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A model of clinker capacity expansion

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Abstract

This paper describes a model which has been applied in practice to determine an optimal plan for clinker capacity expansion. The problem was formulated as an integer linear program aiming to determine the optimal number, size and location of kilns to be introduced each year during a given planning horizon. The optimal solution is defined as the one which maximises the net present value (NPV) of the cash flow generated by the introduction and operation of new kilns subject to capacity and demand constraints. Various demand scenarios and capital expenditure structures were tested by means of the model and a number of possible locations for new kilns were evaluated. Finally, the benefits derived by the company where the application took place are listed.

Keywords: Optimisation; Capacity planning; Integer programming; Location; Scenarios

1. Introduction

In South Africa, cement is manufactured by three main producers: Alpha Cement, Blue Circle Cement and Pretoria Portland Cement. In 1995, the national production was 8.4 million tonnes of cement, representing a 4.5% increase over the previous year. Although South Africa's production is small compared with that of many European, American and Asian countries, it is nevertheless the third largest in Africa after Egypt and Algeria [1].

Clinker is the lumpy calcined substance produced when a mixture of limestone and clay (or shale) is heated at 1500°C in a cylindrical rotary kiln. Subsequent grinding with a small amount of gypsum produces ordinary Portland cement, where the term Portland refers to the similarity between the colour of cement and that of a certain stone found in Portland, UK.

The decision by a cement manufacturer to install additional capacity has serious financial implications. Nevertheless, additional capacity must be installed if the company wishes to survive and retain its market share. The issue has recently become more relevant in South Africa as a result of the creation of a more competitive environment following the recommendation of the Competition Board – and approval by the Minister of Trade and Industries – to disband the cement cartel which had hitherto been dictating strict market shares on the various producers. Therefore, it is imperative that an effective plan for clinker capacity expansion be in place and implemented by the company. A mathematical model has been

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developed by the CSIR at the request of Blue Circle Cement (Pty) Ltd. (BCC), a division of Blue Circle Ltd., and used to determine an optimal plan for clinker capacity expansion.

Besides producing ordinary Portland cement, BCC manufactures cement blends (mixtures of ordinary cement with substances such as granulated fly ash or slag), masonry cements and rapid hardening cements. BCC's main works are at Lichtenburg, in the North West province, where 1.84 million tonnes of cement were produced in 1995 (22% of the national production).

This paper describes the methodology followed in the development of the above-mentioned mathematical model as well as the results obtained from an illustrative but entirely fictitious (at the request of BCC) application. Furthermore, the benefits derived by BCC are listed.

2. Methodology

The problem was originally quite vague. However, there was a general agreement that at least the following four questions had to be answered: how many kilns, how large, when and where? Various relationships were identified early in the project. For example, the location of the plants influences the cost of distributing raw materials from the sources to the kilns, as well as the price of the final product. The size of the plants influences the capital expenditure, fixed costs and satisfaction of demand. Timing influences the cash flow and, in turn, depends on the demand; and so on.

Ideally, a model integrating production and location should have been applied, as suggested in [2], and a theoretical framework for such an integrated model was, in fact, developed. However, due to the ever-present constraints of time and budget, the problem was decomposed into two parts. The first part dealt with the optimal number, size and time scheduling of new kilns if they were to be "centrally" located, i.e. placed at BCC's existing main works at Lichtenburg. The analysis was based on the company's share of the national demand for cement satisfied from this single production point. The second part dealt with the decision on the location of new kilns.

The first part of the problem (henceforth referred to as "optimisation model" or, occasionally, "centralised model"; Sections 3 and 4) was formulated as an integer linear program aiming to determine the "optimal" number and size of kilns (four discrete sizes were considered) to be purchased each year during a given 25-year planning horizon (see [3] for similar formulations). The optimal solution was defined as the one which maximises the net present value (NPV) (at a given discounting rate) of the cash flow generated by the purchase and operation of new kilns, i.e. the solution which maximises the objective function:

NPV [flow of (profit after tax *minus*
capital expenditure *plus* capital tax allowance)] (1)

subject to demand and capacity constraints for each year in the planning horizon.

