Strategic Investment Planning in the Pulp and Paper Industry Using Mixed Integer Linear Programming

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Abstract

The Pulp and Paper industry is continuously making strategic decisions for investments. A modern paper mill is a significant long-term investment, and companies are searching for methods for making good investment decisions. In this paper, a method based in mixed integer linear programming (MILP) for decision support in the Pulp and Paper Industry is proposed. It is shown how an MILP formulation can be used for optimizing revenues on investments based on forecasts on demand, raw material costs, transportation costs, labor costs and energy costs. In addition, a case study illustrating how the methodology works is presented.

Background

One major decision for any industrial activity is where to locate the production units. In the pulp and paper industry, a production unit often is an integrated pulp mill and a paper mill. Moreover, even paper-converting units or sawmill activities may be run on the same site. Large-scale pulp and paper mills are major investments, and the lifetime for these facilities is long. The companies are hence looking for reliable decision support mechanisms for their strategic planning.

The main objective of any company is to produce profits and return on investments (ROI). Using computational tools, the optimal profit and ROI can be obtained for varying scenarios. The profit of a pulp and paper mill is dependent on various factors, such as raw material costs, labor costs, transportation costs, energy costs, demands, paper prices, interest rates etc. Some of these factors vary regionally more, some less. For instance, the labor costs have a strong relation to the local economy, whereas interest rates do not. Hence, the investment decision is actually a geographical decision, the big questions being where to invest, when and how much.

Related work

Even if the pulp and paper industry is a large industry, and only in the Nordic European countries Norway, Sweden and Finland the turnover is US$ 50 billion, and investments are around US$ 400-500 million for one pulp line (Bergman et.al, 2002), there is not very much literature on the area. On a general level Heidenberger (1996) apply MILP to a project selection problem, which can be seen as an investment problem, and show similar problem statements. In process synthesis there is a long tradition in applying mathematical optimization, an overview given by Grossmann (1996). In the case of supply chain optimization, there are numerous examples of applying mathematical optimization. Applying optimization to various scheduling problems the chemical industry has been rather popular (Floudas and Lin, 2004), and the methodology is often reusable for other industries. The development of more sophisticated decision support systems is a general trend shown by Shim et. al (2002). Here has also mathematical programming approaches been used, and the proposed formulation is an addition to this work.

Problem formulation

In this paper we present a Mixed Integer Linear Programming (MILP) model for optimizing the profits and return on investments based on given forecasts for production costs, paper prices and demands. Even if most of the formulation is Linear (LP), the actual investment decisions are discrete, and thus an MILP formulation is used.

This formulation is derived using an example scenario based on real market situation, originally given by Carlsson (1997). In this scenario, a multinational company, producing a number of different paper qualities, is studied. The company has paper mills in a given number of geographical areas, mainly corresponding to country boundaries and it provides paper to a number of market areas, also mainly corresponding to country boundaries. The overall goal of the company is to improve its market position, as same as other aspects, such as profitability and return on investment. This is a typical multiple criteria optimization problem, where several contradictory objectives are to be attained at the same time. Currently, the formulations are used to find optimal solutions for a particular objective function, when other operating conditions are given.

In this study, the main objectives are the operating result (corresponding to profitability) and return on investments. The problem is to decide where (and when) to increase capacity, where to decrease capacity, and where to invest in new paper mills. There is a forecast for both paper price and the demand of paper for each market area and paper quality up to some years in the future. Correspondingly, in each production area, there is a forecast for labor costs, energy costs and raw material costs. There is also given figures for shipping costs from producers to consumers.

Each producer area has a current capacity $C^{0}_{prc,prod}$, where index *prod* denotes the paper quality and index *prc* the producer area. The capacity can be changed by either increasing the capacity in existing plants by a limited amount $C^{I}_{prc,prod}$ or by building new capacity $C^{N2}_{prc,prod}$, $C^{N3}_{prc,prod}$. We assume that the increasing the capacity of old mills is restricted to 20%. New capacity can only be added in fixed sized blocks, e.g. the option is to add either a 200.000

or a 300.000 metric tons/a paper mill. We also assume that paper is produced cheaper in a newly installed plant.

