Capital Planning Under Uncertainty at Fletcher Challenge Canada

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Abstract

Fletcher Challenge Canada Limited (FCCL) is a large pulp and paper producer in British Columbia. FCCL has traditionally been a newsprint producer and has kept pace with increasingly stringent quality requirements by continually rebuilding existing paper machines and ancillary plant. The company is also considering other options, including converting machines to different grades of paper. Because of the complexity associated with the large number of possible options available, the company decided to develop an optimisation model to assist with this strategic decision making. Market forecasts, capital requirements, production and other pertinent data were collated for a ten year planning horizon, and incorporated into a multi-period optimisation model.. Initially this model proved to be extremely difficult to solve. Based on knowledge of the business a number of extra constraints were added that improved its performance and allowed optimal solutions to be obtained. The model has proved to be successful in challenging entrenched views within FCCL regarding strategic direction, and stimulating wide ranging thought and discussion.

1 Introduction

Fletcher Challenge Canada Limited (FCCL) is a partly owned subsidiary of Norske Skog Limited, the second largest newsprint producer in the world. Combined sales in the 1999 fiscal year for FCCL were $CAD 1.3 billion, from deliveries of 920,000 tonnes of newsprint, directory and enhanced printing papers, and 860,000 tonnes of market pulp. The pulp and paper industry is exposed to the vagaries of international commodity markets. It is known as being especially capital intensive and has struggled to deliver satisfactory returns to share holders, relative to other industries. FCCL has traditionally been a newsprint producer. Newspaper publishers are competing for advertising revenue in the face of strong opposition from other media, including the internet. As a result, newsprint specifications are continually being raised. FCCL has historically kept pace with these quality requirements by continually rebuilding existing paper machines and ancillary plant, but recently the company has wished to take a longer view, and consider other options for the paper business, including converting machines to different grades of paper, building completely new machines and divesting in existing machines.

Currently FCCL owns and operates two paper mills located on Vancouver Island. These two mills are named Elk Falls and Crofton. Both have three paper machines that currently produce newsprint, directory and enhanced writing grades of paper. The paper-making process requires pulp mixes, known as furnishes, to be supplied to paper machines that first form a wet sheet of paper and subsequently squeeze and then dry the paper. Pulp mixes comprise wood fibres, clay and synthetic fillers, chemicals and water. FCCL purchases wood chips and converts them into pulp in a Thermo-Mechanical Pulp (TMP) mill at both mills and also in a Refiner Mechanical Pulp (RMP) mill at Crofton. Elk Falls has a peroxide plant that is used to bleach the pulp so that higher brightness paper can be produced. Dried de-inked pulp (DIP) is also purchased and diluted in a pulp mixing facility at each mill. Kraft pulp is produced at both mills. Readers are referred to previous publications [2] for a more detailed description of the paper making process.

A typical paper machine can be modified incrementally by adding or upgrading capital items at different sections of the machine. For instance every paper machine has at least one headbox, through which pulp is sprayed onto, or into, a forming section. There are a number of types of headboxes, each suited to a different set of paper grades. Figure 1 shows an example of a grade capital array, where the crosses indicate the new capital items that are required to produce each grade. A separate array is necessary for each paper machine, because of design and cost differences from one machine to another.

	Grade1	Grade2	Grade3	Grade4	Grade5
Capital Item 1	X	X	X	X	X
Capital Item 2	X		X		
Capital Item 3	X	X	X	X	X
Capital Item 4	X				
Capital Item 5	X				
Capital Item 6		X			

Figure 1 – Grade Capital Array

In order to develop a long-term capital plan, FCCL have recently undertaken the development of a multi-period optimisation model. This model, known within FCCL as SOCRATES (Strategic Optimisation of Capital and Resource Allocations Traversing Extreme Scenarios), is an attempt to construct a capital expansion and improvement plan for each machine that maximises the return to FCCL over a ten year planning horizon. SOCRATES is a very large mixed integer program, developed using AMPL [3] and Cplex 6.5 [4], both available from ILOG [5]. The equations in the model are based on those of PIVOT (see [2]) with a number of changes to make the model specific to FCCL. To be able to run the model themselves, FCCL purchased a copy of AMPL/Cplex and trained one of their senior staff members in their use.

Previous work on optimisation models for the paper industry can be found in a number of papers (see e.g. [2], [6], [7], [8]). In this paper we focus on the features that distinguish SOCRATES from PIVOT, in particular the capital constraints and multi-period aspects of the model. We also discuss the extra constraints and Cplex options that were necessary in order to facilitate returning optimal solutions in a reasonable time. We will also comment on how the model has thus far been used by FCCL. Finally we shall briefly describe recent work we have undertaken to extend SOCRATES to a stochastic optimisation model.

