The development of a system to optimise production costs around complex electricity tariffs

R Maneschijn

20662947

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Supervisor: Dr R Pelzer

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ABSTRACT

Title: The development of a system to optimise production costs around complex electricity tariffs

Author: R Maneschijn

Supervisor: Dr R Pelzer

Keywords: Energy management, cement industry, demand side management, continuous production processes, optimisation modelling

Rising South African electricity prices and reduced sales following the 2008 economic recession have led cement manufacturers to seek ways to reduce production costs. Prior research has shown that reduced electricity costs are possible by shifting load from expensive Eskom peak pricing periods to lower cost times. Due to the complex considerations and variables in cement production, this is not typically implemented.

Several simulation and optimisation models are available in literature to schedule plant operation in an electricity cost effective manner. However, these models have not been implemented in practice. The simulation models are reviewed and evaluated for the task of scheduling cement production on South African factories. A model is identified to be implemented, and the requirements for implementing this model on a cement factory are investigated.

A computerised management system is designed to automatically incorporate the required information and data to implement the optimisation model on a practical level. An interface is also designed to allow factory personnel access to the optimised production plan. The system is implemented and evaluated through system level testing.

Four case studies are presented within which the system is implemented on South African cement factories. The performance of the system is evaluated over a nine month period, within which a total cost saving of R8.6-million is reported.

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Nomenclature

°C	Degrees Celsius
Angle of repose	The maximum angle to the horizontal plane at which a granular material will rest without sliding.
Blaine measurement	The measurement of the surface area of a mass of particles, commonly used in the cement industry to indicate the fineness of cement powder
CBL	Customer Baseline
Comminution	The process of reducing solid materials in size by breaking, grinding or other process
DMP	Demand Market Participation
DSM	Demand Side Management
ESCo	Energy Service Company
GDP	Gross domestic product
GW	Gigawatt
GWh	Gigawatt-hour
kWh	Kilowatt-hour
mm	Millimetre
MVA	Megavolt ampere
MW	Megawatt
MWh	Megawatt-hour
OPC	Object Linking and Embedding for Process Control
PLC	Programmable logic controller
SCADA	Supervisory Control and Data Acquisition
Tonne	1 metric tonne, equal to 1000 kilograms
TOU	Time-of-use
µm	Micrometre

Chapter 1 Introduction

1.1 Preamble

The background surrounding the research problem will be sketched in this chapter. As the study pertains to the electricity sector of South Africa, the role and history of Eskom will be discussed first. Following this, the need for electricity savings in the industrial sector will be motivated, before a case for implementing existing solutions is presented. Finally, research goals will be developed, along with a discussion of the expected results.

1.2 Introduction to the South African electricity environment

In 2010, Eskom generated 95% of the electrical energy consumed in South Africa[1]. Eskom primarily operates coal-fired plants to generate electrical energy, but gas, hydro, renewable energy source plants and the only nuclear power plant in Africa are also operated to generate electrical energy [1],[2]. A breakdown of Eskom generated electricity is given in Figure 1-1. This figure also shows a calculated average international lifetime capital and operation cost per megawatt-hour (MWh) unit per plant.

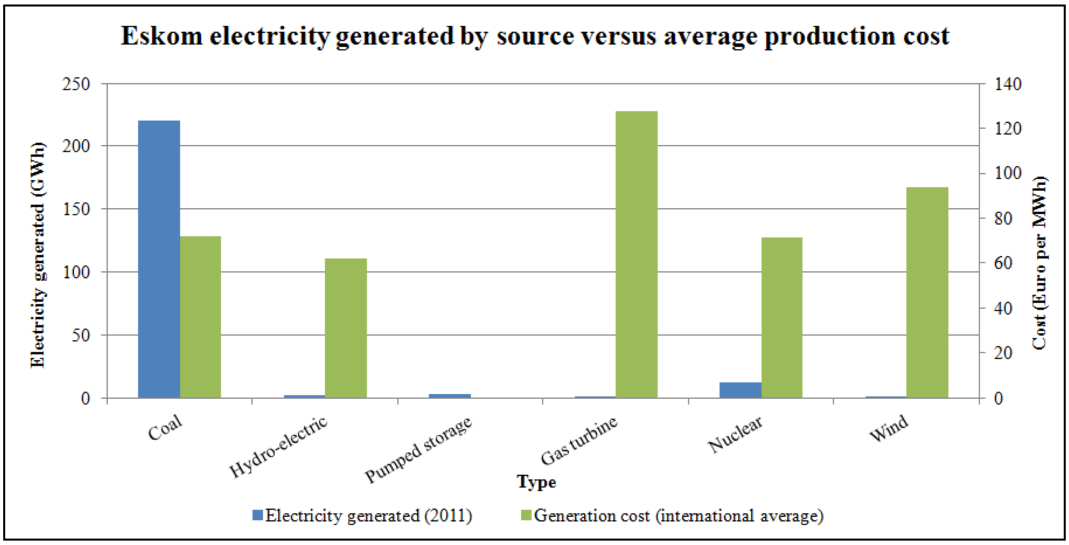


Figure 1-1: Eskom electricity generated by source versus average international cost[1,2,3,4]

Coal fired power plants are internationally considered to be the second cheapest source of electrical energy. South Africa has large quantities of coal reserves[2]. Many of Eskom's coal burning plants were built near coal mines to minimise transport costs [2]. Due in part to these two factors, South Africa

[1] Eskom Holdings Limited, "Eskom Annual Report," Eskom, Johannesburg, 2010.
[2] Department of Energy, "South African Energy Synopsis 2010," Department of Energy, Pretoria, 2010.
[3] J. Morgan, "Comparing Energy Costs of Nuclear, Coal, Gas, Wind and Solar," 2 April 2012. [Online]. Available: http://nuclearfissionary.com/2010/04/02/comparing-energy-costs-of-nuclear-coal-gas-wind-and-solar/. [Accessed 30 September 2012].
[4] J. Klein and A. Rednam, "Comparative costs of California central station electricity generation technologies: Draft Staff Report," California Energy Commission, Sacramento, 2007.

historically enjoyed lower electricity costs than the international average. Figure 1-2 shows that - from 1987 until 2007 - Eskom's tariff adjustments were closely linked to South Africa's inflation rate, resulting in a sustained period of low electricity costs for Eskom's customers[5]. Eskom's customers had little motivation to be concerned with energy efficiency or electricity cost saving measures.

In 2007 and 2008, the increased electricity demand during peak periods caused Eskom to introduce power shedding schedules. Mining and manufacturing companies in particular were subjected to frustrating production losses and delays. As a result, Eskom accelerated the Capital Expansion Programme, aimed at returning decommissioned power stations into service, as well as building new power plants.

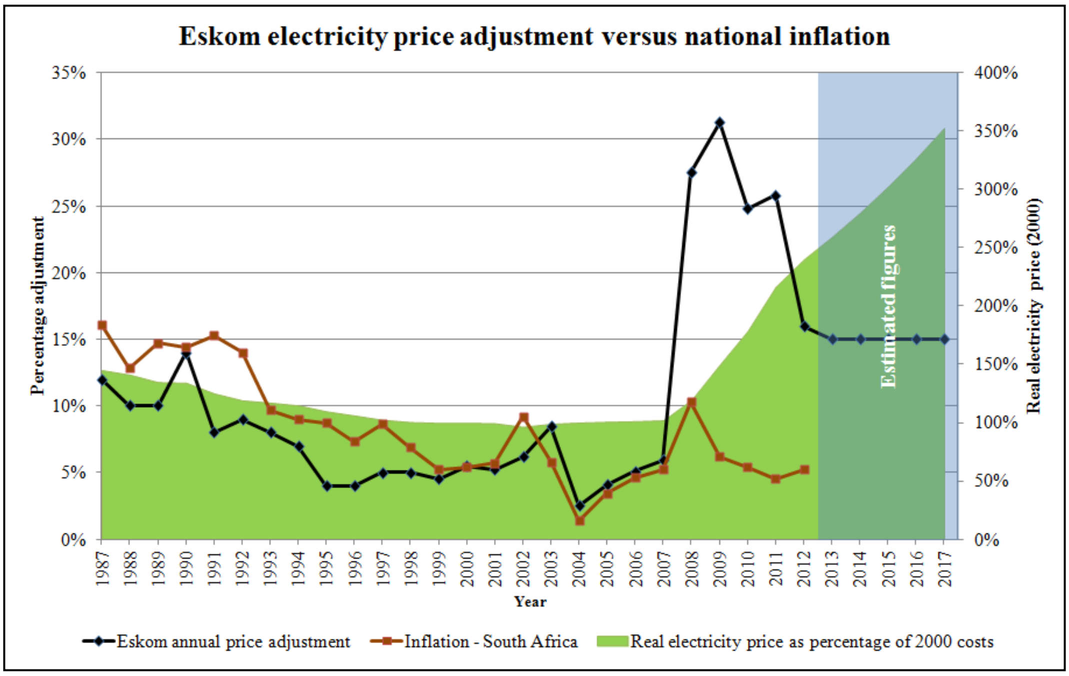


Figure 1-2: Eskom price adjustments versus inflation from 1987 to 2012[1,3]

The cost incurred by Eskom to generate electricity has raised due to the utility's investments in capital extensive expansion projects. As a result, the utility has successfully applied for several large annual tariff adjustments of between 15% and 33%. In 2012, the NUS consulting group compiled a report that indicated that South Africa lost the position of being the country with the cheapest electricity, which it held for many years[6].

As shown in Figure 1-2, in 2012 the average electricity prices were already adjusted by almost 240% compared to 2000. Due to the sudden nature of these cost increases, most consumers did not have any

[5] B. Ramokgopa, "Tariff History," Eskom, Johannesburg, 2005.
[6] NUS Consulting Group, "International Electricity & Natural Gas Report & Price Survey," NUS Consulting Group, New York, 2012.

electricity cost saving initiatives in place. As these increases are expected to continue until 2018, electricity costs have become a significant concern to large consumers.

1.3 Industrial production lines in South Africa

South Africa's economy is highly energy intensive [3],[7]. Energy intensiveness is defined as the number of units of primary energy consumed per United States Dollar unit of gross domestic product (GDP)[8]. This is due to the fact that a portion of South African GDP is dependent on primary extraction and processing of raw materials. Figure 1-3 shows South Africa’s energy intensiveness compared to countries with similar GDP. This figure shows that, when compared to other countries with similar GDP, South Africa has greater energy consumption. This also means that increases in energy costs, such as rising electricity prices, will have a significant impact on high consumption sectors of the economy.

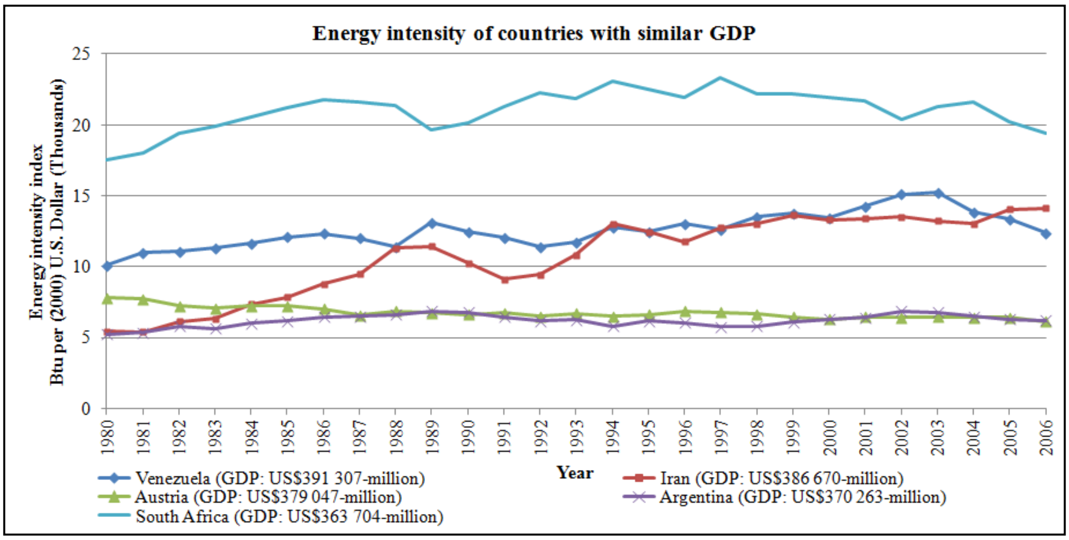


Figure 1-3: Energy intensity of countries with GDP similar to South Africa[9]

Mining and industrial production lines, where primary raw materials are extracted and processed are among these consumers. Industry (including mining) accounts for 44% of electrical consumption in South Africa[1]. Examples of these production lines are steel, iron, copper and aluminium smelters, cement and aggregate lines, and wood milling and pulping lines. The production lines that will be discussed in this dissertation are those of the cement industry.

The cement industry is currently recovering from the global economic recession that started in 2008[10]. Projects for the 2010 Soccer World Cup, the Gauteng Freeway Improvement Project and the Gautrain

[7] M. Altman, R. Davies, A. Mather, D. Fleming and H. Harris, "The impact of electricity price increases and rationing on the South African economy," Pretoria, 2008.
[8] United Nations Department of Economic and Social Affairs, "Intensity of Energy Use," 02 November 2004. [Online]. Available: http://www.un.org/esa/sustdev/natlinfo/indicators/isdms2001/isd-ms2001economicB.htm. [Accessed 30 September 2012].
[9] Energy Information Administration, "International Energy Annual," Energy Information Administration, Washington, 2006.

helped to restrict the overall impact caused by the global recession [4]. However, Figure 1-4 still shows a significant drop in demand since 2008, occurring as the national GDP growth fell.

Overall sales have been rising, but the lack of major national infrastructure projects has slowed the recovery process. Until cement sales recover to pre-recession levels, cement manufacturers have to take all available steps to reduce production costs. This includes cost saving measures on the use of electricity.

Figure 1-4: South African cement sales versus GDP growth for 2000 to 2011[11,12,13]

1.4 Cost saving opportunities at cement production lines

Mathews *et al.* [5] showed that, as early as 2005, electricity cost savings could have been achieved at cement plants in South Africa through improved load management. Mathews showed, through a case study, that the savings measures were not realised by the cement factories. Using a simulation model, with prevailing tariffs and production figures, they showed that a saving of R650 000 was theoretically possible through improved load management. This work did not proceed beyond the theoretical level.

In 2010, Lidbetter [6] conducted a study similar to that of Mathews. Lidbetter used a pilot study to show that theoretical cost savings could be translated to a practical level. The study was conducted over a five

[10] The Office of the Presidency of South Africa, "Framework for South Africa's response to the international economic crisis," The Presidency, Pretoria, 2009.
[11] The Cement and Concrete Institute, "National cementitious sale statistics for South Africa," The Cement and Concrete Institute, Midrand, 2012.
[12] The Cement and Concrete Institute, "Review 2008," The Cement and Concrete Institute, Midrand, 2009.
[13] World Bank, *GDP growth (% Annual): South Africa.*

day period. As it was not the aim of the study, no permanent solution was produced to implement improved load management on a daily basis.

Internationally, Sheen *et al.* [7] showed that cement companies responded to time-of-use (TOU) tariffs to save electricity costs. Other work on the subject has been presented by Paulus *et al.* [8], Castro *et al.* [9] and Mitra *et al.* [10]. Paulus stated that cement mills could be managed to avoid peak costs. However, he was also quick to point out that cement mills operating at maximum utilisation could not be stopped in such a way. With some studies specific to the cement industry, Castro and Mitra have shown that optimising production with regards to electricity costs is possible through improved scheduling. No evidence has been found of such work being implemented on a long term basis.