As we have estimated our market for the paper qualities, linear balances can be used to ensure that the markets will be satisfied. The paper production in each country is divided both for the home market and for the export to the other countries. For example, $E_{F,D,1}$ is the export of paper quality 1 from Finland to Germany. The balances can be written as follows:

$$M_{D,1} = E_{D,D,1} + E_{F,D,1} + E_{S,D,1} + E_{B,D,1} + E_{Fr,D\_1} + Sl_{D,1}$$

which states that the market in Germany should be satisfied by the internal production and the import from other countries. $Sl_{D,1}$ stands for a slack variable that indicates the part of the demand that is not satisfied. Other indices; *m* = market (country), *prod* = product, *prc* = producer (country).

$$M_{m,prodt} = \sum_{prc} E_{prc,m,prod} + Sl_{m,prod}$$

The production should also satisfy the export:

$$P_{prc,prod} = \sum_{m} E_{prc,m,prod}$$

The production must even conform to the capacity in each country:

$$P_{prc,prod} = 0.95 \cdot \left(\left(1 + C^{I}_{prc,prod} \right) \cdot C^{0}_{prc,prod} + C^{N2}_{prc,prod} + C^{N3}_{prc,prod} \right)$$

where $C^{I}_{prc,prod}$ stands for the capacity increase in the old mills, $C^{0}_{prc,prod}$ the respective existing capacity, and $C^{N2}_{prc,prod}$ / $C^{N3}_{prc,prod}$ new invested capacity in 200 kton or 300 kton mills. It is assumed that a productivity of 95 % can be reached at the mills. New capacity can also be added only as 200.000 or 300.000 ton mills:

$$200000 I^{2}_{prc} = \sum_{prod} C^{N2}{}_{prc,prod}$$

$$300000 I^{3}_{prc} = \sum_{prod} C^{N3}{}_{prc,prod}$$

where I^{2}_{prc} and I^{3}_{prc}c are integer variables, which results that new investments are done only if the need for new capacity is sufficiently large.

Production costs can be calculated from the production rates in the different countries:

$$Cost_{tot} = \sum_{prc} \sum_{prod} \left(P^{C}_{prc,prod} P_{prc,prod} - \Delta P^{CN2}_{prc,prod} C^{N2}_{prc,prod} - \Delta P^{CN3}_{prc,prod} C^{N3}_{prc,prod} \right)$$

where $P^{C}_{prc,prod}$ represents the production costs per ton for a product in a certain country. The coefficients $\Delta P^{CN2}_{prc,prod}$ and $\Delta P^{CN3}_{prc,prod}$ represent how much cheaper it is to produce paper in a newly invested modern mill per ton. Total production costs can then be determined by summing all the Cost-variables.

Total sales can be calculated using the estimated prices in the different countries:

$$Sales = \sum_{prod} \sum_{m} Ppt_{m,prod} M_{m,prod}$$

where the Ppt_{mprod} is the price per ton.

The total shipping costs:

$$S_{tot} = \sum_{prc} \sum_{m} (Spt_{prc,m} \sum_{prod} E_{prc,m,prod})$$

where $Spt_{prçm}$ is the shipping cost per ton.

Total investments:

$$I_{tot} = 1800 \sum_{prc} I^{2}_{prc} + 1200 \sum_{prc} I^{3}_{prc}$$

Here should be notified, that the investments directed to the capacity increase are in this model not included to the sum above. The impact is considered via the production costs. Although this introduces an error to the system, it is assumed that the accuracy is good enough for the purpose of the study.

Operating profit:

$$OP = M_{tot} - Cost_{tot} - S_{tot}$$

Return on investment:

$$ROI = \frac{OP}{assets_0 + I_{tot}}$$

where $assets_0$ are the assets before the investments. This constraint is non-linear and in order to be able to solve the problem with a standard MILP solver it must be transformed into a linear form. This is done be generating a set of linear estimators.

In the calculations an interest rate of 6 % and an investment lifetime of 20 years were used (giving an “effective rate” of 8.72 %).

Different case variations can be generated by bounding a set of variables (e.g. the capacity increase in the old mills).

Objective function

As the objective function we decided to use the following:

$\max \quad OP + a \;\; ROI$

where α is a weight parameter.