2 Formulation of SOCRATES

In this section we provide a mathematical description of SOCRATES. We shall focus on a multi-period deterministic version of this model and show in a later section how this can be made into a stochastic planning model. Suppose there are *N* mills indexed by *n*, *M* paper machines indexed by *m*, *C* capital items indexed by *c*, *J* paper grades indexed by *j* and *T* planning years indexed by *t*. We let *M{n}* be the set of machines located at mill *n*. The central decision variables in this model are the nonnegative variables:

x_{mjt} = the number of tonnes of paper of grade *j* produced on machine *m* in year *t*,

and the binary decision variables

$$\sigma_{mcs} = \begin{cases} 1, \text{ if capital item } c \text{ is installed on machine } m \text{ in year } s, \\ 0, \text{ otherwise.} \end{cases}$$

We proceed to show how the different aspects of SOCRATES are formulated using these and other variables.

2.1 Capital Requirements and Costs

Let us define the set *S* indexed by *s* being equal to the set of planning years *T* plus one additional year. We assume that capital item *c* is installed at most once, so

$$\sum_{s \in S} \sigma_{mcs} \le 1, \qquad m = 1,\ldots,M, \qquad c = 1, \ldots C.$$

This means that for each $t=1,2,\ldots,T$, the expression

$$\sum_{s \le t} \sigma_{mcs} = \begin{cases} 1, \text{ if capital item } c \text{ is available on machine } m \text{ in year } t, \\ 0, \text{ otherwise.} \end{cases}$$

Similarly machines can only be shut down at most once, so for each $s=1,2,\ldots,T+1$, we define binary decision variables

$$\alpha_{ms} = \begin{cases} 1, \text{ if machine } m \text{ is shut down in year } s, \\ 0, \text{ otherwise.} \end{cases}$$

and require

$$\sum_{s \in S} \alpha_{ms} = 1 \qquad m = 1,\ldots,M.$$

Therefore for each $t=1,2,\ldots,T$, the expression

$$\sum_{s>t} \alpha_{ms} = \begin{cases} 1, \text{ if machine } m \text{ is still open in year } t, \\ 0, \text{ otherwise.} \end{cases}$$

(Observe that as S includes one more year than T, so a machine that is not closed will in fact set $\alpha_{ms} = 1$ in the year $s=T+1$.)

In addition to the decisions determining capital and machine closure we require binary decision variables determining which grades are produced on given machines. Let

$$\rho_{mjt} = \begin{cases} 1, \text{ if grade } j \text{ is produced on machine } m \text{ in year } t, \\ 0, \text{ otherwise.} \end{cases}$$

Then we can only produce on machines that have not been closed,

$$\rho_{mjt} \leq \sum_{s>t} \alpha_{ms}, \qquad m = 1,\ldots,M, \quad t = 1,\ldots T,$$

and on machines having the required capital;

$$\rho_{mjt} \leq \sum_{s \leq t} \sigma_{mcs}, \qquad \text{if machine } m \text{ requires capital item } c \text{ to produce grade } j. \tag{1}$$

The capital cost of installing capital item c on machine m in year t is denoted by K_{mct}, and is incurred on average a year before deployment. This gives

$$K_{mct} = I_{mc}\,\sigma_{mct+1}, \qquad m = 1,\ldots,M, \qquad c = 1, \ldots C, \qquad t = 2, \ldots, T.$$

$$\sigma_{mct} = 0, \qquad m = 1,\ldots,M, \qquad c = 1, \ldots C, \qquad t = 1.$$

2.2 Production

Each machine will have an annual capacity for each grade of a_{mjt} tonnes. This gives the following inequality:

$$\sum_{j=1}^{J} \frac{x_{mjt}}{a_{mjt}} \leq 1, \qquad m=1,\ldots,M, \quad t=1,\ldots,T.$$

We restrict production of grade j in year t to those machines m that have either invested in capital items necessary to make grade j, thereby allowing $\rho_{mjt} = 1$ by equation (1), or else already have the ability to make grade j, and therefore ρ_{mjt} is unrestricted. This gives

$$x_{mjt} \leq \rho_{mjt}\, a_{mjt}, \qquad m=1,\ldots,M, \quad j = 1,\ldots J, \quad t=1,\ldots,T.$$

2.3 Raw Material Requirements

FCCL purchases a number of raw materials (fibre, wood and chemicals) for both mills. In general the company pays marginally increasing prices for these, although in the case of de-inked pulp (DIP) and some additives, FCCL receives quantity discounts, a feature that requires integer variables to model. Apart from these special constraints the raw material useage amounts to a fixed proportion of the production of each grade, with some substitution of fibre types possible. The raw material useage is thus defined by a set of linear equations.