In 2011, Swanepoel *et al.* [11] started working on an integrated model which could, by taking all necessary constraints into account, produce an optimised schedule to reduce electricity costs. Although an improvement over previous research on the subject, Swanepoel did not develop a method to practically implement this model.

1.5 Research objectives and expected results

Since 2007, the South African price of electricity increased. This trend is expected to continue for several more years. Eskom is also placing increased emphasis on energy efficiency. In addition, the global recession of 2008 has lead to financial strain on South African industrial companies, such as cement plants. Therefore it is important to implement systems to reduce electricity costs.

Previous work has shown that electricity cost savings can be achieved through improved load management, but these savings are not always realised. These savings are made possible by participating in Eskom's TOU tariff structures. Previous studies have included the development of simulation and optimisation models to realise such savings. However, no previous work has demonstrated the ability to implement a practical working model so that sustained savings could be achieved.

This study aims to develop a system through which existing cost optimisation models can be implemented at South African cement plants. To achieve this aim, several objectives need to be accomplished:

Research objectives are to:

- **Evaluate** existing cement production line models.
- **Identify** obstacles preventing the implementation of the previously developed models.
- **Develop** a system to overcome these obstacles.

- **Implement** this system to realise cost savings over an extended period.

The primary benefit of this work is fiscal. By successfully implementing optimisation models at South African cement plants, significant electricity cost savings can be achieved. In addition, these cost savings will have the further benefit of reducing the demand on Eskom's supply network during peak periods. This will assist the electrical utility in maintaining a stabilised and sustainable national power supply.

1.6 Dissertation overview

Chapter 1

In Chapter 1 an introduction to the study was given. The different industrial and economic factors that gave rise to the study were discussed, and motivation was given for the need for the study. Finally, the possible benefits of the study were given.

Chapter 2

The second chapter provides an overview of the Eskom tariff model applied to large consumers. Following this, an overview is given of typical South African cement plants, along with a discussion of savings opportunities. Next, the different simulation and optimisation models available in literature are presented, and their viability within the framework of this study is discussed. Finally, the requirements for implementing an optimisation model are discussed. Based on this, a decision is made regarding the research methodology to be followed.

Chapter 3

Chapter 3 discusses the research and design process. Firstly, an operational analysis is conducted to show the technical environmental context of the study. Secondly, a verification plan is formulated to evaluate the system. Thirdly, a conceptual design of the intended solution is posed, and lastly the detailed design is discussed.

Chapter 4

In Chapter 4, the results of implementing the system as described in Chapter 3 are discussed. The results of applying verification methods are presented and analysed. Following this, the validation of the research is presented in the form of case studies. Finally, the different results achieved are discussed and evaluated.

Chapter 5

In the final chapter, a summary of the study is given. Conclusions are derived from the observed results (Chapter 4). Finally, suggestions are made for further research within the field of research.

Chapter 2 Background and literature review

2.1 Preamble

This chapter will begin by providing background on South African electricity tariffs applicable to cement plants. This will be followed by a brief overview of the cement production process. A review of literature relevant to the study will be presented to meet the first two objectives of the dissertation. The simulation and optimisation models available in literature will be discussed. The suitability of these models will be evaluated with regards to present electricity tariffs, as well as the characteristics of cement plant operation.

2.2 Utility tariffs and demand management programs

2.2.1 Tariffs

The tariff structure applied by an electrical utility is regarded as one of the key factors in the development of an electrical energy efficient consumer base [12]. Some tariff structures expose clients to the cost incurred by electrical utilities to meet demand, while others do not. Typically, tariff structures that do not change over time (static or fixed tariffs) do not reflect operating costs incurred by a utility at specific times. Opposite to this, some modern utilities provide real-time pricing, where prices change hourly to reflect generation costs.

A varying rate tends to impose a level of complexity and risk, and is rarely applied to residential customers. Therefore, these consumers have no financial incentive for reducing demand during peak periods [13], [14]. These consumers are often the most active during (and the root cause of) system peak times[14], causing problems for utilities to meet the electricity demand.

Figure 2-1 shows different tariff structures for the risk faced by customers versus the utility. As indicated, time-variant tariffs reduce the risk faced by the utility, but increases the risk faced by the customer. Tariff complexity also increases as it becomes more time-variant.

[14] T. Nortje, "South Africa's demand side management programme," EE Publishers, Johannesburg, 2006.

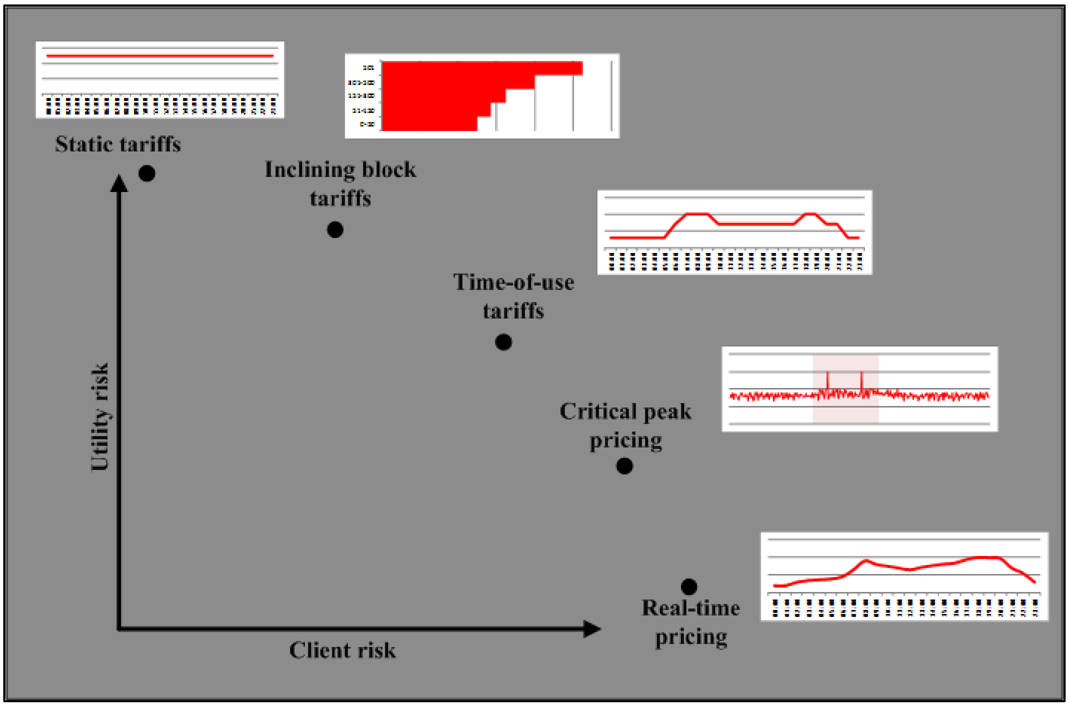


Figure 2-1: Chart of tariff structures versus utility and customer risk[15]

Applying TOU tariffs to residential customers may not solve the peak demand problem. Torriti showed through a study in Italy that TOU tariffs for residential customers may cause even higher peaks and increases in overall consumption [15]. A possible cause of these higher peaks is that most of the residential users may switch on high consumption equipment such as air conditioners and boilers as soon as peak times have passed to enable comfortable living conditions.

Eskom provides a variety of tariffs to clients, including static, inclining block and various TOU structures. Static and inclining block rates are intended for basic consumers, such as residences and small businesses. Eskom has recently started a pilot programme for domestic TOU tariffs, but this has only been applied to customers with a monthly electrical consumption of more than 500 kilowatt-hour (kWh). As such, the industrial and commercial sector represents the main body of clients on TOU tariffs.

Eskom clients with a notified maximum demand of 5 megavolt-ampere (MVA) or greater are billed according to the Megaflex tariff structure[16]. First implemented in 1991, this structure makes use of a TOU based cost[17]. The Megaflex tariff structure is also seasonally adjusted to allow for the increased demand during winter periods. Table 2-1 illustrates average Megaflex tariffs for winter and summer weekdays. As

[15] Charles River Associates, "Primer on Demand-Side Management," The World Bank, Washington, 2005.
[16] Eskom, *Tariffs & Charges Booklet 2012/13*, Johannesburg: Eskom Holdings Limited, 2012.
[17] B. Ramokgopa, "Tariff History," Eskom Holdings Limited, Johannesburg, 2005.

shown, the seasonal differences in electricity costs are significant, with winter peak periods costing R1 511 more per MWh consumed compared to summer peak periods.

Table 2-1: Average 2012/13 Megaflex price per MWh, sorted by season and weekday[3]

	Summer			Winter		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
00:00	R251	R251	R251	R291	R291	R291
01:00	R251	R251	R251	R291	R291	R291
02:00	R251	R251	R251	R291	R291	R291
03:00	R251	R251	R251	R291	R291	R291
04:00	R251	R251	R251	R291	R291	R291
05:00	R251	R251	R251	R291	R291	R291
06:00	R359	R251	R251	R545	R291	R291
07:00	R586	R359	R251	R2 097	R545	R291
08:00	R586	R359	R251	R2 097	R545	R291
09:00	R586	R359	R251	R2 097	R545	R291
10:00	R359	R359	R251	R545	R545	R291
11:00	R359	R359	R251	R545	R545	R291
12:00	R359	R251	R251	R545	R291	R291
13:00	R359	R251	R251	R545	R291	R291
14:00	R359	R251	R251	R545	R291	R291
15:00	R359	R251	R251	R545	R291	R291
16:00	R359	R251	R251	R545	R291	R291
17:00	R359	R251	R251	R545	R291	R291
18:00	R586	R359	R251	R2 097	R545	R291
19:00	R586	R359	R251	R2 097	R545	R291
20:00	R359	R251	R251	R545	R291	R291
21:00	R359	R251	R251	R545	R291	R291
22:00	R251	R251	R251	R291	R291	R291
23:00	R251	R251	R251	R291	R291	R291

*Note that 00:00 refers to the time period 00:00 – 00:59.

One of the goals of implementing this structure was to encourage more efficient consumption among customers[4]. However, Eskom's tariffs were ineffective in doing so and South Africa's national electricity demand is characterised by a morning and evening peak. Figure 2-2 shows the national load profile for 2012, with peak demand periods indicated. Peak demand refers to the maximum instantaneous demand on the electricity supply network, and is measured in MW.

Due to the relatively low cost of electricity throughout the 1990s and early 2000s, Eskom's rates were ineffective in achieving DSM among Megaflex customers. Residential customers received no incentives for reducing load during peak periods as only large, industrial customers were subject to lower rates. However, relative to their overall consumption, South African residential users contribute significantly more to peak period consumption than other consumers [16].

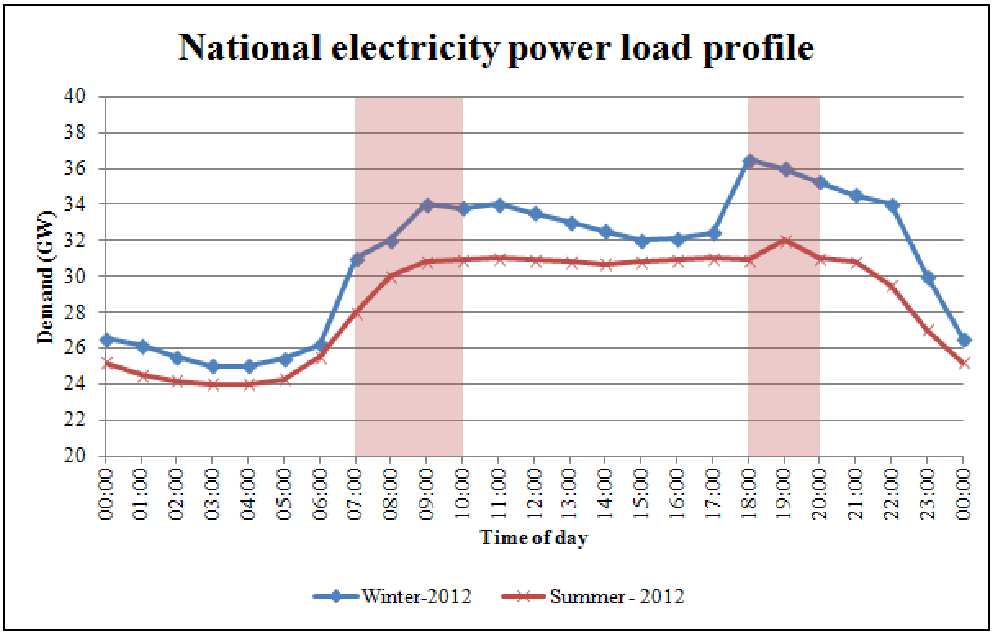


Figure 2-2: Eskom national load profile for winter 2012[18]

The morning and evening peak periods shown in Figure 2-2 present a difficult scenario for supplying cost effective electricity. Eskom is forced to provide sufficient capacity to meet the demand during peak periods which last only a few hours of the day. Figure 2-3 shows that periods where 95% of maximum demand is exceeded account for less than 3 hours per weekday during winter.

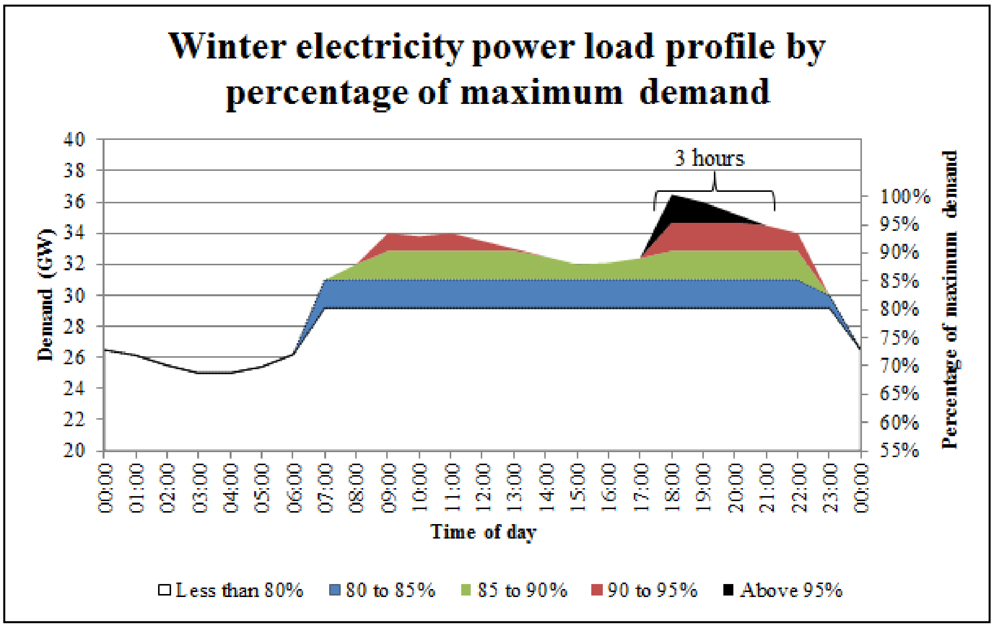


Figure 2-3: National demand bands as percentage of peak demand

[18] Eskom, "Update on the State of the Power System," Eskom Holdings Limited, Johannesburg, 2012.