Formulation summary

Indices

prc	producing country
m	market country
$prod$	product quality

Parameters

α	weight factor for ROI
$assets_0$	total assets before investments
$C^0{}_{prc,prod}$	existing capacity before investments
$P^C{}_{prc,prod}$	production cost
$\Delta P^{CN2}_{prc,prod}$	the difference in production costs in a new 200 kton mill compared to the old mills
$\Delta P^{CN3}_{prc,prod}$	the difference in production costs in a new 300 kton mill compared to the old mills
$Ppt_{m,prod}$	Sale price per ton
$Spt_{prc,m}$	Shipping cost per ton

Variables

$C^I{}_{prc,prod}$	capacity increase
$C^{N2}_{prc,prod}$	new capacity in 200 kton mills
$C^{N3}_{prc,prod}$	new capacity in 300 kton mills
$Cost_{tot}\,t$	total production costs
$E_{prc,m,prod}$	export
I^2_{prc}	number of new 200 kton mills
I^3_{prc}	number of new 300 kton mills
$M_{m,prod}$	market demand
OP	Operating profit
ROI	return on investment
S_{tot}	total shipping costs
$Sales$	total sales
$Sl_{m,prod}$	slack variable

FORMULATION

maximize $\quad OP + a \;\; ROI$

subject to

$$M_{m,prod} = \sum_{prc} E_{prc,m,prod} + Sl_{m,prod} \qquad \forall\ m, prod \tag{1}$$

$$P_{prc,prod} = \sum_{m} E_{prc,m,prod} \qquad \forall\ prc, prod \tag{2}$$

$$P_{prc,prod} = 0.95 \cdot \left(\left(1 + C^{I}{}_{prc,prod} \right) \cdot C^{0}{}_{prc,prod} + C^{N2}_{prc,prod} + C^{N3}_{prc,prod} \right) \qquad \forall\ prc, prod \tag{3}$$

$$200000\, I^{2}_{prc} = \sum_{prod} C^{N2}{}_{prc,prod} \qquad \forall\ \ prc \tag{4.1}$$

$$200000\, I^{2}_{prc,prod} = C^{N2}{}_{prc,prod} \qquad \forall\ \ prc, prod \tag{4.2}$$

$$300000\, I^{3}_{prc} = \sum_{prod} C^{N3}{}_{prc,prod} \qquad \forall\ \ prc \tag{5.1}$$

$$300000\, I^{3}_{prc,prod} = C^{N3}{}_{prc,prod} \qquad \forall\ \ prc, prod \tag{5.2}$$

$$Cost_{tot} = \sum_{prc} \sum_{prod} \left(P^{C}{}_{prc,prod} P_{prc,prod} - \Delta P^{CN2}_{prc,prod} C^{N2}_{prc,prod} - \Delta P^{CN3}_{prc,prod} C^{N3}_{prc,prod} \right) \tag{6}$$

$$Sales = \sum_{prod} \sum_{m} Ppt_{m,prod} M_{m,prod} \tag{7}$$

$$S_{tot} = \sum_{prc} \sum_{m} \left(Spt_{prc,m} \sum_{prod} E_{prc,m,prod} \right) \tag{8}$$

$$I_{tot} = 1800 \sum_{prc} I^{2}{}_{prc} + 1200 \sum_{prc} I^{3}{}_{prc} \tag{9}$$

$$OP = M_{tot} - Cost_{tot} - S_{tot} \tag{10}$$

$$ROI = \frac{OP}{assets_{0} + I_{tot}} \tag{11*}$$

Illustrative example

In the example presented in this paper, the task is to supply seven geographical areas in Europe with five different paper qualities. The areas are Germany, France, UK, Benelux, Italy, Spain and others. The current producers are Finland, Sweden, Germany, Benelux countries and France. Figure 1 gives a general overview of the problem at hand.