In a scenario generation phase (see Appendix A, Section A.1), a spreadsheet is used to generate relevant input data required by the optimisation model, such as forecasts of BCC's clinker demand and cement sales. The optimisation model is subsequently applied to various scenarios – our illustrative example considers a range of demand growth rates (1–6% p.a.) and two CAPital EXpenditure (CAPEX) structures (large and reduced economies of scale) (Appendix A, Section A.2) – thereby producing a set of optimal capacity expansion schedules (Section 4.1). During an evaluation phase (Section 4.2), the output of the optimisation model is fed into a spreadsheet which calculates various financial and production-related parameters, such as utilisation rate, fixed and variable costs, tax liability, capital allowance, profit, discounted cash flow, NPV, return on investment (ROI) and economic value added (EVA). The development of spreadsheets for the scenario generation and evaluation phases was requested by BCC because of their user friendliness. Furthermore, the evaluation spreadsheet can be used to compare optimal with "interesting" non-optimal solutions.

In the second part of the problem (henceforth referred to as "location analysis" or, occasionally, "decentralised model"; Section 5) the aim was to assign size and time slots to regional locations for new kilns.

The above decomposition, as opposed to an integrated exercise, was acceptable because, as indicated by BCC, (i) the main works at Lichtenburg would absorb any demand fluctuations by adjusting production accordingly, (ii) BCC's share of the national market is expected to remain relatively constant during the planning horizon, and (iii) only small kilns would be feasible at decentralised locations.

The software and methodology were transferred to BCC and, despite the simplification in the model, the company has been provided with a valuable tool which led to useful guidelines for its strategic implementation programme (Section 6).

3. Optimisation model formulation

Indices and parameters

- i time index (year)
- j kiln size index (kiln type)
- M number of kiln types
- N number of years in the planning horizon (the cash flow horizon – as distinct from the planning horizon – is extended to $2N$ years due to the fact that the life time of a kiln is also assumed to be N years (see Appendix A, Section A.1)).

Decision variables

- x_{ij} number of kilns of type j purchased during year i (these kilns will only start producing in year $i + 1$).

Functions of the decision variables

- A_{ij} total capital tax allowance during year i due to the purchase of type j kilns in any year k, $i - 4 \leqslant k \leqslant i$, provided $0 \leqslant k \leqslant N-1$ (this is a tax benefit distributed uniformly over a period of 5 years, including the year CAPEX is incurred)
- C^{F}_{ij} total fixed costs of kilns of type j during year i
- C^{V}_{ij} total variable costs of kilns of type j during year i
- E_{ij} total CAPEX incurred during year i due to the purchase of type j kilns in that year (CAPEX is incurred one year before a kiln starts producing)
- S_{ij} BCC cement sales generated by all kilns of type j operating in year i

Input data

- D_i incremental demand (i.e. over and above the demand pertaining to year 0 of the planning horizon) for BCC *clinker* in year i incremental demand for BCC *cement* in year i times clinker to cement ratio (h),
- e_j capital cost (CAPEX) of kiln type j
- f_j annual fixed cost of kiln type j
- g_j capacity of a kiln of type j
- h clinker to cement ratio
- p cement price per tonne (at Lichtenburg)
- r time value of money (discounting rate), excluding inflation
- T company tax rate
- v variable cost per tonne (all kiln types)

$$u(r,n) = \sum_{i=1}^{n}(1+r)^{-i} = r^{-1}(1+r)^{-n}[(1+r)^n - 1].$$

The objective function (1) can then be written as follows:

$$\text{maximise} \quad \sum_{i=0}^{2N}(1+r)^{-i}\sum_{j=1}^{M}[(1-T) \times (S_{ij} - C^{\mathrm{F}}_{ij} - C^{\mathrm{V}}_{ij}) - \mathrm{E}_{ij} + A_{ij})]. \qquad (2)$$