These peak periods represent a gross inefficiency of electricity consumption [17]. Due to the high peak-average ratio, Eskom is forced to provide capacity far in excess of what would have been necessary if the distribution profile was evenly spread [18]. One of the negative effects of this is that a large number of power plants must be kept on standby when they could normally undergo maintenance.

Most utilities, including Eskom, have measures in place to deal specifically with this problem. Eskom operates four gas-fired power plants with a capacity of 2 400 MW, two pumped storage schemes with a capacity of 1 400 MW, and has a third pumped storage scheme under construction[19,20,21].These plants are intended only to be used during peak demand periods. However, if the distribution profile was evenly spread, these facilities would not be necessary, except for emergency standbys. These peaking plants are especially suited for such situations, as they can be brought online much faster than slow-reaction time coal plants. If coal plants are used as standbys, they must be kept at a certain operating level, which wastes fuel. This is known as spinning reserve.

2.2.2 Demand Side Management programme

As a result of the capacity problem, Eskom has implemented an incentive based Demand Side Management (DSM) programme. This programme allows Energy Service Companies (ESCos) to intervene on a technical level with large consumers to reduce load during peak periods, or to improve overall energy efficiency [19]. Such projects are either partially or fully Eskom funded, allowing customers to enjoy reduced electricity costs with little or no financial input or risk.

In general, three different projects are implemented to alter electricity demand in South Africa, namely energy efficiency, peak clipping and load shifting. Energy efficiency projects aim at doing the same amount of work with less electrical energy (i.e. lowered overall consumption). Peak clipping projects aim at energy efficiency during peak hours and load shifting aims at removing load from peak hours by moving it to off-peak hours. The DSM project of interest for this dissertation is load shifting. Figure 2-4 shows the effect of distributing load evenly throughout the day, which could significantly lower peak demands.

[19] Eskom, "Revenue Application: Multi-Year Price Determination 2012/13 to 2017/18," Eskom Holdings Limited, Johannesburg, 2012.
[20] Department of Energy, "South African Energy Synopsis 2010," Department of Energy, Pretoria, 2010.
[21] Eskom, "Eskom Annual Report," Eskom Holdings Limited, Johannesburg, 2011.

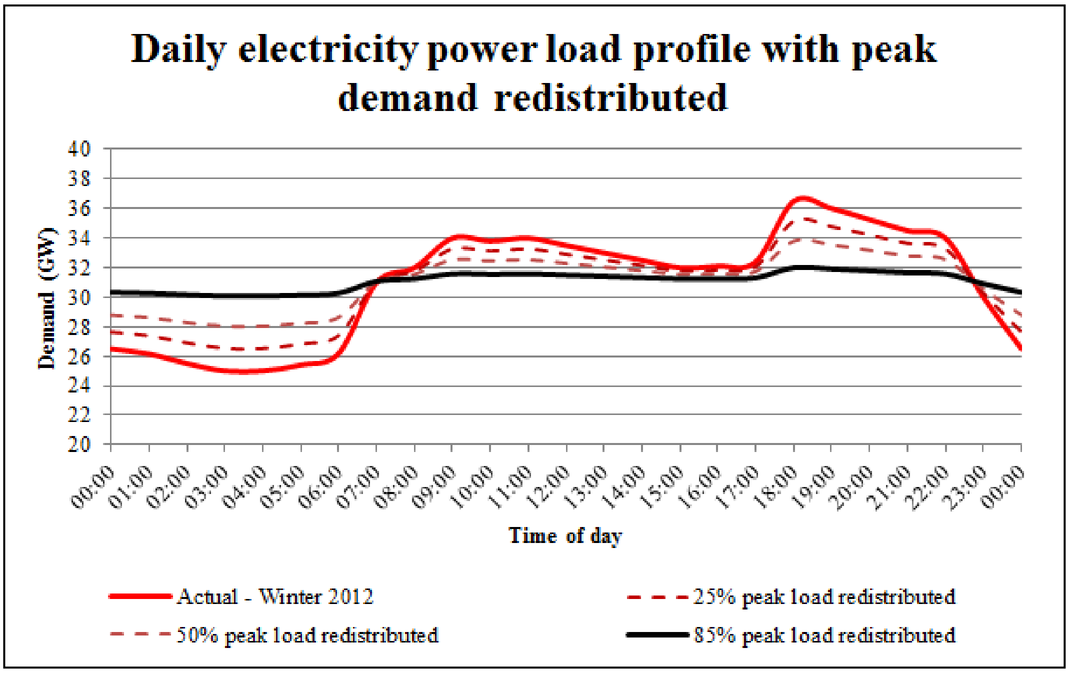


Figure 2-4: National weekday electricity demand with exaggerated load shifting applied

2.2.3 Demand Market Participation programme

Eskom has recently implemented the Demand Market Participation (DMP) scheme. This programme is based on the principle of load curtailment and Eskom buying electricity back from customers [19]. Participants are paid a small standby schedule fee on days Eskom believes there may be supply constraints. If the constraint is realised on the network, Eskom notifies participants to reduce load. Repayment for energy shed during actual events is much higher than the standby payment.

DMP presently caters for several distinct customer pools [20],[22]. The first pool involves customers who can immediately reduce a significant load, usually 10 MW to 80 MW or more, but only for a limited period of time, usually 10 minutes. These customers have automated units installed on site which can react to an emergency on the national grid in under 0,02 seconds. A second pool involves customers who can be notified at least 30 minutes ahead of time to reduce load, but have to maintain the reduced load for two hours. A third pool involves customers who cannot reduce load on a daily basis, but their annual maintenance periods are flexible enough to be scheduled for periods when Eskom believe they might experience capacity problems . An example of this would be the shutdown of Xstrata smelters early in 2012[23].

[22] Eskom, "Demand Market Participation". [Online] Available: http://www.eskom.co.za/c/article/167/demand-market-participation/ [Accessed: 2013-03-14]

[23] Idéle Esterhuizen, "Xstrata-Merafe JV shuts furnaces as it joins Eskom buy-back", Mining Weekly [Online]. Available: http://www.miningweekly.com/article/xstrata-merafe-jv-shuts-furnaces-as-it-joins-eskom-power-buy-back-2012-12-12 [Accessed 2013-03-14].

The second pool will be considered by this dissertation. Figure 2-5 shows an example of such a DMP event. A Customer Baseline (CBL) is calculated based on three previous days of similar tariffs (i.e. three working weekdays if the event day is a weekday). This CBL is then scaled according to the customer's load for a one hour interval starting 1,5 hours before the notified reduction time. The customer's performance is then measured against this scaled baseline to determine the power demand reduced for the event. Clients are paid for the MWh reduced during the event period.

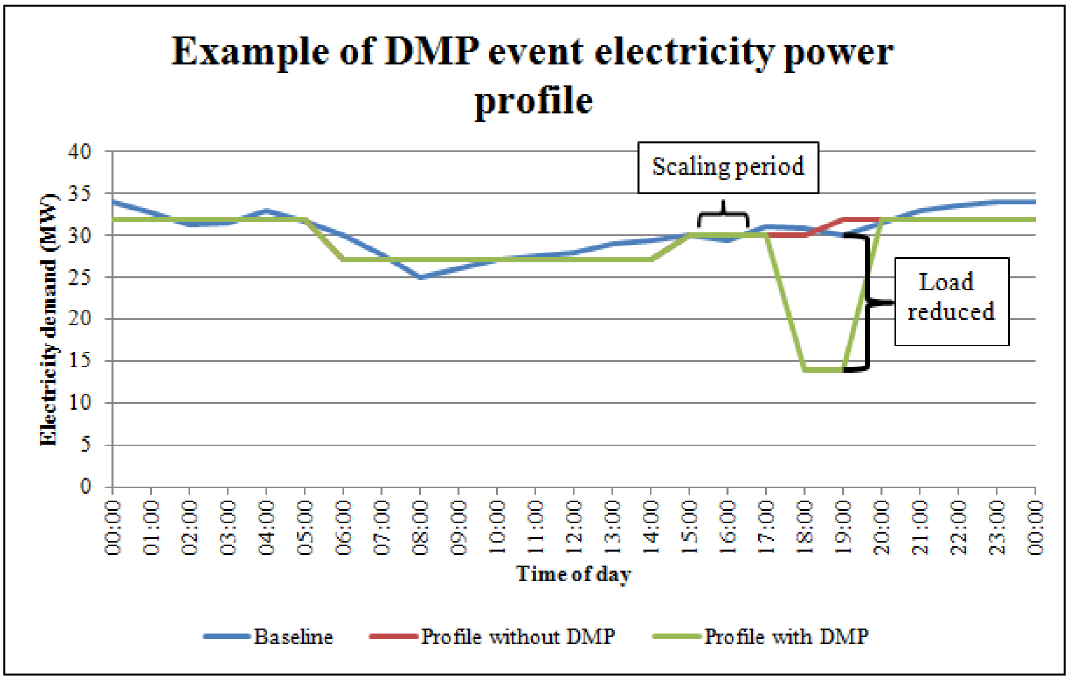


Figure 2-5: Example of DMP event performance calculation **[21]**

DMP has several benefits to clients. To those who are capable of reducing demand, the load reduction repayment can be lucrative. In addition, by participating with 25% or more of the client's average load, a client is removed from stage 1 and 2 load shedding schedule[24]. This means that a client, where possible, will not be included in these two stages of national load shedding events. This is an important benefit for some production lines, such as aluminium smelters, as loss of power to an aluminium smelter for more than 4 hours will cause irreparable damage in the order of billions of Rands [22].

This also holds a benefit to Eskom, as it assists the utility in stabilising the grid while supply capacity is constrained. However, considering the infrastructure involved in setting up the DMP programme as well as the cost incurred per MWh load reduced through DMP, this solution may be too expensive.

[24] NRS, "048-9:2010," Eskom Holdings Limited, Johannesburg, 2010.

Eskom utilises a bidding market for DMP customers. This market takes all available generation sources into account, as well as the cost of utilising each. Depending on the expected load on the network, Eskom dispatches the required amount of generation capacity to ensure that the demand can be met. Table 2-2 provides an example of this process. If a demand of between 3 200 MW and 3 600 MW is forecast, all available sources up to Gas unit 2 is utilised, thus providing electricity to meet the demand at the least cost. As is shown, DMP participants are then utilised.

Table 2-2: Supply market example

Source:	Price per MW [R]:	Capacity [MW]:	Cumulative MW:
Gas unit 1	115	400	4 000
Gas unit 2	110	400	3 600
DMP group 1	100	200	3 200
DMP group 2	100	200	3 000
Coal station B, unit 1	55	300	2 800
Coal station A, unit 1	52	500	2 500
Coal station A, unit 2	50	500	2 000
Coal station B, unit 2	44	300	1 500
Pumped storage 1	20	600	1 200
Pumped storage 2	16	600	600

2.3 Cement production lines

2.3.1 Overview of cement production in South Africa

South Africa has at least 19 cement production facilities with a total production capacity of 18,8 million tonnes of cement per year. A further 3 facilities are planned to start operation by 2015. The country is presently only utilising around 75% of this capacity, as demand for cement has reduced during the global economic recession[25].

All South African cement producers manufacture Portland cement. Portland cement is an example of hydraulic cement, and a comparatively inexpensive construction material when used as an ingredient in concrete. Ordinary and rapid hardening types of Portland cement are produced in South Africa. Rapid hardening cement has higher early strength than the ordinary variety. Early strength is an indicator of the strength of the cement after only setting for two days. Cement with high early strength requires greater energy expenditure and more time to be produced.

Although cheaper than other construction materials to produce, cement manufacturing is still an energy intensive process. The estimated electrical energy consumed to produce one tonne of cement is 100 kWh [23]. In addition, a significant quantity of thermal energy, produced directly by coal fired sources, is used

[25] The Cement and Concrete Institute, "National cementitious sale statistics for South Africa," The Cement and Concrete Institute, Midrand, 2012.

during the calcining phase. Most notably, cement production is an inefficient process with regards to the consumption of energy. Some have estimated that the overall energy efficiency of the comminution process is less than 5% [23], while large amounts of waste heat and vibration are generated. Further, the production of cement has adverse environmental effects, due to the release of large quantities of greenhouse gasses into the atmosphere [24]. A significant concern in cement industry research is to find ways in which these emissions can be reduced [25].

2.3.2 The cement production process

As the focus of this paper is to facilitate the practical implementation of an optimisation model, the scope of this discussion will be restricted to control, throughput and the use of various forms of energy. Attention will also be given to the interaction of each stage of the process with those surrounding it. Readers interested in the detailed processes of cement production are referred to Bye [26].

A basic overview of the cement production process is given in Figure 2-6. This figure indicates four distinct processing stages, namely raw material sourcing, kiln feed preparation, pyroprocessing (also termed calcining) and finish grinding. Most of these processing stages either include, or are separated by storage facilities. The different energy sources used during the production process are indicated, where red denotes primarily electrical energy, while yellow indicates a combination of electrical and thermal energy.

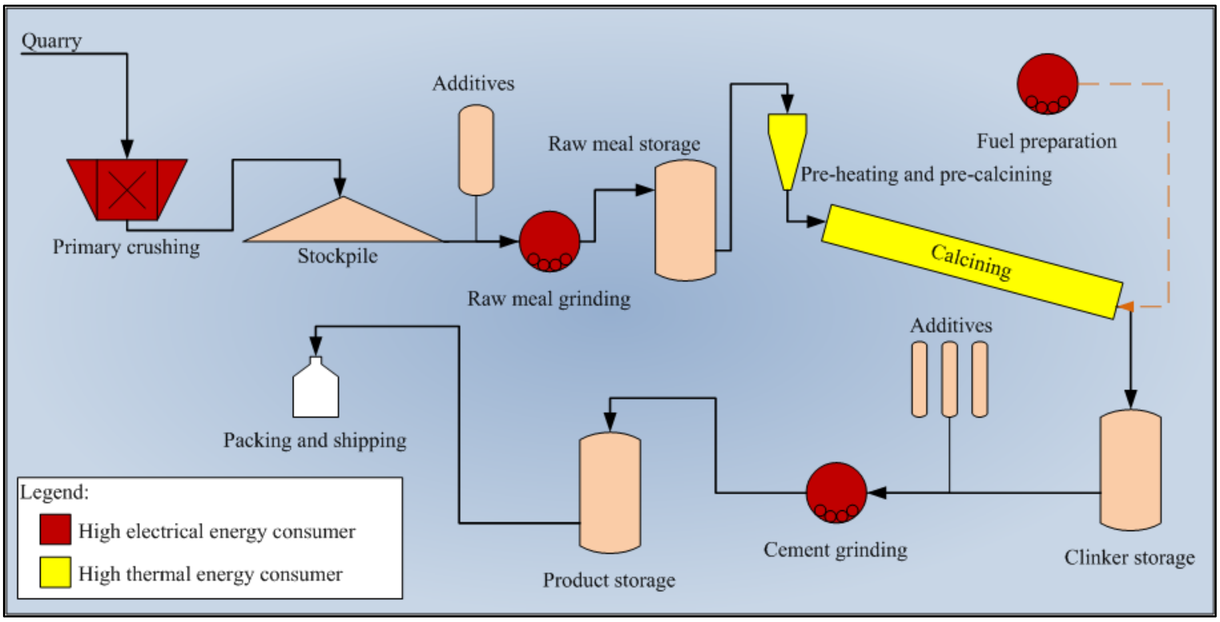


Figure 2-6: The cement process in stages according to primary energy type

Quarrying

Limestone mined from quarries is the primary ingredient of Portland cement. The mining process used in South Africa consists of blasting the rock out of the rock face, before transporting the pieces to a nearby primary processing facility. Most cement plants are located near quarries to reduce transportation costs [27]. Cement plant quarries will often mine additional materials such as shale and lava to make up the required composition for the calcining process.