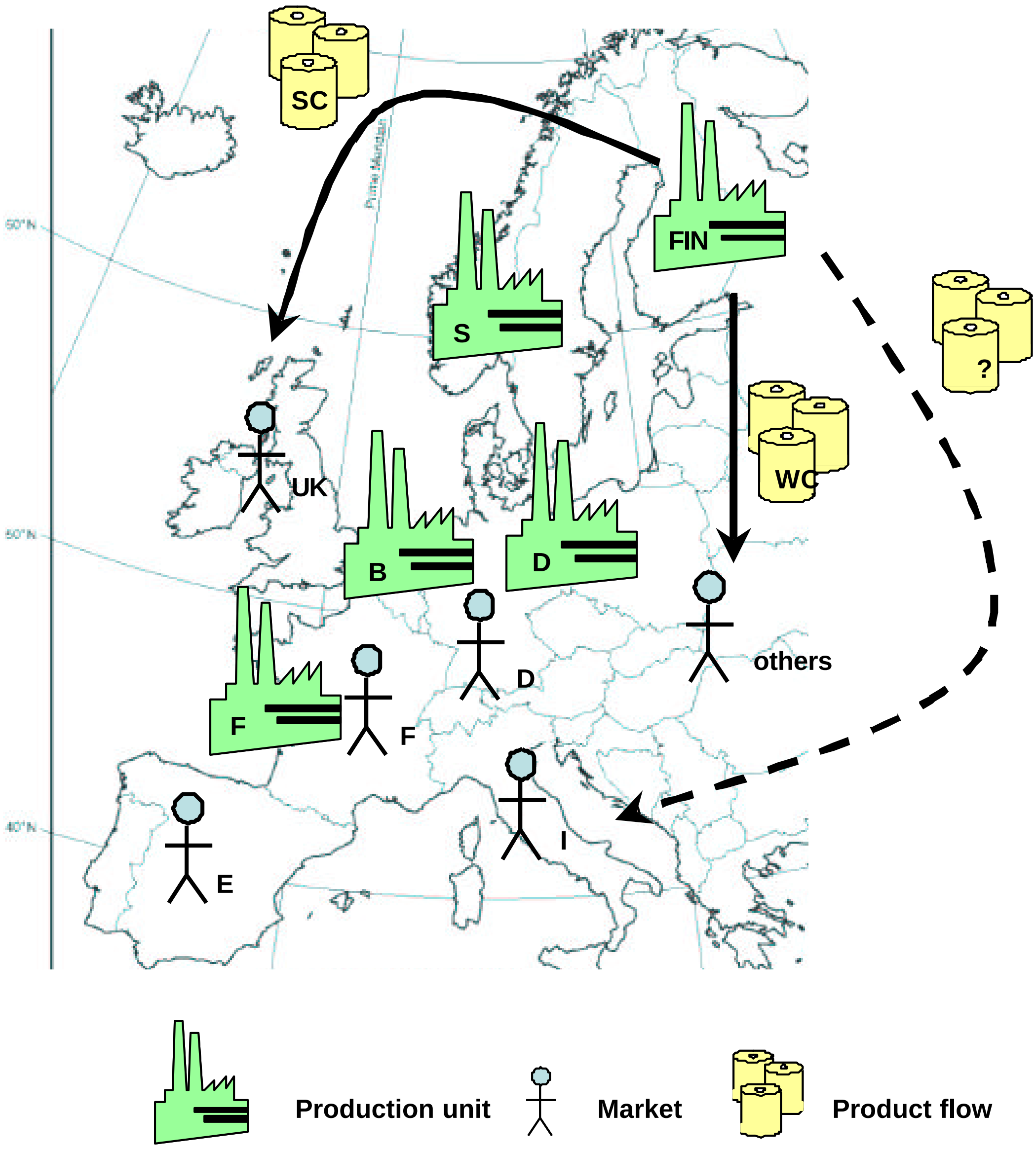

Figure 1. Overview of the strategic investment planning problem.

Each area has a forecasted demand for five different paper qualities. The paper qualities are Newsprint, Supercalendered (SC), Light Weight Coated (LWC), Wood Free Uncoated (WFU), and Wood Free Coated (WFC).

The market is supposed to increase according to a growth plan. Costs for raw materials, labor, and logistics are given as forecasts for the next upcoming 5-year period. Using the optimization methods proposed in the previous section, optimal solutions to support the strategic planning can be obtained. A solution provides information on where to produce each paper quality, where the investments should be done, and how the logistic should be arranged.