Assuming that the variable cost, C^{V}_{ij}, is independent of the kiln type then Eq. (2) reduces to Eq. (3) which is expressed explicitly in terms of the integer decision variables x_{ij}. The term by term equivalence between Eqs. (2) and (3) (but not the full derivation) is shown in Appendix B. The optimisation model can then be stated as follows:

$$\text{minimise} \quad \sum_{i=1}^{N}(1+r)^{-i+1}\sum_{j=1}^{M}\{(1-T)u(r,N)f_j + [1-(T/5)(1+r)u(r,5)]e_j + (1-T)[(p/h)-v](1+r)^{-N} \times u(r,N+1-i)g_j\}x_{i-1,j} \tag{3}$$

$$\text{subject to} \quad \sum_{j=1}^{M}g_j\sum_{k=1}^{i}x_{k-1,j} \geqslant D_i, \quad i=1,\ldots,N, \tag{4}$$

$$x_{ij} \geqslant 0 \text{ and integer}, \quad \forall i,j. \tag{5}$$

Constraints (4) ensure that the available clinker capacity in each year satisfies the demand in the same year ($\sum_{k=1}^{i} x_{k-1,j}$ is the number of kilns operating in year i, i.e. the number of kilns purchased between year 0 and year $i-1$). Constraints (5) ensure that the number of kilns purchased in a given year is a non-negative integer.

The original problem was solved exactly by means of the commercial procedure SAS/OR. However, it was impractical for either this or other commercial packages to be transferred to or acquired by BCC and, at any rate, it takes a considerable amount of time to solve the exact problem. Therefore, a special algorithm was developed to solve the BCC capacity expansion problem under different scenarios. In the solution procedure, the following heuristics were used to limit the size of the tree to be searched: (i) no more than one kiln should be purchased each year, and (ii) no kiln should be purchased unless the failure to do so would result in a shortfall in production capacity. No differences between the solutions of the exact and simplified problems were observed in any of the cases considered.

4. Results of the optimisation model

4.1. Optimal schedules

Table 1 gives the optimal capacity expansion schedules for six growth scenarios and two CAPEX structures (for the input data see Appendix A). The data in the table are read as follows (using 3% p.a. growth in demand as an example): In the case of large economies of scale (L) a type 3 kiln (500 000 tonnes p.a.) is purchased in each of the years 2000, 2008, 2015 and 2021. In the case of reduced economies of scale (R) a type 1 kiln (100 000 tonnes p.a.) is purchased in the years 2004, 2010 and 2011; a type 2 (250 000 tonnes p.a.) in the years 2000 and 2006; and a type 3 (500 000 tonnes p.a.) in the years 2013 and 2019.

The case of 3% p.a. growth rate in demand (both large and reduced economies of scale) is illustrated graphically in Fig. 1 where the incremental demand and optimal incremental capacities are plotted *versus* time.

From Table 1 it appears that the threshold for introducing large kilns (types 3 and 4) is a demand growth rate of roughly 2.5% p.a. for large economies of scale and of 3.5% p.a. for reduced economies of scale. The significant differences in the results produced by the two CAPEX structures at 2% p.a. and 3% p.a. warrant a closer look at the capital costs of small kilns (types 1 and 2).

Finally, it should be mentioned that sustained annual growth rates of a specific magnitude are theoretical whereas real demand shows fluctuations. Therefore, cement demand and its forecasts should be closely monitored and the optimisation model applied accordingly to take into account any deviations.

4.2. Evaluation

The optimal solution of each of the 12 scenarios considered was evaluated by means of a spreadsheet which calculated NPV, ROI, cumulative EVA and the number of years it takes for the latter to become positive (see Appendix C for the relevant definitions). The results are given in Table 2. The case labelled R(dec) should be ignored at this stage; it will be considered in Section 5.