Crushing

The first processing facility in the cement production process is the crushing plant which consists of a series of electrically powered machines designed to break up the large limestone rocks. The primary device in a crushing line is typically a jaw crusher, which breaks the rocks into small enough pieces for the succeeding steps of the crushing process. The primary crusher is usually followed by secondary, and if necessary, also tertiary crushing machines [28]. Unlike the primary crusher, these devices often operate in a closed loop with a classifier. The classifier determines whether the material exiting the crusher is fine enough to be passed to the next phase. If not, the material is fed back into the crusher through a return loop.

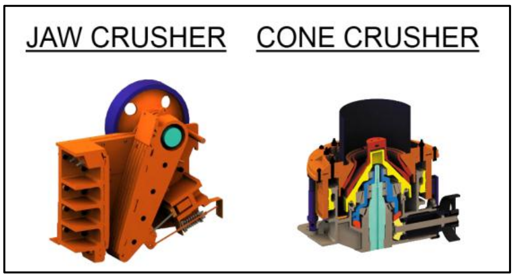


Figure 2-7: Typical crushing equipment of Limestone quarries[26]

The product of this process is pebbles of between 25 mm and 75 mm in diameter. The crushing plant must operate according to the schedule of the quarry personnel, as the material bin between the quarry and the crushing line is very small. This makes it difficult to manage the electricity consumption of the crushing plant.

Stockpiling

The resulting material is conveyed to a stockpile. Most such facilities are configured to homogenise the stockpiled material. The most modern of these is the circular blending bed. As different parts of the rock face contain different impurities, it is important to homogenise the blend to ensure a consistent quality of feed. Some cement plants employ analysing devices to track the chemical consistency of stockpiled materials.

[26] Images courtesy of CMB International Limited.

Consistency in feed quality is important, as limestone alone is not a sufficient ingredient for calcination. Depending on the qualities of the limestone, different additives are required to correct the chemical balance. If the quality of the limestone varies, the quantities of additives required must be changed simultaneously to compensate for these changes. Therefore, a poor homogenisation process will result in extra workload for process engineers on site.

Raw milling

The stockpiled limestone will then be fed into a raw mill along with other raw materials. The raw mill uses mechanical attrition, compression and collision to grind the material into fine particles.

All South African raw mills are dry process mills; the moisture within the material is removed during grinding by passing hot air through the mill. In efficient installations, this hot air is supplied through kiln waste gasses. Some South African plants use a furnace to provide the necessary heat, which requires another stage of thermal energy development to be added to the process. Drying usually occurs along with grinding, as it is more efficient to continually remove moisture from particles while they are refined.

There are several types of mills available for this part of the production process, including ball mills, hammer mills, high-pressure rolls presses, horizontal roller mills and vertical roller mills, shown in Figure 2-8. South Africa hosts at least three newer, more efficient vertical roller mills for raw milling. Studies have shown that these mills consume less energy per tonne of product produced than ball mills [29]. For raw milling specifically, ball mills consume approximately 25 kWh per tonne produced, while vertical roller mills consume 17 kWh per tonne [25].

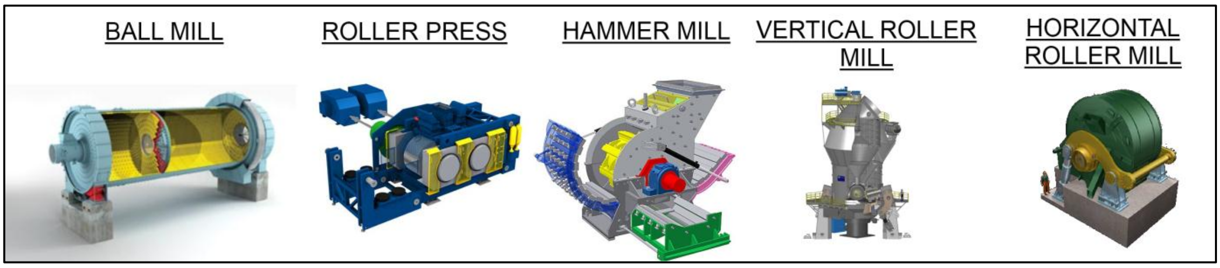


Figure 2-8: Different mill types used in the cement industry[27]

Most raw mills utilise classifiers and feedback loops to ensure that a consistent fineness of material is provided. The material is swept out of the mill by using hot air and then passed through a measuring device to determine the fineness. If the material is fine enough, it is passed and conveyed to storage, while material that could not pass the screens is re-circulated through the mill.

[27] Images courtesy of FLSmidth

The raw meal is usually milled to a point where at least 98% of the meal is less than 150 micrometre (μm) in diameter and 80% to 90% of the mix is less than 90 μm in diameter. Although an unavoidable by-product, care is usually taken to avoid a fineness distribution where the mean is far less than 90 μm, as over-grinding has no benefit and consumes more energy.

Operation of the raw mill is dependent on stock being available from the stockpile, and the stock level of the kiln feed silo. The quarrying, crushing and stockpiling process is typically managed so that there is always stock available for the raw mill to process. The kiln feed silo level usually has a set minimum and maximum level, and the raw mill is operated to ensure that the fill level remains between these two points. Due to the buffer provided by the silo, raw mill stops can be scheduled to coincide with peak periods through careful planning.

Raw meal storage and blending

The product of the raw milling process is called either raw meal or kiln feed. This material is stored in a silo, which serves two important purposes. First, by storing material, a reserve capacity is available should there be a breakdown on the raw mill. In this way, the kiln does not need not be stopped as long as the kiln feed silo is stocked.

Another important role of kiln feed storage is to allow further homogenisation and blending of the raw meal. Figure 2-9 gives a graphic representation of the three common methods used to blend raw meal in silos.

The type of homogenisation silo, as well as the requirements for effective homogenisation, is important to implement effective load shifting. As the quality of the clinker is dependent on the composition of the raw meal entering the kiln, the raw meal blend should remain as consistent as possible. For effective homogenisation, the silos must typically be filled to above a certain minimum level. If the silo level falls below this level, homogenisation is impeded and the plant is in danger of producing poor quality clinker. The minimum silo level requirement must therefore be considered when attempting to manage the production of the raw mills.

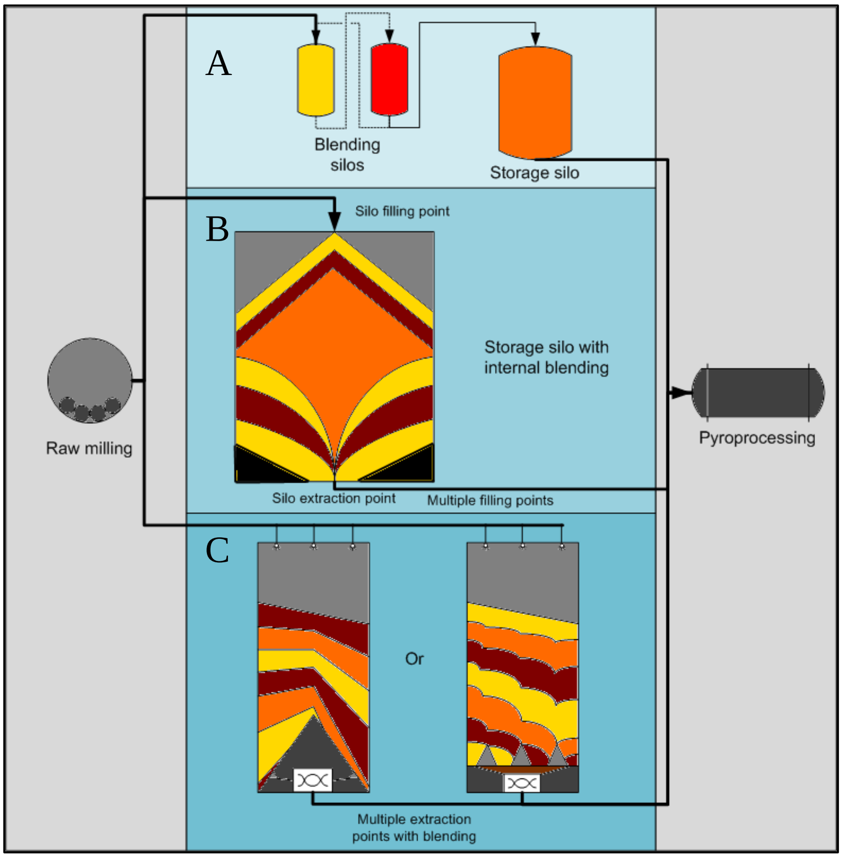


Figure 2-9: Silo types with homogenisation process illustrated (Adapted from **[30, p. 126]**)

The first option (see A, Figure 2-9) is to utilise multiple, smaller silos to blend the raw meal. Cross feeding between the silos enhances the forming of a homogenised blend, which is finally fed to a storage silo. This method is expensive to implement, and takes a great deal of effort to manage. The second option (see B, Figure 2-9) is to utilise comparatively large silos to blend the meal. These types of silos are designed to make use of the angle of repose of the stored material to enhance the blending. This type of raw meal silo usually has a minimum fill level in order to ensure that a well homogenised mix can be extracted continually. The third option (see C, Figure 2-9) is to utilise more modern raw meal silos which are often comparatively small. Advanced computerised homogenisation is built into the infrastructure of these silos using multiple filling and extraction points. This system automatically layers the material fed into the silo so that multiple layers are sampled when the feed is extracted.

Fuel preparation

A combustible fuel is required during the pyroprocessing stage. The fuel used during this stage of the South African cement process is coal, which is ground and pulverised on site to a fine powder before being fed into the kiln. This is done in either a ball mill or vertical roller mill specially designed for this application. There are three methods by which fuel is fed to the pyroprocessing equipment, each playing an important role in how a plant is controlled and managed.

These are [31]:

- direct firing
- semi-direct firing
- indirect firing

The primary difference between these methodologies lies in the method used to feed the coal to the kiln. In the case of direct firing, there is no storage container between the mill and the kiln. Hot gasses from the clinker cooler or kiln exhaust is fed through the coal mill to pneumatically convey ground coal to the kiln. This means that a fault in the coal milling line will require stoppage of the kiln. Another difficulty encountered with this process occurs when coal with high moisture content is milled. This moisture is evaporated into the gas and fed into the kiln, causing variations in flame temperature.

In the case of semi-direct firing, gas passed through the coal mill is fed into the kiln. This gas is passed through a screen, often a cyclone collector, which removes most of the pulverised coal. The latent particles in the gas serve as an added fuel for the kiln. These very fine materials are often more reactive, and help to keep the flame in the correct section of the kiln. In such cases, there are storage bins maintaining a supply of fuel for the kiln. Should the coal mill be stopped and the gas no longer fed as part of the fuel into the kiln, the feeding bins are emptied quicker as more fuel is required.

Finally, the indirect firing process separates the coal mill operation from the kiln. The pulverised coal is stored in a silo or bunker, and latent warm gasses are not fed to the kiln. This process helps to achieve a consistent temperature and position of flame within the kiln (functions of the reactivity and moisture content of the feed). The process is more expensive, however, and care needs to be taken to ensure that combustion does not occur in the storage silo.

Most South African plants make use of semi-direct or direct firing. Because of this, control and management of a coal mill is highly dependent on the kiln it is feeding. Most factories prefer to match the throughput of the coal mill to the feed required for the kiln. Because of this, these components cannot be shut down as part of load management.

Pyroprocessing

The raw meal is then transported to the calcination stage, where thermal energy provided by a flame is used to induce chemical reactions. This typically includes at least a kiln, but may include pre-calciner and pre-heater stages. The fuel for the kiln is a plant’s largest energy expense during the production process [32]. As such, proper kiln management is essential.

The basic steps during the calcination process are as follows:

1. At 100 °C, water not chemically combined in the kiln feed evaporates.
2. Up to 430 °C, dehydration occurs, forming silicon, aluminium and iron oxides.
3. From 900 °C to 982 °C, calcination occurs. Carbon dioxide (CO_2) is formed, reducing the mass of the solids.
4. From 900 °C to 1 300 °C is termed the solid state reaction zone.
5. From 1 300 °C to 1 550 °C oxides previously formed are sintered to form clinker.

This basic process is universal to the Portland cement production process, although several different methods are used to complete it. These methods are usually varied by the choice of kiln type [33]:

- wet process rotary
- semi-wet process rotary
- vertical shaft
- dry process long rotary
- dry process rotary kiln with suspended pre-heater stage
- dry process rotary kiln with suspended pre-heater stage and pre-calciner

Of these, the wet, semi-wet, and vertical methods are no longer used in South Africa, and will not be discussed.

Dry-process kilns are long (up to 200 m), steel tubes lined with refractory bricks. These tubes are mounted at a slight angle (less than 5°) to the horizontal and rotated. Kilns are equipped with at least one burner pipe at the lower end, which feeds fuel into the kiln. The coal fed into the kiln will combust due to hot gasses of 800 °C being blown into the kiln from the clinker cooler. Manual ignition is only required when warming up a kiln.

Material is fed into the kiln at the upper end of the tube. This material is slowly tumbled through by the rotation of the kiln, passing through several temperature zones. Heat transfer further away from the flame is done by the passing of hot gas over the material, a prohibitively slow and inefficient process. Long dry kilns are slow, as material spends between 1,5 hours and 2,5 hours in the kiln.

Adding pre-heater stages to a kiln increases efficiency and throughput significantly. The kiln feed is passed through vertically mounted cyclones on a tower, with hot exhaust gasses from the kiln being passed through. Heat transfer is quicker in a hot gas suspending particles than when gas is passed over particles gathered at the bottom of the kiln. This allows for better heat transfer than in the kiln, and also reduces the length of kiln required as 20% of the calcining process can occur in the pre-heaters.

Pre-calciners are a further improvement of the process. During the pre-calcining process, fuel is injected into a combustion chamber at the base of the pre-heater tower. By blowing in hot air either from the kiln or directly from the clinker cooler, combustion occurs. In systems where hot air from the kiln is required for the pre-calcining process, around 40% to 60% of the calcination process is completed before the feed reaches the kiln. Where clinker cooler waste gasses are used, 100% of the calcination process is completed, and only sintering needs to be done in the kiln.

Clinker cooling is an essential step for the hot clinker passing out of the kiln. An effective cooler can recover up to 30% of kiln system heat [34]. This avoids waste heat being released into the atmosphere. This also enables the transport of the clinker to storage by conventional rather than heat-protected equipment. Fast cooling will also improve the chemical composition of the clinker. The resulting clinker produced takes the form of hard, gray nodules of between 3 mm and 50 mm in diameter.

Two clinker cooler types are used in South Africa – planetary coolers and cooler grates. Ambient air is passed through the cooler in which the hot clinker is collected. Heat transfer occurs, and the hot air is blown into the kiln for combustion purposes. Some of the hot air may also be passed directly to the pre-calciner. Due to the time required to start and stop a kiln, as well as the cost of fuel for warming up the kiln, stopping during peak demand periods is not done.