There are however a number of various capacity options for some raw materials, requiring specific constraints to be written. For instance the peroxide plant at Crofton that is used to bleach TMP pulp, can be expanded incrementally by B_h (in H stages indexed by h) to yield a total extra capacity in year t denoted by EC_{nft}, where n denotes Crofton and f is the raw material index of bleached TMP. To model this we define binary decision variables

$$\beta_{hs} = \begin{cases} 1, \text{ if the TMP plant stage } h \text{ capacity increases in year } s, \\ 0, \text{ otherwise.} \end{cases}$$

giving

$$EC_{nft} \leq \sum_{h=1}^{H} \Big(\sum_{s\leq t} \beta_{hs}\Big) B_h, \quad f = \text{bleached TMP}, \; n = \text{Crofton}$$

$$\sum_{s\leq t} \beta_{hs} \leq \sum_{s\leq t} \beta_{h-1s}, \qquad h > 1.$$

The capital costs incurred are then $\sum_{h=1}^{H} \Big(\sum_{s\leq t} \beta_{hs}\Big) J_h$ where J_h is the incremental capacity cost for stage h.

2.3 Market Constraints

Suppose that there are K markets indexed by k. The market inputs for SOCRATES consist of demands d_{jk}, prices p_{jk} and freight costs f_{mjk} for grade j in market k in year t. We define

y_{mjkt} = tonnes of grade j made on machine m and delivered to market k in year t.

This gives the following constraints, which ensure that deliveries do not exceed either market demand, or paper machine capacity.

$$\sum_{k=1}^{K} y_{mjkt} = x_{mjt}, \qquad m = 1,\ldots, M, \quad j = 1, \ldots,J, \quad t = 1, \ldots,T.$$

$$\sum_{m=1}^{M} y_{mjkt} \leq d_{jkt}, \qquad k = 1,\ldots, K, \quad j = 1, \ldots,J, \quad t = 1, \ldots,T.$$

Sales, S, are simply the price of grade j at market k multiplied by the number of tonnes supplied:

$$S_t = \sum_{m=1}^{M} \sum_{j=1}^{J} \sum_{k=1}^{K} p_{jkt} y_{mjkt}, \qquad t = 1, \ldots, T.$$

Freight Costs, F, are the cost of delivering grade j, from machine m to market k multiplied by the number of tonnes supplied:

$$F_t = \sum_{m=1}^{M} \sum_{j=1}^{J} \sum_{k=1}^{K} f_{mjkt} y_{mjkt}, \qquad t = 1, \ldots, T.$$

2.4 Fixed Costs

Each mill and paper machine has annual fixed costs FN_{nt}, and FM_{mt} respectively. As long as a mill or paper machine is not closed, these costs must be incurred.

We define binary decision variables for each mill:

$$\mu_{ns} = \begin{cases} 1, \text{ if the mill } n \text{ is permanently closed in year } s, \\ 0, \text{ otherwise.} \end{cases}$$

As with α_{ms}, summing μ_{ns} over s up to and including any year t will be zero, if mill n has not closed. We also add constraints to ensure that mill n can only close once, and if it remains open for every year t, will be shut in the artificial year $s=T+1$.

$$\sum_{s \in S} \mu_{ns} = 1, \qquad n = 1, \ldots N.$$

A mill can only be permanently closed when all the machines at that mill have been closed.

$$\mu_{ns} \le \sum_{s \le t} \alpha_{ms}, n = 1, \ldots N, \qquad m = 1, \ldots, M\{n\}, \qquad t = 1, \ldots T.$$

We define Z_t to be the total annual fixed costs in year t:

$$Z_t = \sum_{m=1}^{M} \Big(\sum_{s>t} \alpha_{ms}\Big) FM_{mt} + \sum_{n=1}^{N} \Big(\sum_{s>t} \mu_{ns}\Big) FN_{nt}, \qquad t = 1, \ldots T.$$

2.6 Objective Function

The purpose of the SOCRATES model is to provide capital plans and associated production, marketing and supply chain plans to maximise earnings for FCCL over the next ten years. Annual earnings (AE_t) for each year are equal to sales less the sum of raw material costs, pulp processing variable costs, paper machine variable costs, mill and paper machine fixed costs, freight costs and capital costs.