5. Location analysis

In the second part of the problem, a number of locations for new kilns were identified by BCC and a standard location problem was solved. Three

Table 1
Optimal capacity expansion schedule for demand growth rates of 1–6% p.a. and two CAPEX structures

Year		Type of kiln purchased												Year	
		1% p.a.		2% p.a.		3% p.a.		4% p.a.		5% p.a.		6% p.a.			
		L	R	L	R	L	R	L	R	L	R	L	R		
0	2000	1	1	1	1	3	2	3	3	4	4	4	4	2000	0
1	2001													2001	1
2	2002													2002	2
3	2003			2	1									2003	3
4	2004						1							2004	4
5	2005				1									2005	5
6	2006	1	1				2	3	3					2006	6
7	2007											4	4	2007	7
8	2008				1	3				3	3			2008	8
9	2009			1										2009	9
10	2010						1							2010	10
11	2011				2		1	4	4					2011	11
12	2012	1	1	3						4	4	4	4	2012	12
13	2013						3							2013	13
14	2014													2014	14
15	2015					3						4	4	2015	15
16	2016													2016	16
17	2017	1	1		1					4	4			2017	17
18	2018													2018	18
19	2019				1		3	4	4			4	4	2019	19
20	2020													2020	20
21	2021				1	3				4	4	4	4	2021	21
22	2022													2022	22
23	2023	1	1	1	1									2023	23

Notes: L represents large economies of scale and R the reduced economies of scale.
Type 1 kiln is 100 000 tonnes clinker p.a., Type 2 kiln, 250 000 tonnes clinker p.a., Type 3 kiln, 500 000 tonnes clinker p.a., Type 4 kiln, 1000 000 tons clinker p.a.
Year 2024 is not listed as it presents boundary problems.

data sets were used as inputs. Firstly the optimal kiln size and year of commissioning, as determined by the optimisation model, served as the benchmark in terms of time and size of kiln. Secondly, the difference ("conversion gap") between the regional market price, and the resource, energy and transport costs per tonne of cement, pertaining to the various locations, served as the primary basis of evaluating the locations. Thirdly, an assessment of the expected demand on a provincial basis was used to construct a ranking table which assisted, in a secondary manner, in choosing the preferred locations.

The identified locations were assigned size and time slots by applying a set of qualitative rules. One of the solutions (3% p.a. growth in demand and reduced economies of scale CAPEX scenario) was evaluated and the result compared with the corresponding one obtained from the centralised model (see Table 2).

As shown in Table 2 (case R(dec)), the improvement in financial performance is quite remarkable. This finding emphasises even more strongly the need for an integrated model which could further improve the solutions.

6. Benefits

During an interview with the Managing Director of BCC, one year after completion of the project, it was ascertained that the following benefits have been derived by the company as a result of the acquisition and application of the model:

- The model has provided BCC with a valuable decision support tool enabling them to quantify

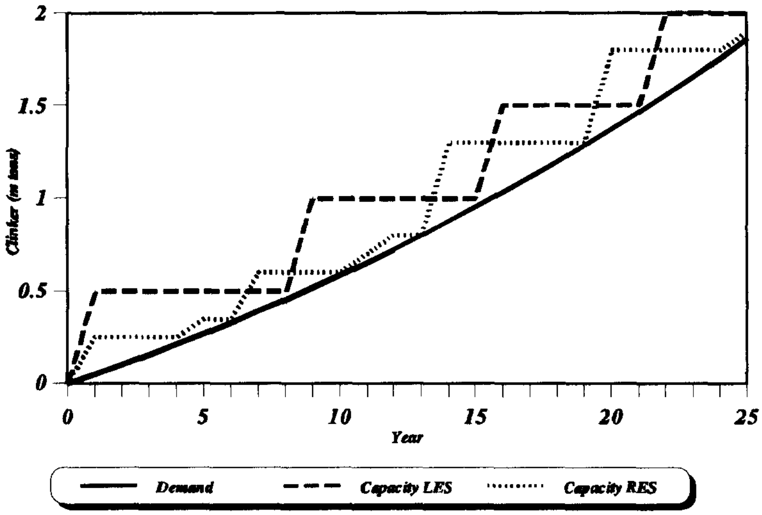

Fig. 1. Incremental demand and optimal incremental capacity vs. time (growth in demand = 3% p.a.) (LES = Large economies of scale, RES = Reduced economies of scale).