Clinker storage

Clinker is typically stored in large silos, although some South African operations utilise roofed clinker sheds. Closed silos are preferred, as water coming into direct contact with the clinker will start chemical processes and lead to increased humidity in the material fed into the cement mills. When stored in a waterproof silo, clinker can be kept for months without a reduction in quality. In an open area, clinker needs to be used up quickly to prevent degrading.

Clinker silos tend to be the largest on a plant, usually capable of holding three to six weeks of stock. This is due to the fact that annual or semi-annual kiln maintenance results in a period of two to six weeks of kiln unavailability. In these cases, clinker stocks are the preferred option, although some South African companies do transport clinker between production facilities while kilns are down for maintenance.

Although a common by-product of the large silos, homogenisation within the clinker silos is typically not required. As such, there are no control considerations other than ensuring that sufficient reserve stock is maintained.

Cement grinding

Cement milling is the final processing phase during cement production. As with kiln feed preparation, a mix of materials is fed into a mill and ground until a specific fineness is achieved. The primary ingredient fed into the cement mill is clinker, which has historically made up the majority of the feed [35]. Most modern plants make use of waste fly ash [24] and added limestone [35] during the cement production process, allowing some of the clinker bulk to be replaced. In these cases, the feed usually consists of between 60% to 90% clinker, and 5% to 35% fly ash.

Another important ingredient in cement is gypsum, which helps to retard and control the setting process [36]. Without added gypsum, thermal runaway and flash setting is likely to occur, either making the structure unusable or significantly reducing final strength [37]. Gypsum usually constitutes between 3% and 5% of the finished cement. Other materials are sometimes added during the finishing process, such as special limestone with a unique chemical composition.

The majority of finishing mills in South Africa are ball mills. Until recently, vertical roller mills could not be used effectively during the cement finish grinding process, as these mills had too narrow a band of particle size distribution. Recent advances eliminated this problem, and at least one vertical roller mill is assembled in South Africa for the purpose of cement milling. This is one of two important advances in reducing the energy consumption during the cement production process.

The second is termed pre-crushing. As explained by Jankovic *et al.* [38] and supported by Madlool *et al.* [33], conventional ball mills are not efficient during the initial stage of clinker grinding. As clinker is a very hard substance, breaking it through collision is difficult. By implementing a pre-crusher such as a high pressure rolls press, the efficiency and throughput of the cement grinding process can be greatly increased [29]. This is especially effective when the rolls press is implemented within a closed circuit with a classifier [39].

Air is blown through the cement mill as milling occurs. This is done to partially dehydrate additives. It is important to control the temperature in the mill carefully, as excessive temperatures will produce cement that will not set [40, p. 74]. Air is also used to pneumatically convey the cement powder to the classifier. There, coarse particles are stopped and returned to the cement mill, while fine particles are allowed to pass.

Different grades of cement are measured according to their hardness after 7 days and 28 days of setting [41]. The surface area of the material is the determining factor in the first of these, graded according to the Blaine measurement ($m^2 \cdot kg^{-1}$). The larger the available surface area, the higher the early strength will be [42]. Early strength is important in certain applications, as cement hardening takes a considerable time. A high surface area does not significantly improve final strength, however [42]. As such, over grinding of cement products if not required is a considerable waste of energy.

Cement storage, packing and shipping

The fine cement powder is also stored in silos. From there, the cement is sold either in bulk or packed into bags. Cement can be shipped either by road or rail (most South African cement plants are linked to the national railway network) either to be sold by company branches, or directly to building sites.

Factory packing facilities are often informed directly of sales quantities and formats. As such, cement mills are often operated at the behest of packing plant management. The sales forecast, as well as the format specified (bag or bulk) are two determining factors in cement plant management.

2.3.3 Energy management in the cement industry

A great deal of work has been done on identifying the potential for energy savings on cement production lines. International work includes that of Madlool *et al.* [33] and Hasanbeigi *et al.* [29], and locally the work of Lidbetter [6] is important. These works are mostly aimed at improvements that can be made through infrastructure upgrades. As these can be prohibitively expensive and provide payback periods often in excess of 10 years, such options are not always viable in the present economic climate.

The energy and cost savings that should be targeted first are those that come through better planning and management. One report emphasised the importance of making the best use of existing equipment, concluding that:

> '*Before improving a process, activities of "good housekeeping" and "equipment improvement" should be applied to promote energy conservation* [31]*.'*

Cement plant personnel do not typically implement scheduling techniques to reduce electricity costs. The cause of this is that developing a schedule that takes varying electricity tariffs into account adds a great deal of complexity to planning. When considering the factory as an integrated system, the scheduling problem also becomes too complex to be solved manually [43]. After this plan is fully developed, any deviation, such as when a breakdown occurs, renders it obsolete. The plan would then need to be revised. As stated by Wang and Sun [44], *'the plan can not* [sic.] *catch up with the change'*. Instead, equipment is typically operated as sales demand dictates.

2.4 Optimisation models for cement production lines

2.4.1 Research of Jordaan and Lidbetter

Jordaan [45] and Lidbetter [6] presented simulation models for the raw mills and cement mills of cement plants with shifting load out of evening peak as primary focus. Both of the models presented considered the kiln feed silos in a raw milling line. By assuming a fixed filling rate when the mill is operating and a constant emptying rate while the kiln is running, silo levels could be simulated. Both models also took maintenance schedules into consideration.

Jordaan’s simulation model allowed for the optimisation of the system in a 24 hour window. Applied to a weekday, the model would show what degree of load shift would be possible on a given day. This is illustrated in Figure 2-10. Due to its simple nature, this model can be easily applied to give a general indication of load shift savings available. However, there were some notable shortfalls.

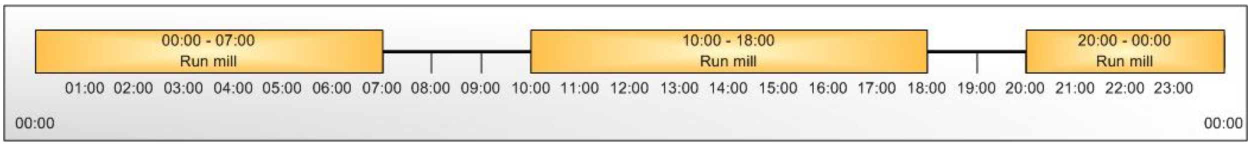


Figure 2-10: Example of Jordaan scheduling model

Firstly, this model used a function which simply increased the cost of peak periods by a thousand fold, rather than using the actual prevailing cost of electricity at certain times of the day. Secondly, this model was limited to being applied in a 24 hour period, from 00:00 to 23:59. Most silos at cement plants hold in excess of one day’s stock; others have sufficient capacity to store stock that will last for several weeks.

An example of the problem this could potentially cause is shown in Figure 2-11. In this example, the model would schedule a peak-hour stop the evening of the first day. As the model is limited to a 24-hour window, it cannot predict a possible stock shortage that may result due to the following day’s maintenance. Because of these two important factors, Jordaan’s simulation model provided only an improved running schedule, and not an optimal one.

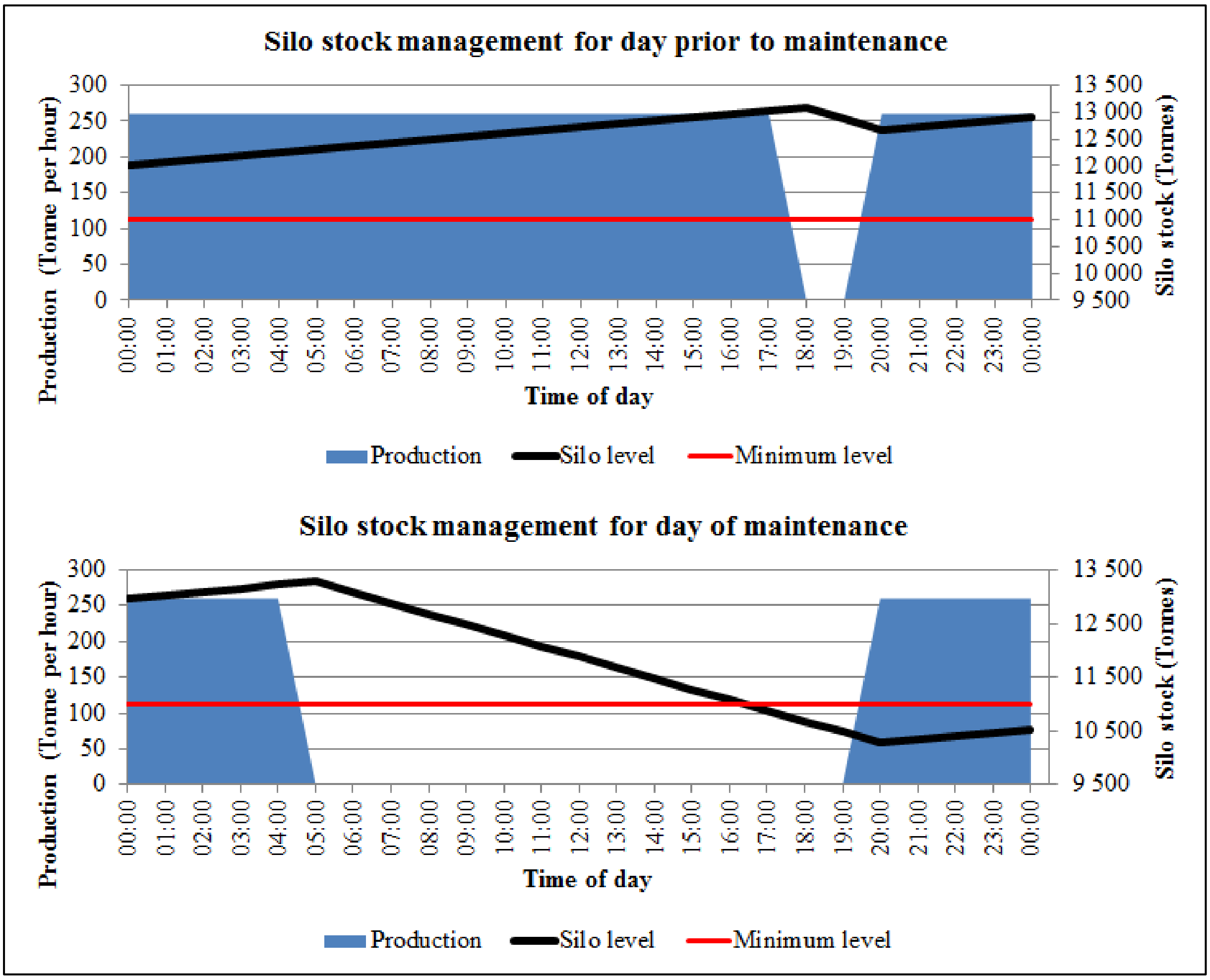


Figure 2-11: Illustration of potential flaw in the Jordaan model

Lidbetter's simulation made up for the second of these two shortfalls, but sacrificed resolution to do so. Lidbetter's model could provide a simulation of silo levels on a daily basis, up to 31 days ahead. This is illustrated in Figure 2-12.

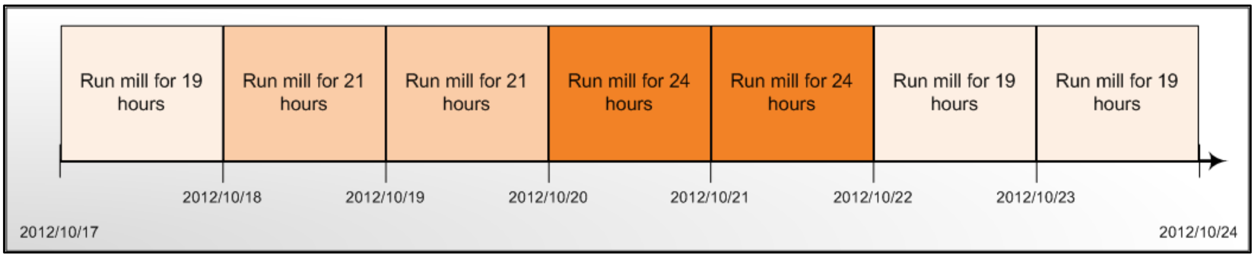


Figure 2-12: Example of Lidbetter scheduling model

Unlike Jordaan's model, Lidbetter did not provide built in optimisation. Instead, controllers were required to manually input the number of operating hours in which load would be shifted. The software model would simulate the resulting silo levels for the month ahead. If the simulation indicated that operating constraints would not be met, the values had to be changed manually to compensate. Again, actual prevailing electricity costs were not considered, and the only concern was to reduce demand during peak hours.

By reducing the resolution of the model to the daily level, Lidbetter's model invites a potential flaw. Figure 2-13 illustrates this problem. In the model, consideration is only made for the silo level at the end of the day. This means that the model may suggest a schedule which could result in silo levels falling below minimum at certain points during the day.

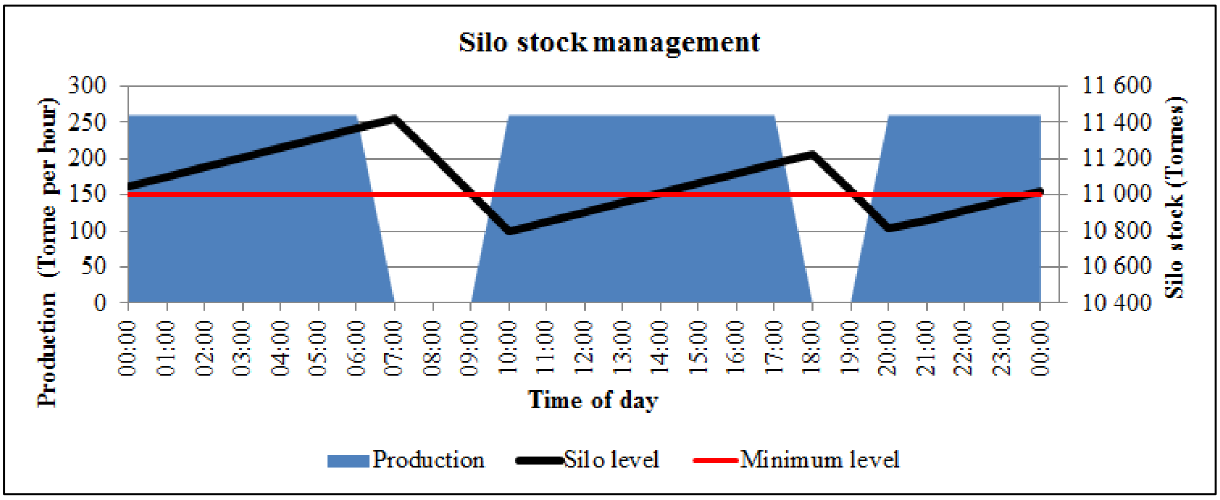


Figure 2-13: Illustration of potential flaw in the Lidbetter model

On closer inspection, it appears that Lidbetter's simulation failed to take the mass reduction that occurs in a kiln into account. A quantity of the particles in the kiln feed is combined with oxygen during pyroprocessing, and is ejected from the kiln with the hot exhaust gasses [34]. This means that a reduced mass of clinker is produced for every tonne of feed. Mass reduction can be calculated using the following simplified formula:

$$m_o = m_f \cdot C \qquad \text{[tonne]} \qquad (1)$$

Where

m_o is the mass of the clinker exiting the kiln, [tonne]

m_f is the mass of the raw meal fed into the kiln and [tonne]

C is the specific conversion factor.