The goal is to reach an overall market share of 15% of the total market. This is supposed to be achieved by gaining market shares from the increasing market. The formulations presented here are not used for gaining markets, but to calculate how to provide products for the increasing markets. The actual figures used in the optimization are not presented here, but can be obtained from the authors.

Results

Using the optimization system presented in the previous sections, some results from the optimizations can be found in table 1.

Table 1. Optimization results for some cases.

	Operating profit (MEUR)	Inv. (MEUR)	Market share (%)	Production costs (MEUR)	Shipping costs (MEUR)	Total Production (ktons)
Case 1 Multi-quality mills, Inv < 2 OP	1682	3232	13,6	3068	449	5590
Case 2 Single quality mills, Inv < 2 OP	1676	3232	13,9	3143	449	5681
Case 3 Single quality mills, Inv=0 Restricting reduction of cap.	1139	0	11,9	3047	344	4874
Case 4 Single quality mills, Inv < 2 OP, Restricting reduction of cap.	1614	3131	14,4	3363	352	5908
Case 5 Single quality mills, Inv < 5 OP, Restricting reduction of cap.	1626	3434	14,9	3487	362	6098
Case 6 Single quality mills, Inv < 5 OP	1962	6465	15,1	3226	484	6196

Case 1: New multi-quality mills

First optimization (*Case 1*) was performed using a weight factor 10^{11} for the Return on Investment part of the object function, as the ROI varies between 0-1 and the Operating Profit for the cases was rather large. The upper limit to the total investments was in this case set at twice the operating profit.

With this data, the system suggested to build 6 new 300.000-ton mills in Finland for producing all paper qualities except Newsprint. The greatest increase in new capacity was allocated for WFC paper, at the same time as the production of WFC was discontinued in both France and Germany. In Benelux, two 300.000-ton mills (producing Newsprint and WFU) were suggested.

In Finland, capacity in old mills should be increased by maximum 25 % for Newsprint, SC and WFC. In Benelux, the Newsprint capacity in old mills should as well be increased by 25 %. In Germany, the SC production should be decreased by 28 % and the LWC production by 42%. In Sweden, the production of LWC should be decreased by 44 % and of WFC by 82 %.

Case 2: New single-quality mills

In the first test (*case 1*), it was assumed that new mills could produce several paper qualities (eqs. 4.1 and 5.1). This might be the case, especially when only the coating differs. However, the model was modified so that new mills only can produce one paper quality (eqs. 4.2 and 5.2) (*case 2*). This resulted in two new 300.000-ton (Newsprint) mills in Benelux, altogether 6 new 300.000-ton mills in Finland (4 of them producing WFC, one LWC and one WFU) and one 200.000-ton SC mill in Sweden. At the same time, the optimizer suggested a completion of the WFC production Germany, 42 % resp. 55 % reduction of the LWC resp. WFC production in France, and an 82 % reduce for WFC and 48 % reduce for LWC in Sweden. Existing capacity was increased in Finland for Newsprint, SC and WFC, and for Newsprint in Benelux. To conclude, the production of WFC and other "fine" papers should be concentrated to Finland, and the Newsprint production could be transferred to the continent, where Benelux seems to be the most economical location.

The model included some slack variables, which made it possible not to cover the market for some paper qualities and market areas. The optimization suggested that the planned market share for WFU should not be covered in Benelux, Sweden, France, Spain and Italy. This seemed at first a bit surprising, but after analyzing the result we found out that the estimated price level rises only 6 % for the WFU paper, whilst the price levels for other qualities rise 18-38%. At the same time the costs for producing WFU rise between 5 % (in Finland) and 66 % (in Germany). So if the capacity is scarce, WFU is the first product to drop. This strategy can of course be seen as opposite to the goal of achieving market dominance. This can thus be seen as a "political" matter, and our task is to provide the knowledge for the decision makers.

However, an interesting notice is that the system was able to detect a property, which was in no way obvious when working with the data. However, when looking at the results closer, this property was identified and proper actions can be taken according to this. The system is very sensitive for the selection of the variables. The allowable investment is one such variable. The optimization (*case 2)* produced an investment of 3.2 billion EUR, which on a five-year period is 0.8 billion EUR annually, or roughly two 300.000-ton mills. The calculated annual profit at the end of the investment period was 1,7 billion EUR. Since the calculated operating profit seemed to be quite large, to verify the reasonableness of the model the mean costs for paper production was calculated to 553 EUR/ton, and the average shipping costs 71 EUR/ton.