The terminal value (TV) of the business is defined as being equal to the earnings in the final year of the planning period, projected for a further ten years and appropriately discounted at a discount rate δ.

$$TV = \sum_{t=1}^{T} \frac{AE_T}{(1+\delta)^t}.$$

The model objective value is then defined as being equal to the sum of discounted annual earnings, plus the discounted terminal value of the business.

$$\text{Objective Value} = \sum_{t=1}^{T} \frac{AE_t + TV}{(1+\delta)^t}$$

3. Model Implementation and Solution

3.1 Formulation strengthening

The initial formulation of Socrates, as described above, was implemented using AMPL and Cplex 6.5, both available from ILOG [3]. This formulation was unable to return optimal solutions, due to the large number (3,244) of binary decision variables. We proceed to describe how the structure of the model can be used to reduce the number of binary variables required, whilst ensuring that the optimal solution is not compromised.

First observe that the variables σ_{mcs} are naturally binary, allowing us to instead define them as real variables. This occurs because capital costs are minimised by making $\sigma_{mcs} = 0$ for all years s up to the year t having $\rho_{mjt} = 1$, at which point the optimiser may choose $\sigma_{mct} = 1$. A second simplifying observation is that many of the grades have zero demand in some of the years t in T. This is a function of the change in specifications, e.g. a grade j_1 being consumed in early planning years may be superseded by a grade j_2 with improved quality specifications in later years. This observation allows us to add constraints so that ρ_{mjt} is zero if total demand for grade j is zero

$$\rho_{mjt} \le \sum_{k=1}^{K} d_{jkt} \qquad m = 1,\ldots,M, \quad j = 1,\ldots,J, \qquad t = 1,\ldots T.$$

Furthermore some of the machines are incapable of making certain paper grades regardless of capital expenditure, so we can set $\rho_{mjt} = 0$ for these grades and machines. Similarly, for each machine m in year t that has not closed we can set the ρ_{mjt} variables to be one for those products j that can be produced without any capital expenditure. These constraints apply to only those grades for which total market demand is nonzero and machine capacity is nonzero.

In practice the collection of capital items required for some grades is identical to others. (e.g. grades 4 and 5 in Figure 1). For these grades with common capital items, the ρ_{mjt} variables can be set equal to each other, provided that none has a machine capacity of zero or a total market demand of zero. Similarly if machine m is capable of making grade j in year t, then it will generally be capable of making grade j in year $t+1$, so we impose the constraint $\rho_{mjt} \geq \rho_{mjt+1}$, except when a machine closes, total market demand for grade j shrinks to zero, or another grade requires the same capital items.

3.2 Cplex Branch and Bound Directives

Cplex 6.5. allows the user to have some control over branching directions and priorities. We adopted a trial and error process for using these features to guide the branch-and-bound algorithm. We set the branch direction for the ρ_{mjt} variables to be *down* for unpromising grades, and set the priority for μ_{ns} and α_{ms} to be higher than any other binary variables. This means that the mill and machine closure decisions will be made first; once SOCRATES decides to keep a machine open it could then decide the grades to make on it for each year. Since the production plan in the final planning period determines the terminal value (which makes a significant contribution to the objective) we set ρ_{mjt}, $t = T$ to have the next highest branching priority. We set the priority of all remaining ρ_{mjt} variables to be proportional to the capital costs required in order to produce them. (Setting the priority of the remaining ρ_{mjt} variables for early planning years to be higher than for later years did not seem to provide any improvements). No other attempts at directing the branch-and-bound process yielded noticeable improvements.

3.3 Improvements in Solution Times

Prior to including the formulation strengthening and branch and bound directives SOCRATES was essentially unsolvable. Once these changes had been made, solutions to a mipgap of around 5% were obtained in approximately eight hours running on a Pentium III PC with processor rating of 500 MHz and 256 MB of RAM.