The conversion factor is a value that is dependent on the type and physical characteristics of the kiln, the chemical composition of the kiln feed, and moisture content of the feed. A value of 0,59 to 0,63 is common [34]. As such, a kiln producing clinker at a rate of 120 tonnes per hour will require a feed of approximately 196 tonnes per hour from the kiln feed silo. Therefore, some of Lidbetter's work would need to be redone to calculate the viability of her results.

Another concern with Lidbetter's work was the simulation of cement mills. Cement mills feed from the clinker silos at a plant, as modelled by Lidbetter, and feed into cement silos. This second consideration was ignored by Lidbetter. Ignoring the availability of cement stock for the packing plant is not an acceptable solution.

The work of Lidbetter and Jordaan provided a solid foundation to build forward. Their most important contributions were to show that improved load management was possible, even though neither produced a viable method through which this could be done in a mostly automated manner.

2.4.2 Research of Castro and Mitra

The work of Castro *et al.* [9] and Mitra *et al.* [10] in the field is extensive, with case studies showing simulation results for various electric power intensive processes. Castro first showed that the problem can be approached as a Resource-Task Network. This process is simple in theory, based around the idea of implementing each step during the production process as a task and each component as a resource. At cement plants, this can be difficult to execute due to the complexity and integrated nature of the process, but is still possible.

Castro's solution is implemented in discrete time, which means that his schedules are presented in discrete blocks of time with a specific status. One noted problem with this solution is that it does not allow for accurate modelling of periods while product switches occur. As the case study in Castro's work also shows, for a single stage process such an algorithm requires significant computational time to solve to optimality. When placed in the framework of a cement plant, it is possible that the computation of this model would be too time consuming to be useful.

Mitra's work continues in the same vein as that of Castro. One of the important developments of this work is the inclusion of transition periods, which is made possible by working in continuous time. This is illustrated in Figure 2-14. By introducing concepts from several different models, a solution is presented capable of accurately simulating and optimising a production line with transient modes, and limits on the number of transitions.

Figure 2-14: Example of Mitra scheduling model

One of the notable aspects of Mitra's framework is that it applies multiple models to the same problem so that different constraints can be addressed. Another interesting consideration is that Mitra's work shows a case study with parallel production lines. Although suitable for optimisations on a monthly level, this can be prohibitively limiting for optimising long term solutions. Finally, Mitra's model considers only electricity costs, the minimum time allowed between state changes and the maximum number of state changes. It seems possible that maintenance can be catered for if necessary, but not reliability.

2.4.3 Research of Swanepoel

In 2012, Swanepoel proposed an Energy Management System, the core of which would consist of an integrated optimisation model for cement production lines [11]. This model was intended to improve upon previous efforts, take all known system constraints into account and provide an operation plan for the entire factory which would be optimised to minimise electricity costs. It does this by mathematically modelling plant constraints, and then optimising the running hours of the integrated system. Optimisation would be done by implementing a third party optimisation engine.

Swanepoel's model provided simulation in both the yearly and monthly context. As actual electricity costs were considered, the model was capable of taking the higher winter tariffs into account, thereby allowing production to be scheduled to cheaper summer periods. Where plant personnel would allow, the model was also capable of scheduling kiln maintenance periods. An example of the Swanepoel scheduling philosophy is shown in Figure 2-15.

As Figure 2-15 shows, the model is broken up into different scheduling layers. For each deepening layer, the model optimises the number of production hours required in that period. This value is then passed to the next layer, to be distributed within a higher-resolution context. This allows the model to quickly and effectively produce schedules in the long, medium and short term. In the figure, each deepening lower is indicated as part of a higher level by blue lines.

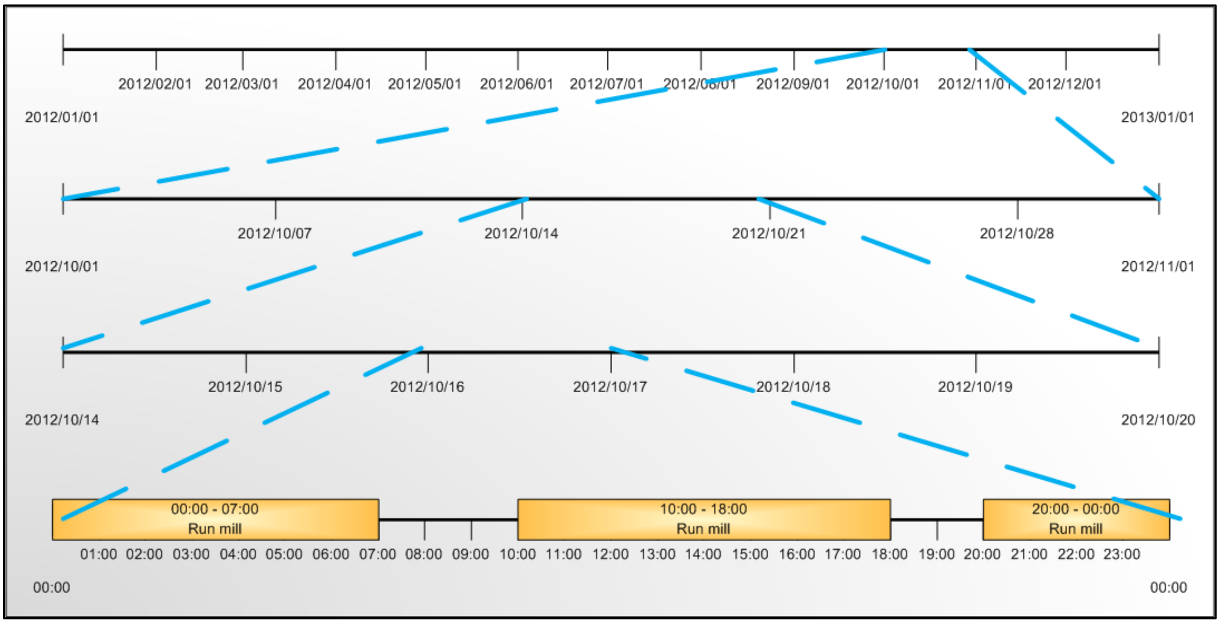


Figure 2-15: Example of Swanepoel scheduling model

On the monthly level, Swanepoel's model took maintenance, silo levels, and cement sales on a daily basis into account. Again, as actual electricity costs could be taken into consideration, the result was an optimal or near-optimal solution. Figure 2-16 shows an interface for the earliest version of Swanepoel's model. As seen on this interface, this model was the first to consider the reliability factor of individual components without resorting to random number generators.

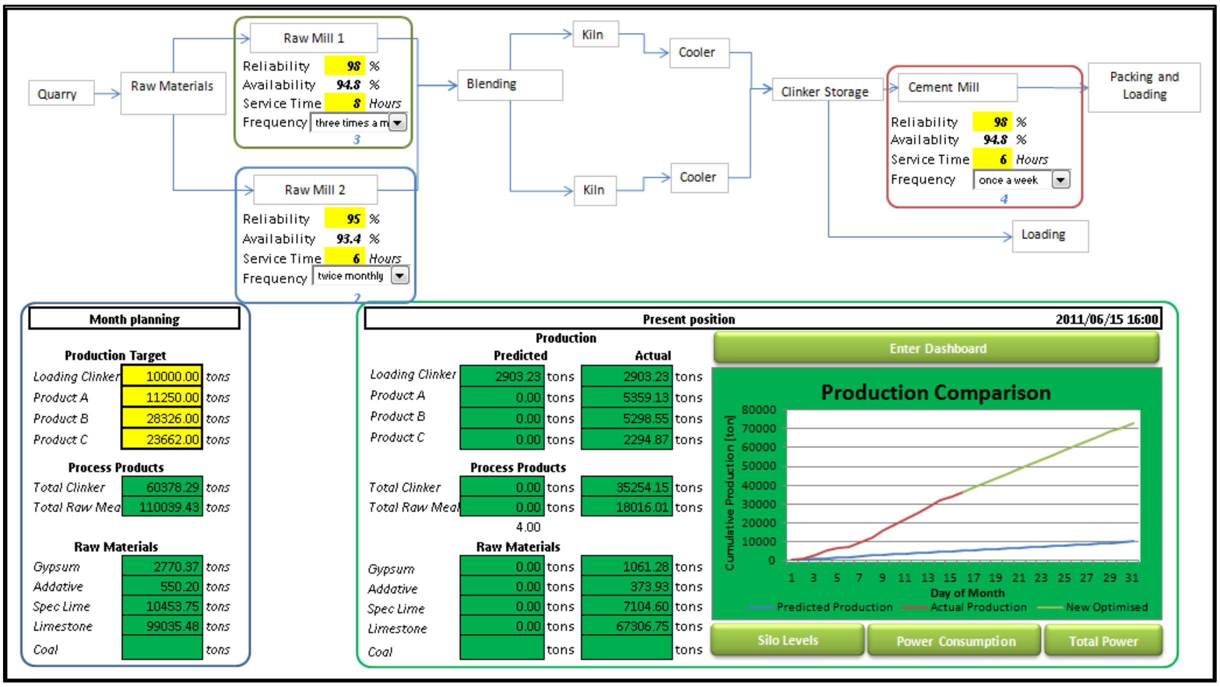


Figure 2-16: Example of the original interface for the Swanepoel model

2.4.4 Commercial optimisation software

Several commercial software packages are available for plant optimisation [46]. However, no literature could be found indicating that these software packages were implemented at a cement production line. Literature surrounding these systems is generally absent. Wang and Sun also indicated this lack of cement plant directed software and literature in [44].

Aspen Plant Scheduler

Aspen Plant Scheduler, a part of AspenTech's AspenOne family of products, includes an interactive scheduler and optimiser. Although literature is scarce, the system seems to be capable of integrating with information sources on site. Schedules can be created by using these sources, including incoming customer orders. Visual interfaces assist users with planning, and also quickly indicate when system constraints are not being adhered to.

The system also includes an optimiser, which is capable of generating a production schedule based on plant constraints. The cost variables that the system considers include penalty costs associated with being unable to produce on time, setup costs in preparing plant components and costs of holding stock in inventory. An apparent limitation is the time period available for optimisation, which seems to be limited to several weeks at most. Although the results achieved with *Aspen Plant Scheduler* indicate that the system may prove to be beneficial in certain environments [47], the considerations pointed out in the previous paragraph indicate that the application of this system would not yield the best possible results.

VirtECS Schedule

VirtECS Schedule from Advanced Process Combinatorics is another scheduling solution aimed at making short-term production decisions. Again, the emphasis seems to be on ensuring that customer orders are met. The system is capable of producing optimised schedules, as well as simulating the improvements that can be achieved through various plant upgrades.

No evidence in literature could be found of the practical implementation of *VirtECS Schedule*. Without verifiable research, it is impossible to give a confident academic opinion regarding the use of this system at a South African cement plant. A single case study is available, but the application seems to be on theoretical level only[28]. However, it seems if the system does not take varying operating costs into account.

[28] Advanced Process Combinatronics, Inc., "VirtECS Scheduler Showcase," 17 February 2005. [Online]. Available: http://www.combination.com/APC_documents/VirtECS_Scheduler_V6_Showcase.pdf. [Accessed 30 October 2012].

SAP advanced planner and optimizer

The *SAP advanced planner and optimizer* is a software system capable of simulating and optimising large and complex systems. Based on available literature, it appears that the system's optimiser only attempts to solve for feasibility, rather than minimum cost. In such case, the system will be comparatively ineffective in reducing the operating costs of South African cement plants with regard to electricity.

2.4.5 Implementing an optimisation model

By comparing the available models, the Swanepoel and Mitra models appeared to be the most favourable to be implemented. Swanepoel's model was developed specifically for the South African cement industry, and support for this model was available in house. As such, it was decided to implement this model.

Swanepoel's model is typically implemented as a mathematical model within a spreadsheet-type workbook. The model optimises plant component operation for discrete time intervals of specific and equal length. The model can be implemented for various time units, including years, months, weeks and days. In each case, the time intervals can be changed to suit the application.

Swanepoel's model has several constraints and requirements for operation. The first set of these are termed static constraints, and are identified and implemented only once in the model. This includes:

- Plant components (Number of kilns, silos, mills, etc.) and component types (Vertical roller or ball mill).
- Layout of components (Position in the production process. For instance, is a ball mill for cement or raw meal grinding?).
- Transport lines available between components (Which components feed which other components).
- Electricity tariff structure applied to the plant.

Next, certain variables were identified as being mostly constant, but may change over time. These items are those which can change without large infrastructure installations on the plant. This includes:

- Cement products manufactured.
- Material blending recipes for raw meal and cement products.
- Component specific constraints (Milling rates, ability to make specific products, electricity consumption when operating).
- Reliability of various components.

A set number of variables were identified as having to be constantly monitored. Some of these were to identify the plant's operating characteristics, and others are important to keep the plant operating within appropriate safety and quality constraints. These are:

- Component statuses (Operating, offline or in maintenance).
- Component feed rates in or out.
- Silo levels.
- Component actual electricity consumption.

Finally, information regarding future plant operation was considered important to the optimisation abilities of the model. These include:

- Maintenance schedules (monthly for mills, and yearly for kilns).
- Sales or production schedules.

This set of information and data requirements indicate that most of the information is required while the model is being constructed. Such information is typically gathered through interviews, investigations, Piping and Instrumentation Diagrams and other technical documents made available by factory management personnel.

Information regarding actual plant status, although smaller in scope, is far denser. For instance, the available information regarding the feed into a ball mill can be split into four to six different ingredients, as well as the circulating feed. These values are constantly updated, usually every second, on the plant network. Although theoretically possible, it would significantly reduce the usability of the Swanepoel model if it was implemented in such a way that this information needed to be gathered manually.

The next basic step regarding the Swanepoel model is the integration of data. The different data sources are specific to different time intervals, and would likely be available in different formats. For instance, a silo level would be available as an instantaneous measurement at a point in time, either from the plant Supervisory Control and Data Acquisition (SCADA) system or from plant operation sheets. In contrast, planned maintenance information is usually available as a calendar with several time periods booked as maintenance periods. This calendar would be available either as a workbook, or as knowledge of plant personnel. The process is shown in Figure 2-17.