Table 2
NPV, ROI and EVA of the optimal solutions

Growths cenario	CAPEX structure	NPV (Rand mill.)	ROI (% p.a.)	Cumulative EVA (Rand bill.)	Years to (+) cumul. EVA
1% p.a.	L	−134	2.6	9	23
	R	−88	4.4	12	17
2% p.a.	L	−167	6.2	66	20
	R	−89	7.3	85	15
3% p.a.	L	−98	8.6	167	12
	R	−59	9.0	175	10
	R(dec)	141	12.5	226	3
4% p.a.	L	60	10.6	309	9
	R	60	10.6	309	9
5% p.a.	L	236	11.8	555	8
	R	236	11.8	555	8
6% p.a.	L	534	13.4	927	7
	R	534	13.4	927	7

Notes: L represents large economies of scale (centralised), R, reduced economies of scale (centralised), R(dec), reduced economies of scale (decentralised).

different options, in terms of costs and benefits, and to select attractive options.

- It has enabled BCC to answer strategic questions which had so far been perplexing, such as determining the "best" size, timing and location of new kilns.
- Although the model is not the only strategic tool used in the expansion decision making process, it has, nevertheless, made the process considerably easier than before.
- It has been useful and user friendly to the extent that the Managing Director himself has used it "to play around with 'what if' questions".
- An Environmental Impact Assessment study has already been commissioned at one of the decentralised locations (East London in the Eastern Cape province) as a result of its being an attractive proposition in the model.
- BCC had been considering two short-term expansion alternatives, in terms of the type of kiln to be introduced at its Lichtenburg plant. As a result of the model's recommendation of a specific type kiln, BCC has decided to proceed with the groundwork for this type. The groundwork involves the preparation of plant lay-outs, cost estimates, draft tender documents, etc.
- A comparison of the above-mentioned alternatives at Lichtenburg, including the associated longer-term expansion possibilities, has shown that substantial improvements in NPV of over R40 million can be achieved as a result of choosing the correct implementation plan.

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Appendix A. Input scenarios for the optimisation model

A.1. Scenario generation

The purpose of scenario generation was to produce relevant input data required by the optimisation model, for example, BCC clinker demand and sales. This was done by means of a spreadsheet with the following content and parameters:

Planning horizon: Year 0 (2000) to year 25 (2025). New kilns are purchased during this period and produce for (co-incidentally) 25 years after which they leave the system. This has the consequence of extending the cash flow horizon to 50 years (2000–2050).

Total (national) annual cement demand (tonnes p.a.): Compound growth rates of 1% p.a., 2% p.a., 3% p.a., 4% p.a., 5% p.a. and 6% p.a. were applied on the 1995 figure of 8.4 million tonnes. Other growth rates or even different methods of forecasting demand can easily be substituted in the spreadsheet.

Total (national) annual clinker demand (tonnes p.a.): Given % of total cement demand.

Annual demand for BCC cement (and clinker) (tonnes p.a.): Given % of total cement (and clinker) demand.

Annual BCC cement sales (Rand p.a.): Demand for BCC cement × price per tonne (at Lichtenburg).

Incremental annual demand for BCC cement (and clinker) (tonnes p.a.).

Incremental annual BCC cement sales (Rand p.a.)

A.2. Other inputs

Kiln capacities

100 000 tonnes clinker p.a. (type 1).
250 000 tonnes clinker p.a. (type 2).
500 000 tonnes clinker p.a. (type 3).
1 000 000 tonnes clinker p.a. (type 4).

