIVOT the distribution of product j from machine m to market k incurs a shipping cost σ_{mjk} per tonne. This is an approximation to the true cost which has a fixed as well as a variable component. In most cases this approximation is close enough to the true cost to be valid. At Albury, however, the RCF waste from Sydney, Melbourne, Canberra, Brisbane and Adelaide is transported to the mill using the same fleet of trucks as those that carry the paper in the reverse direction. This represents a considerable cost saving.

To model this situation in PIVOT, we divide each of the appropriate y_{mjk} and w_{mr} variables into two nonnegative variables

$$y_{mjk} = y_{mjk}(b) + y_{mjk}(u)$$

$$w_{mr} = w_{mr}(b) + w_{mr}(u)$$

Here $y_{mjk}(b)$ denotes the number of tonnes of paper transported in trucks that return *balanced* with $w_{mr}(b)$ tonnes of waste. An additional constraint

$$w_{mr}(b) = \alpha y_{mjk}(b)$$

reflects the fact that trucks carry fewer tonnes of waste than paper. Each tonne of balanced transportation can be shipped at a lower cost than the remaining *unbalanced* transport ($y_{mjk}(u)$ and $w_{mr}(u)$).

3.5.2 Bleaching at Boyer

The FCPA mill at Boyer in Tasmania has two paper machines and a bleach plant. When a Boyer machine produces bleached paper, all the pulp produced is bleached. If they are making unbleached paper on the other machine then the bleached pulp is dyed back to close to its original state. This means that there is an extra cost B per tonne of unbleached paper made at Boyer while producing bleached paper.

This is modelled in PIVOT using a cost adjustment variable A that is subtracted from the objective function. Suppose we let $m = 1, 2$ denote the two Boyer machines, and j denote bleached paper. The value of the variable A is determined using the following constraints:

$$t_1 \geq \frac{x_{1j}}{a_{1j}} - \frac{x_{2j}}{a_{2j}}$$

$$t_2 \geq \frac{x_{2j}}{a_{2j}} - \frac{x_{1j}}{a_{1j}}$$

$$A = (t_1 \sum_{i \neq j} a_{2i} + t_2 \sum_{i \neq j} a_{1i})B.$$

3.6 Machine shutdown

PIVOT can be used to investigate whether it is advantageous to shut down any paper machines. This saves the fixed cost of running the machine, but means that we cannot allocate any clusters to it. To model this we define

$$\epsilon_m = \begin{cases} 1 & , \text{ if we keep machine } m \text{ running} \\ 0 & , \text{ otherwise,} \end{cases}$$

and change the last term in the objective function to $\sum_{m=1}^{M} F_m \epsilon_m$. Now constraint (1) becomes

$$\sum_{l=1}^{L} \delta_{ml} \leq \epsilon_m, \qquad m = 1, \ldots, M.$$

4 The Use of PIVOT

Before the PIVOT model could be used a major exercise had to be undertaken across the FCPA organisation, collating all supply chain costs. Once these costs were gathered a small group of employees at the Fletcher Paper head office commenced a supply chain optimisation process using the PIVOT model.

The first step was to constrain PIVOT so that it produced a solution that matched the budgeted supply, manufacturing, and sales plans. This verified that the model was functioning correctly, as well as providing a benchmark against which all further solutions could be compared.

A number of versions of the model were then run. This entailed relaxing the benchmark constraints, and using PIVOT to investigate a number of pertinent questions. The first set of these looked at relaxing some current contractual obligations to see the extent to which these were constraining the solution. Secondly the efficiency and cost adjustments were varied to test the sensitivity of the model to the estimated values. The model was then used to investigate some of the alternative production plans obtained by imposing various management constraints. The flexibility afforded by using a modelling language (AMPL) was a key factor in enabling this exploration to be carried out easily.

Finally an acceptable optimal solution was determined. This solution was compared with the benchmark case, and differences were highlighted. It was important to understand how the additional value was created, so that the FCPA organisation would be convinced and prepared to change business practices to emulate the plan recommended by the model. It turned out that costs were increased in some areas of the business, but were offset by larger savings in other areas. The overall increase in profitability was a very significant amount, and certainly justified the effort invested in the PIVOT project.

As well as delivering improvements in profitability the development of PIVOT has accompanied a cultural change in FCPA, which began when the remaining 50% share in ANM was purchased by Fletcher Paper in 1997. Obviously a large amount of this change can be attributed to re-structuring and management leadership. However PIVOT also played a role, and helped individuals throughout the organisation grasp how the different segments of the company fitted together as part of an overall system.

In fact the origins of PIVOT date back to 1996, prior to the company merger. At that time Tasman was considering its strategic direction, and how it should place itself given the market trends towards improved newsprint grades. It was realised that Tasman could not make decisions in isolation, as any capital decisions and changes in production would have an effect on ANM. Previously all strategic planning analysis involved using spreadsheet business models. By and large these spreadsheets were used to very good effect, but as the company grew larger, the increase in the number of product allocation options made it more difficult to obtain provably optimal production plans. It was decided that the best approach was to utililise mixed integer programming techniques to produce a production planning and product allocation model. In late 1996, capital expansion options were added to this model to form what was then called ATOM (ANM-Tasman optimisation model).

Although ATOM produced good results, its value was not fully appreciated until after the 1997 merger. At that time a team was established to investigate synergy gains, and one of the items investigated was the allocation of products to machines and customers. This project fitted together well with the ATOM model, and essentially provided data to ATOM. It was decided that the scope of ATOM should be expanded to include raw material procurement and a number of other wider supply chain details. Given this, and the name change of the company, ATOM evolved into PIVOT.

The interest in supply-chain optimistaion has grown considerably at FCPA and recently the company created a new position of Supply Chain Manager. This role has a number of functions, one being the ongoing management and use of PIVOT to continually test new assertions, or to evaluate changes to any supply chain parameters.

Another recent development has been a major project to evaluate a large number of capital investment decisions, which are dependent on market forecasts. This project has involved using a simplified version of PIVOT as the core of a time-staged model that includes a number of capital options. The resulting model is a very large mixed integer program, which provides decision makers in the company with optimal capital plans. A simplified version of PIVOT was also used to evaluate the efficiency gains which could be achieved if all the paper machines in the Fletcher Challenge group were pooled together.

5 Conclusions

Development of PIVOT was largely carried out in-house by individuals who are well versed in both the paper industry and operations research techniques. Because of the need to model unusual industry-specific constraints, off-the-shelf supply chain packages were not adopted by the company. Instead the modelling language AMPL and Cplex solver were chosen because of their flexibility to accommodate a wide range of modelling details. This approach has created a living model, which is able to adapt to suit ongoing changes in business conditions, as well as creating a confidence within the company to use PIVOT as a planning tool.

The FCPA supply chain is a large and complicated process. The PIVOT model provides FCPA with a powerful decision aid with which to optimise its supply chain variables, and create value. The resulting economic benefits are substantial. PIVOT has established itself in the company as state of the art technology, and it is often consulted by management to evaluate new ideas and the effect of changes to supply chain parameters.

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[1] Fletcher Challenge Paper Annual Review, 1999.