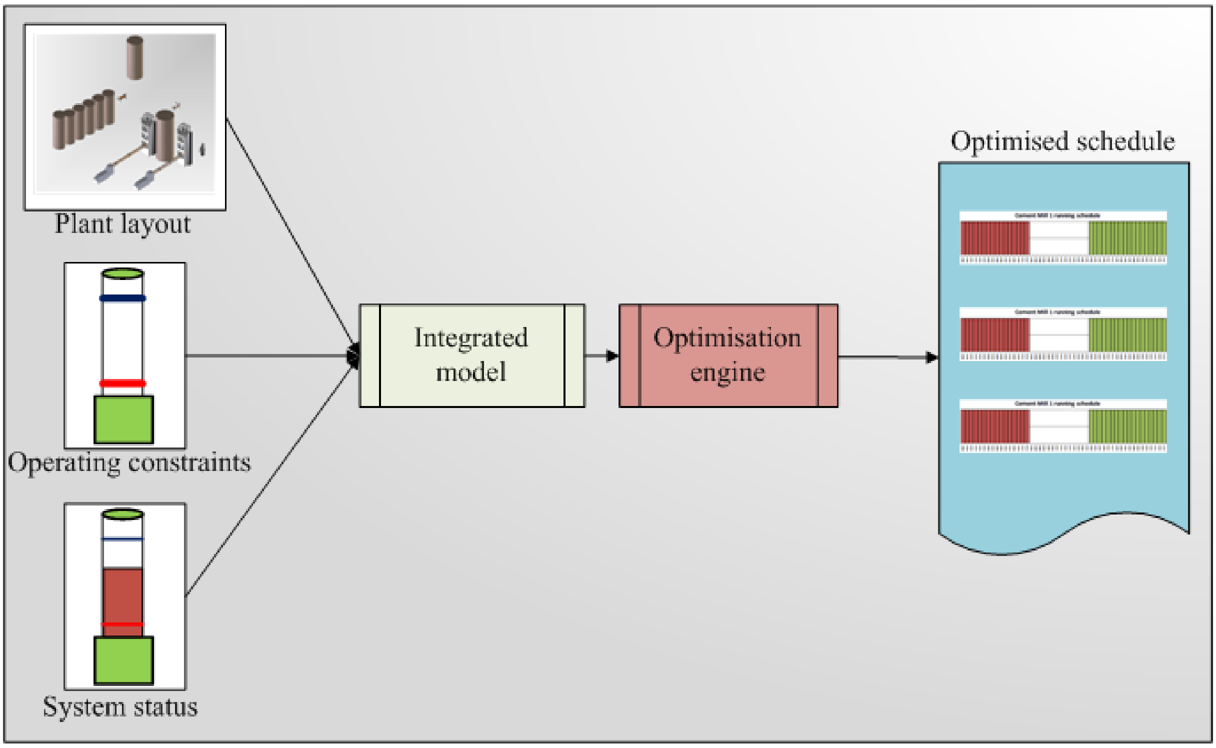


Figure 2-17: The process of the Swanepoel model

Due to the varied nature of information and its sources, an effective solution would need to be able to gather and incorporate all the available information sources automatically. In addition, this system needs to be adaptable when new and different sources of information are added without having to introduce significant changes.

During the next step, an optimisation engine needs to be applied to the Swanepoel model that has been populated with the gathered data. This optimisation will attempt to reduce production costs to a minimum level while still keeping all parameters within plant constraints. Finally, the resulting optimised operation would need to be communicated in a timely, clear and comprehensible form to plant personnel responsible for making operational decisions.

The most important considerations for implementing the Swanepoel model can be summarised as follows:

1. Data needs to be collected from various sources.
2. The gathered data must be incorporated into the model.
3. An optimisation engine must be applied to the model.
4. The results need to be distributed to relevant personnel.

As these steps are mostly concerned with the gathering, processing, and distribution of data, it was decided that an automated computer system would be the best solution.

2.5 Conclusion

In this chapter, the Eskom tariffs, which are fundamental to the intended result of the study, as well as different Eskom initiatives aimed at load management were presented and discussed. Following this, an overview of the cement production process commonly practiced in South Africa was given. It was followed by a review of the available simulation and optimisation models. Following this, the Swanepoel model was designated as the model to be implemented. Finally, the challenges presented by implementing a model in general, as well as the Swanepoel model specifically, were investigated.

Chapter 3 Design of the optimisation system

3.1 Preamble

This chapter describes the development of a system to implement a cement plant optimisation model at a practical level. The design requirements for the system will be identified and explained. A verification and validation plan is developed to measure the results of the implementation. Following this, a conceptual design is performed to develop the framework required for the solution. Finally, a detail design is performed.

3.2 Design requirements

3.2.1 Scope

The scope of this design process is limited to the system level. While attention will be given to certain software specific requirements, code level analysis will not be presented. The purpose of the system is to automate the process of implementing the Swanepoel optimisation model. The placement of the intended system is shown in Figure 3-1.

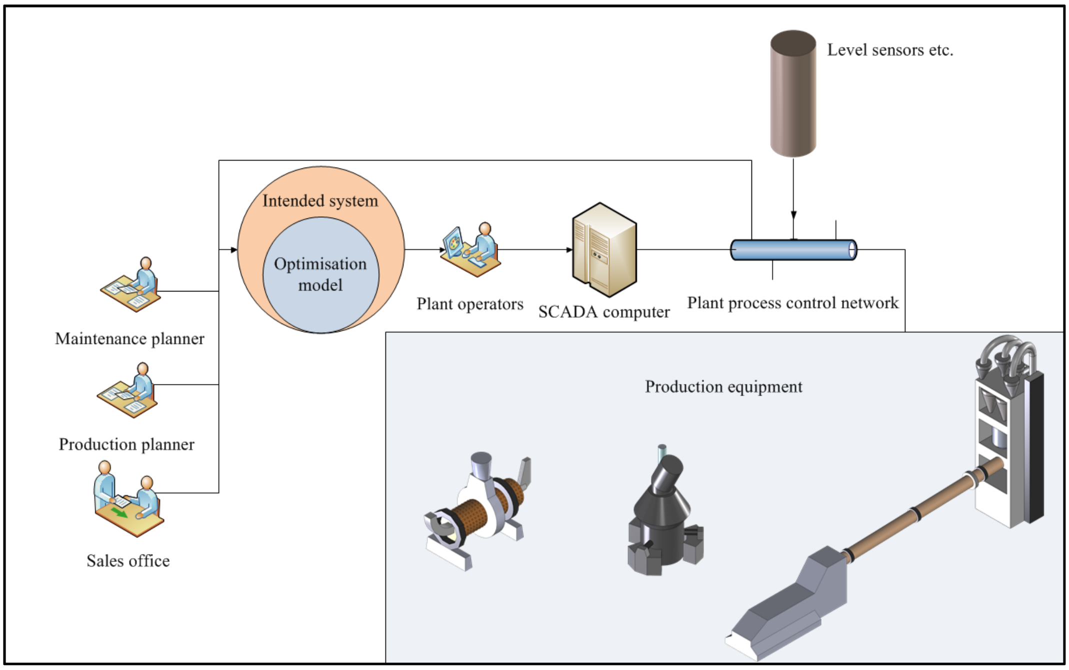


Figure 3-1: Placement of the intended system

To do this, the following steps are required:

1. Collect data and information automatically.
2. Process input data and information.

3. Integrate the processed data and information with the Swanepoel model.
4. Apply an optimisation engine to the model.
5. Record and communicate the optimised results.

All inputs from the plant to the Swanepoel model are to be managed by the system. Control of the model, as well as its outputs, must also be managed by the system. The system should be designed to include multiple factories. It should therefore either consist of one system that can be easily duplicated, or a system that can be expanded to include more than one plant.

3.2.2 Input requirements

In Chapter 2, the different information requirements of the Swanepoel model were discussed. These requirements will now be summarised according to type and component. Of key importance is the fact that some of the information will remain constant, while others will be time variant. For instance, the maximum storage capacity of a silo group will remain the same, unless an additional silo is constructed at the factory. An example of a varying data source is the stock level of a silo. A list of each component and the information inputs assumed to remain constant are given in Appendix A, Table A-1.

Each component also has a number of variables that will change over time. These variable values need to be recorded and updated within the Swanepoel model. A list of such variables, sorted by component, is given in Table A-2.

Certain components also have operating constraints, such as the maximum number of times a mill may be shut down during a day. These constraints also allow the factory personnel to manage the risk involved with altering normal operating schedules by allowing plant personnel to specify safety margins. A list of such constraints is given in Table A-3.

Certain information inputs were identified as being related to calendar events. These include tariff rates at different times of the day, week, and year, as well as scheduled maintenance. Public holidays also enjoy different tariff rates. Finally, if sales offices expect high sales volumes, packed stocks may need to be built up during the preceding weeks. A summary of such events is given in Table A-4.

Four different methods of data input were identified and should be included in the system. The first method is to program values directly into the Swanepoel model. Secondly, data should be logged from the plant SCADA system. Thirdly a user interface, where plant personnel could manually adjust constants and constraints, should be used to record data. Finally, where possible, the plant status- and log sheets distributed on a daily, weekly, or monthly basis should be collected and incorporated automatically.

Outputs from the Swanepoel model typically take the form of graphs, charts and tables. The system needs to be designed to handle a varying number of graph and table outputs. An example list is given in Table A-5. Supplementary graphs may be requested to suit particular requirements.

3.2.3 Quality assurance and system verification

Prior to the design phase, criteria to evaluate the quality of the resulting system will be established. A set of verification tests were developed based on the requirements identified. The verification methods considered in this section are aimed at integration and system level. System tests are aimed at the performance of the system as a whole. Component tests will be conducted during implementation to ensure that individual units meet requirements within specifications, but the results will not be reported.

Table 3-1 represents a verification table developed for the system under consideration and shows the different verification methods that will be used. These include inspection of components, demonstrations, mathematical analysis, and tests.

Table 3-1: Verification table for the intended system

Verification Methods		Verification Tests	
1	Inspection	A	Development
2	Demonstration	B	Simulation
3	Analysis	C	System
4	Test		

Requirement:	Verification Method: 1	2	3	4	Verification Tests: A	B	C
1. User interface for inputs and outputs	x	x		x		x	x
2. SCADA data logging			x	x		x	x
3. Collection of data				x		x	x
4. Processing and integration of data		x	x	x	x	x	x
5. Implementation of optimisation engine		x	x	x	x	x	x
6. Communication of optimised schedule			x	x	x	x	x

3.3 Conceptual design

Figure 3-2 represents the simplest form of the functional flow diagram of the proposed solution. The system's goal is to gather several inputs, process these inputs, and generate a specified output. The information and data from the various plant data sources must be gathered, processed and integrated into the system. This processed information should then be inserted into the Swanepoel model. An optimisation engine must then be applied to the model. After an optimised solution has been generated, the schedule and simulation data needs to be presented in a logical, concise and informative way to plant personnel.

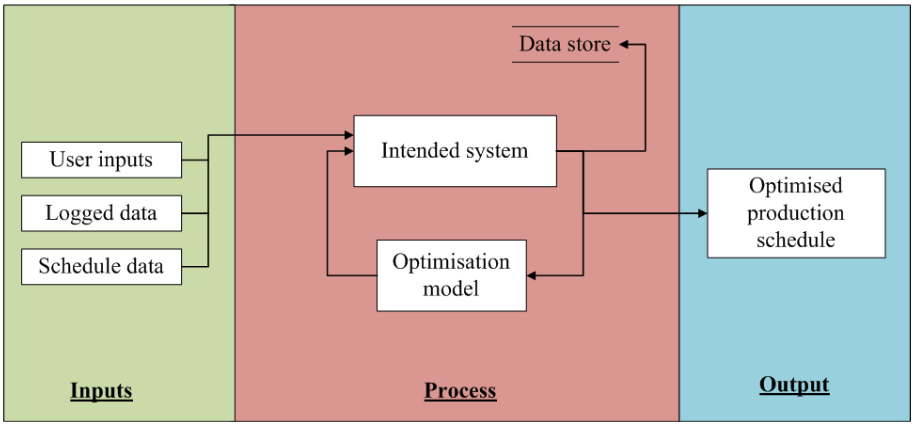


Figure 3-2: Functional flow diagram for proposed solution

Figure 3-3 shows the functional architecture of the system. First, all relevant information needs to be collected from various sources and transferred to the data integration process. The data is processed and integrated into the simulation model, and this model is optimised. The results are sent to the despatch process.

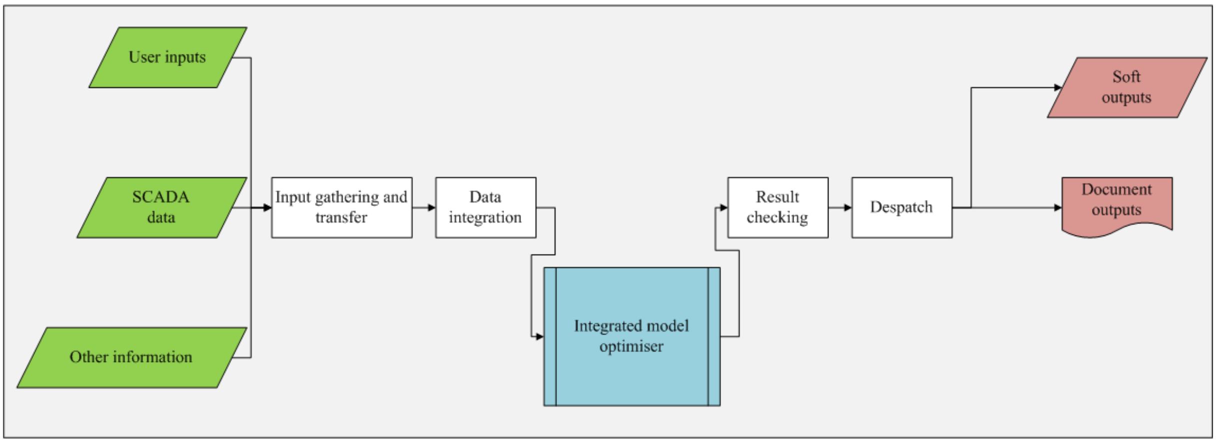


Figure 3-3: Functional architecture of the system

3.3.1 Functional layout

Cement plants usually have an integrated computer network, allowing data and control inputs to communicate with various other production components and equipment in the plant. Typically, this includes Programmable Logic Controllers (PLCs) to control individual plant components such as fans, oil pumps and drive motors. These PLCs are linked to a SCADA computer system, which receives data and transmits instructions to PLCs. The SCADA receives instructions either manually from plant personnel (via a computer terminal) or automatically from a software control program.

The SCADA computer is housed in a server room within the factory control room. From the control room, operators monitor components and adjust operating conditions to achieve desired outputs. Plant operators receive instructions from the production management team which include planned running times and information regarding feed mixtures. Because the Swanepoel model provides production schedules, the system would need to be able to communicate either directly with the control room, or with production managers. In addition, as data available from the SCADA computer would be necessary, communication with the factory network would be essential. This is typically done either by directly connecting to the SCADA computer through Object Linking and Embedding for Process Control (OPC), or by retrieving data from the data historian computer. As not all factories have data historians, the latter option was ruled out. Two layout options were presented and analysed.

Option A: Centralised system on plant

The first option was to design and implement a system centralised at the factory site. A single computer would be installed on site, connected to the plant process control network and administration network. This would enable data communication with the plant SCADA system, as well as access to files on the plant management network. A computer screen and standard input devices would also be installed, allowing plant personnel to access to the system. This configuration is shown in Figure 3-4.

This option has the advantage of being the simplest to implement, as all data and information can be collected from the same physical network. Once the information arrives, it can be processed at a single location, and results are kept locally for operators to browse.

The primary disadvantage of this option is cost. An individual optimisation engine would need to be purchased per project, along with a server computer capable of running the engine. It is also likely that the dedicated optimisation engine would not be fully utilised, as running optimisations continuously would not lead to significant improvements of the optimised schedule. Another disadvantage is that it would reduce the effectiveness of maintenance, as project engineers would have to travel to site to discover why faults occurred and to correct them.

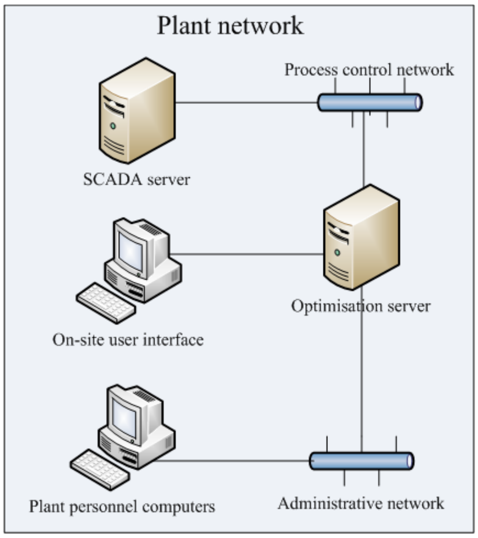


Figure 3-4: Physical layout for Option A

Option B: Remote system

The second option involves only a single computer system being put in place at a central location. This computer would be placed on an electronic network to allow communication with the project sites. Data and information would need to be sent by plant personnel on site. This data would then be processed locally, where after a schedule would be sent to plant personnel.