CAPEX: This is introduced in the model a year before a kiln starts producing. Two structures were tested in our example: (i) large economies of scale and (ii) reduced economies of scale. This was due to the fact that there are substantial differences between the unit costs of various models of the smaller kilns (kiln types 1 and 2) compared with the larger ones. For example, the cost of a small, type 1 kiln (100 000 tonne annual capacity) can vary between R100 million and R200 million (i.e. between R1 000 and R2 000 per annual tonne of capacity) whereas the cost of a large, type 4 kiln (1 000 000 tonne annual capacity) varies between R650 million and R800 million (i.e. between R650 and R800 per annual tonne of capacity). The choice of more expensive small kilns corresponds to large economies of scale whereas the choice of less expensive small kilns corresponds to reduced economies of scale. In making this choice, manufacturers would, indeed, have to consider additional criteria, such as quality, productivity, flexibility, reliability, etc.

Life time: 25 years (all kiln sizes).

Fixed costs for each size kiln (Rand per tonne of capacity p.a.).

Variable costs for each size kiln (Rand per tonne of production): These costs are usually independent of the kiln size.

Company tax rate (0.35).

Annual capital allowance: 0.35 ÷ 5 × CAPEX for 5 years (including the year CAPEX is incurred).

Time value of money (discounting rate): Given annual rate, excluding inflation (0.1 in our example). Inflation is excluded as this is a cash flow exercise.

Appendix B. Term by term equivalence between Eqs. (2) and (3)

$$\sum_{i=0}^{2N}(1+r)^{-i}\sum_{j=1}^{M}(1-T)(S_{ij}-C_{ij}^{\mathrm{V}})$$

$$\doteq \text{constant} - (1-T)[(p/h)-v](1+r)^{-N}$$

$$\sum_{i=1}^{N}(1+r)^{-i+1}u(r,N+1-i)\sum_{j=1}^{M}g_{f_j}x_{i-1,j},$$

$$\sum_{i=0}^{2N}(1+r)^{-i}\sum_{j=1}^{M}(1-T)(-C_{ij}^{\mathrm{F}})$$

$$= -(1-T)u(r,N)\sum_{i=1}^{N}(1+r)^{-i+1}\sum_{j=1}^{M}f_jx_{i-1,j},$$

$$\sum_{i=0}^{2N}(1+r)^{-i}\sum_{j=1}^{M}(-E_{ij})$$

$$= -\sum_{i=1}^{N}(1+r)^{-i+1}\sum_{j=1}^{M}e_jx_{i-1,j}, \sum_{i=0}^{2N}(1+r)^{-i}\sum_{j=1}^{M}A_{ij}$$

$$= (T/5)u(r,5)(1+r)\sum_{i=1}^{N}(1+r)^{-i+1}\sum_{j=1}^{M}e_jx_{i-1,j}.$$

The change in the upper limit of the summation over i, from $2N$ in Eq. (2) to N in Eq. (3), is due to: (i) the fact that the life time (N) of a kiln coincides with the number of years in the planning horizon, (ii) no kilns are purchased when $i \geqslant N$, i.e. $x_{ij}=0$ when $N \leqslant i \leqslant 2N$ and (iii) all variables S_{ij}, C_{ij}^{F}, C_{ij}^{V}, E_{ij} and A_{ij}, $0 \leqslant i \leqslant 2N$, can be expressed in terms of x_{ij}, $0 \leqslant i \leqslant N-1$ or, equivalently in terms of $x_{i-1,j}$, $1 \leqslant i \leqslant N$.

Furthermore, the entities $T/5$ and $u(r,5)$ in Eq. (3) are explained by the fact that capital tax allowance is distributed uniformly over a period of five years.

Appendix C. Measures of investment worth

- *(NPV):* Sum of discounted cash flows.
- *(ROI):* The value of the discounting rate which makes NPV equal to zero [4].
- *(EVA):* Net operating profit after tax in a given year *minus* capital charge in that year [5].
- *Cumulative EVA:* Sum of annual EVAs; it starts at a negative value for a series of new investments and may become positive at some stage within the planning horizon; the earlier it becomes positive the better; also, the larger it is in the end the better the investment.

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