As a comparison, a model where no investments were allowed, was examined (*case 3)*. This resulted in an operation profit of 1.13 billion EUR. Another variant (*case 4)*, where capacity decrease was restricted to maximum

25 % was also tested. In this case, the operation profit became 1.60 billion EUR, and the total investments during the period 3.13 billion EUR.

By not restricting the investments but keeping the restriction of not decreasing the capacity in existing mills too much (*case 5)*, an operating profit of 1.62 billion EUR was achieved. In this case, the capacity was decreased in Germany, Sweden and France. Investments were suggested for Finland (two 300.000 ton WFC mills, one 300.000 ton WFU mill and one 200.000 ton LWC mill) and for Benelux (three 300.000 ton Newsprint mills, and one 200.000 ton and one 300.000 ton WFU mill). Total investments during the 5-year period were 3.43 billion EUR.

A further test run with unrestricted investments was also done, without restricting the reduction of the capacity (*case 6)*. As a result we got an operating profit of 1.96 billion EUR, but the investment costs rose to 6.47 billion EUR. This was also the only case where the 15% overall market share was achieved. The resulting strategy was nine 300.000-ton mills in Finland (five for WFC, two for LWC, one for SC and WFU), seven 300.000-ton mills (four Newsprint, two WFU and one LWC) in the Benelux-countries. We also stopped producing SC, LWC and WFC in Germany, and both LWC and WFC in France.

Shipping costs

The system calculated simultaneously the optimal logistical system for the mill. The required shipping amounts from producer to consumers are not presented here, but can be extracted from the optimizer output data.

Market position

Using the restrictions and goals specified, the specified overall market share of 15 % was not achieved. This was mostly due to the fact that the producing of WFU was not profitable enough to cover the planned market share for this quality. However, by adding some restrictions, the plan for reaching this goal could easily be reached.

Return on Investment

The return on investment turned out not to be a very important measurement in this survey. The changes in ROI were rather small and that part seldom affected the optimal configuration very much.

Conclusions

Given the estimates for both price, market and cost development, the indications these test runs give us, are all of the same direction: more production in Finland and less production in the more expensive countries, e.g. Germany. This trend would probably not be affected by moderate changes in the costs in production, investments or deliveries, only the detailed numbers in the results. Here should also be considered that there are no costs for capacity reduction of existing mills, which is not the case in reality. For example, the decreases in production can occur for mills that are not fully paid for and, therefore, it is certainly not profitable to shut down such mills.

Mathematical programming can give a very good base for the decision-making. The MILP model presented will certainly give the optimal mill configuration for the given data. As mills are either built or not built, basic Linear Programming methods would not do very well, because of the discrete decisions involved, whereas MILP methods can cope with the discrete nature of the problem.

The number of possibilities of placing new mills is huge. The "traditional" approach for solving the combinatorial problem would be to manually enumerate all possible configurations and then calculate the performance for each. This task is usually far too heavy. But using MILP, it can be guaranteed that all possibilities have been considered.
MILP only guarantees the optimal solution for a given set of data. Thus, the most difficult part is to obtain such a data set that represents the real situation as well as possible. In most cases a number of estimations, approximations and "rule of thumb" data must be used in the modeling. This can, of course, also lead to incorrect results, which must be kept in mind while studying the solutions.

The sensitivity of the presented model could have been explored further. For example, how do different changes in costs affect the configuration? If the costs in Germany did not rise that much, would it lead to that all mills would be placed in Germany? The MILP model could in this case be used for the examination of the sensitivity. If some parameters are very sensitive, and it is believed that the model does not provide reliable information, the human reasoning should take a dominating position in the decision procedure.

An obvious shortcoming of the current formulation is however that forecasts for market development, prices, costs etc. are uncertain. Hence, the formulations could be developed to also handle optimization under uncertainty. This could further help the decision makers, not selecting strategic plans that easily fail due to high sensitivity to uncertainty.

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