4. Use of the SOCRATES Model in FCCL

SOCRATES was applied to a number of cases with different demand scenarios. Some scenarios were solved to a mipgap of 0.01%, but others did not advance much past 8%. In order to improve these solutions we fixed a number of binary variables at their incumbent values and re-solved. We chose to fix variables that we considered likely to have been branched on already, such as the μ_{ns} and α_{ms} variables and a number of ρ_{mjt} and pulp mill expansion decisions. With a significant number of binary variables effectively removed, Cplex was then able to improve the incumbent. These new solutions were significantly better than those found with a mipgap of 5%, effectively improving the mipgap to below 1% (as measured with respect to the best upper bound computed by the model with the variables unfixed)

Once an approximately optimal solution was obtained for the initial base case scenario, considerable interest arose within FCCL, and a number of 'what-if' questions were posed. These questions were answered simply by altering the relevant data inputs, and re-solving the model, using similar methods to improve on a 5% mipgap when necessary.

Interpreting the model solutions was difficult in many cases, because the huge number of options available created considerable opportunities for value to be created from counter-intuitive outcomes. It was necessary to construct comprehensive reports that allowed planners to progressively drill down from summary to highly detailed results in order to understand the model solutions.

5. Extension to Stochastic Programming

We conclude this paper with a description of the extension of SOCRATES to a stochastic optimisation program with recourse (*RP*). Three market scenarios were developed in detail: an expected, optimistic and pessimistic forecast. A deterministic equivalent mixed integer programming model was developed by duplicating the variables and constraints of SOCRATES for each scenario, multiplying each objective by an estimate of its probability, and adding *non-anticipative* constraints on some of the binary decision variables (for an account of formulating stochastic programming problems using non-anticipative constraints see e.g. [9]). For flexibility, a new set *U*, indexed by *u*, was defined as the set of planning years in which decisions were unable to adapt to the market scenario data, and non-anticipative constraints were added for all the binary decision variables with *t* indices in *U*. In the first instance we defined *U* to be the same as *T*, so that all years in the planning period were non-anticipative. Effectively this did not increase the number of binary decision variables from any of the single scenario model runs. However to date, due to the very large number of constraints, Cplex has not been able to produce a solution to this problem (or indeed one with any smaller set *U*) that is better than the solution to the deterministic model with the expected market constraints. Developing techniques for solving large capital planning problems of this type is an area of our ongoing research.

In order to obtain bounds on the solution to *RP*, SOCRATES was run separately on each scenario, and produced three separate solutions, comprising three different capital plans. There were a number of common capital decisions, and a number that were dependent on the scenario. The optimal capital plan from each scenario was simulated for each of the other two scenarios, and a matrix of returns was produced. There was considerable variance between good and bad possible outcomes, highlighting the risks involved with each capital plan.

An upper bound for the value of *RP* can be found by summing the objective values of each scenario, weighted by their associated probabilities. This is often referred to as the wait and see (WS) solution value. We simulated the solution from the expected market forecast under each of the three individual scenarios. The sum of these values multiplied by their associated probabilities gives the expected value of the expected value solution, which is a lower bound on the value of *RP*.

We were also able to estimate an upper bound for EVPI, the increase in value that FCCL can expect to obtain from receiving perfect information about which of the three proposed scenarios will occur.

Here *EVPI* ≤ *WS* value – *E(Expected value solution)*

The upper bound on *EVPI* obtained by this formula was relatively small compared with the overall objective values. This indicated that the differences between the three sets of scenario data were not great, and in fact indicated the need to re-evaluate the basis upon which the marketing study had been undertaken.

6. Conclusions

In this paper we have described SOCRATES, a capital planning model for FCCL. The deterministic formulation of this model has proved to be extremely difficult to solve, but near optimal solutions have been obtained by reformulating some aspects of the model and setting priorities sensibly in Cplex. The stochastic version of SOCRATES has not yet yielded a provably optimal solution, but it has provided useful insight into the risks associated with FCCL's business. SOCRATES has been used by FCCL strategic planners to analyse a number of market forecasts under a variety of different input assumptions.

References

[1] FCCL Annual Report, 2000.

[2] Philpott, A.B. and Everett, G.R., Supply Chain Optimisation in the Paper Industry, Proceedings 34th ORSNZ Conference, Hamilton NZ, December 1999.

[3] http://www.ampl.com

[4] http://www.cplex.com

[5] http://www.ilog.com

[6] Raghavendra B.G. and Arivalagan A., Applications of operations research techniques in paper industry: a review of the state of the art, *IPPTA*, 5(3) 1993

[7] Ferguson I.S. and Johnston R.E., Fibre Supply models for the Australian and New Zealand paper industry, *Appita J.* 52(3) , 1999

[8] Filmer P.J., Operations research! To use or not to use?, *Appita J.*, 32(3) 1978

[9] Birge J.R. and Louveaux, F., *Introduction to Stochastic Programming*, Springer Verlag, 1997.