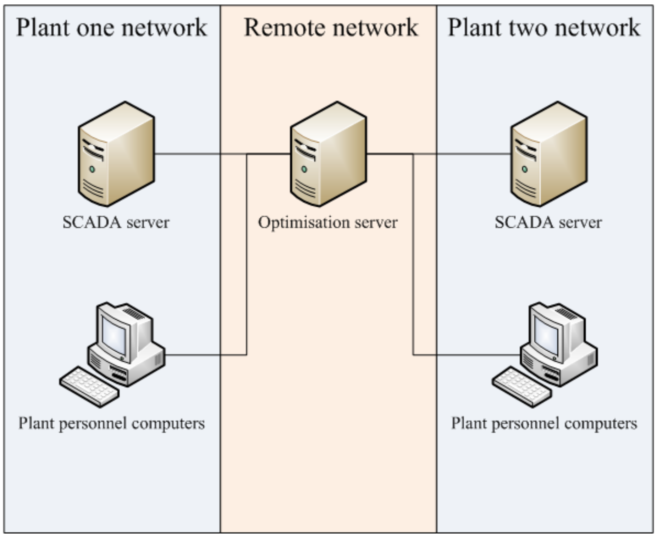


Figure 3-5: Physical layout for Option B

This system significantly reduces capital investment to implement the project, as a single computer system is required. Only one optimisation engine would have to be purchased to perform the necessary work for multiple plants. Finally, the system could be located near engineering and maintenance personnel, reducing system downtime after a fault occurs.

There are some significant disadvantages involved as well. The system becomes dependant on multiple links in a communication chain, and any one failure would prevent the operation of the entire system. Secondly, the remote nature of the system might hinder plant personnel who attempt to integrate the system into plant operating procedure. Finally, this system would be dependent on either an automated solution being developed to log and retrieve SCADA data remotely, or plant personnel being relied on to send the data on a daily basis. This increases the risk of failure of this option. The two options are compared side by side in Table 3-2.

Table 3-2: Comparison table of system architecture options

	Option A: Centralised system on plant	Option B: Remote system
Cost	Very expensive	Low
Reliability	High	Moderate
Maintenance	Difficult	Easy
Complexity	Simple	Moderately complex
Ease of use	Easy	Difficult, requires extensive training.
Level of interactivity	High	Low
Security	High	Moderate

Although it is obvious that a single system at a project site is the more reliable option, the prohibitive cost is a problem. Only very limited funding was available for the research task. The implementation of Option A was calculated to be 400% more expensive than Option B. In addition, adding an additional project using Option A would mean incurring the full system cost again. By contrast, option B could handle multiple projects without incurring additional costs until the processing time available on the centralised computer was expended. As the optimisation engine was the primary expense, the preferable option would be to purchase only one such engine. As such, it was decided to hybridise the system to include the most desirable qualities of both options.

Hybrid system

The hybrid system would utilise both a remote and an on-site computer, linked through a secure communication network. The on-site computer would provide both an interface between the system and plant personnel, as well as a data logging system. This data would then be transmitted to the remote computer.

Software would be developed for the remote computer to sort, process and integrate the incoming data from the various information sources. Once integrated, the system could then run the optimisation engine on the simulation model, resulting in an optimal schedule. This optimal schedule could then be returned to the on-site computer and displayed to plant personnel.

The advantage of this system is that it reduces the overall cost of the system. The hybrid system was estimated at 211% of the cost of implementing Option B. This system would be far easier to integrate into plant operations, as a user interface would be easily accessible on site. Maintenance of the model and integration of the system would be much easier.

The primary disadvantage of this system is increased overall complexity. However, as each component of the system has less diverse tasks to perform, individual parts of the system become simpler and more reliable. As each component of the system is now responsible for a task, fault finding also becomes easier.

3.4 Detail design

3.4.1 Detail architecture

Due to the varied tasks that need to be performed by the system, the tasks were split into several different software programs. Figure 3-6 shows an overview of the system architecture, with each individual program indicated. These programs are split between the on-site and the centralised computer servers. Each of these programs has its own set of interfaces.

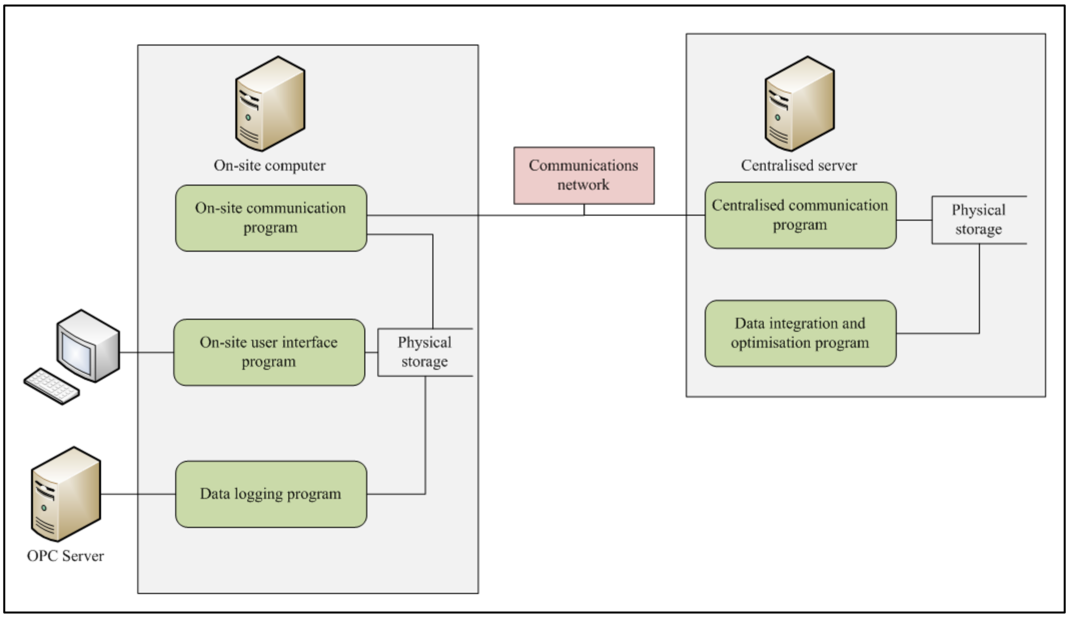


Figure 3-6: Overview of system architecture

Figure 3-7 shows how data communication was secured. All data file were sent via regular e-mail. These e-mails were sent through client servers, which scanned both incoming and outgoing messages to ensure that no unsafe/harmful content passed through the system. In addition, both the central server and the remote computer were fitted with active anti-virus software. Remote access for maintenance was done through a secured Virtual Private Network.

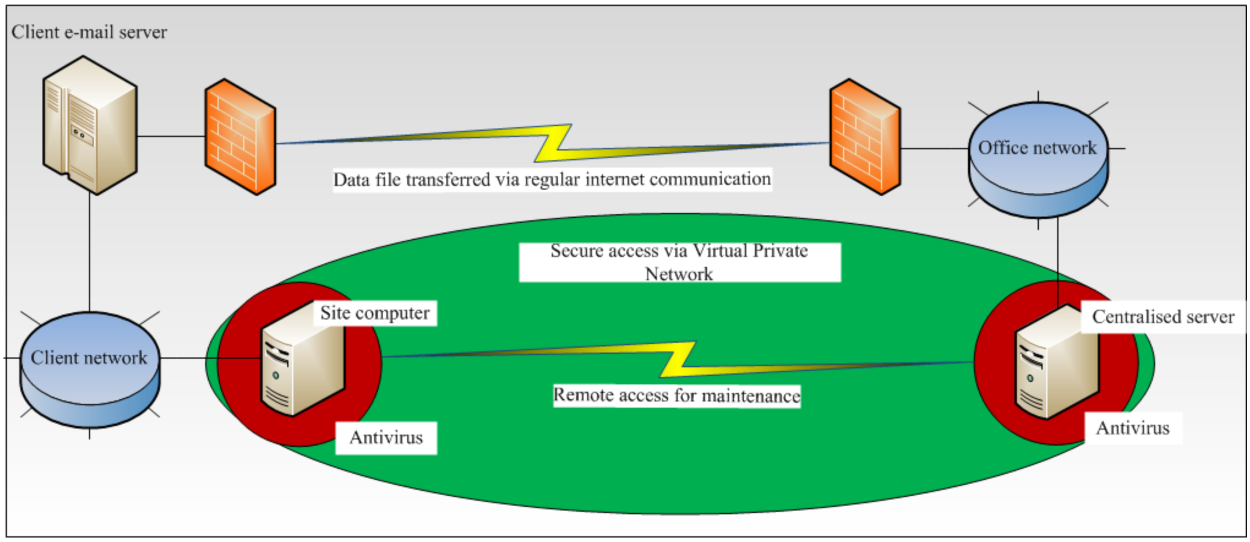


Figure 3-7: Overview of data communication security

Figure 3-8 shows the interfaces of the on-site user interface program. As shown, this program must provide an interface for users to interact with it. The program must also be able to interface with the optimised model and on-site data workbook.

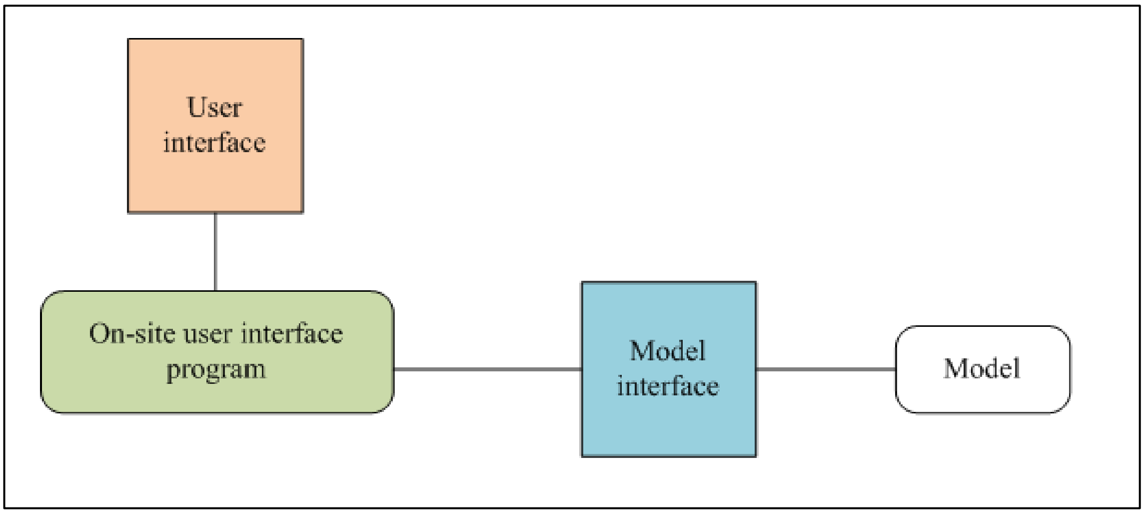


Figure 3-8: On-site user interface program interfaces

Figure 3-9 shows the different interfaces for the data logging program located on the plant network. This program requires a user interface for setup purposes, as well as an OPC interface to communicate with plant data sources. Finally, the data retrieved must be logged and stored on the local hard drive.

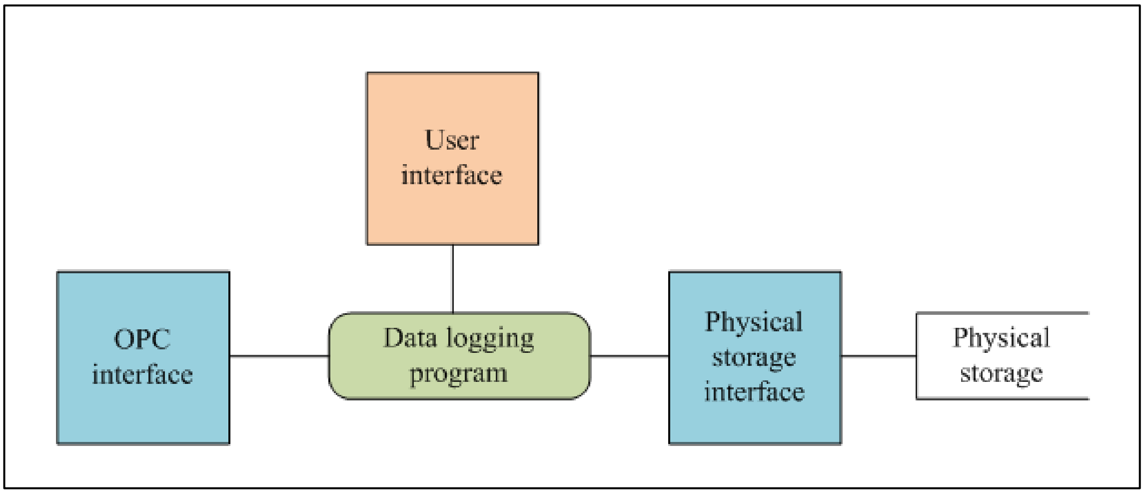


Figure 3-9: On-site data logging program architecture interfaces

Figure 3-10 shows the interfaces of the on-site communication program. This program requires a user interface for initial configuration. It also requires an interface with the physical storage of the on-site server, as well as a communications network which allows data to be sent and received.

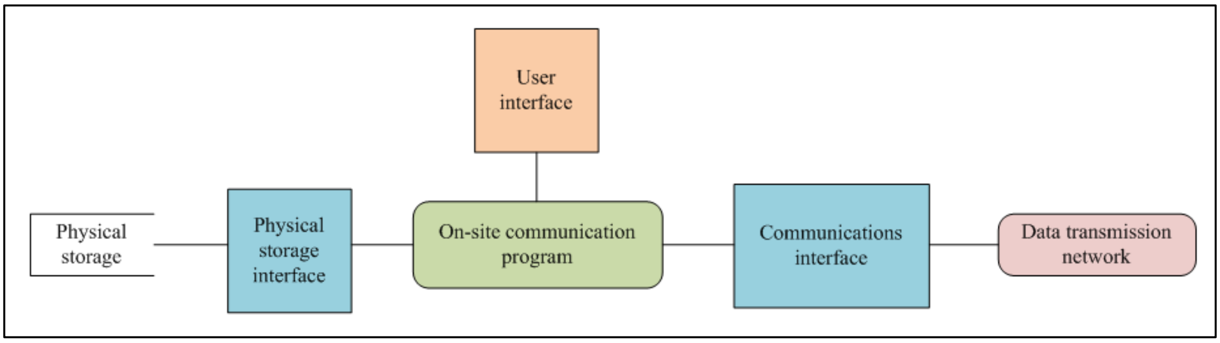


Figure 3-10: On-site communication program interfaces

Figure 3-11 shows the interfaces of the centralised communication program. It possesses the same interfaces as the on-site communication program. It is important to note that the data transmission network shown in Figure 3-10 and Figure 3-11 are either the same, or linked to each other.

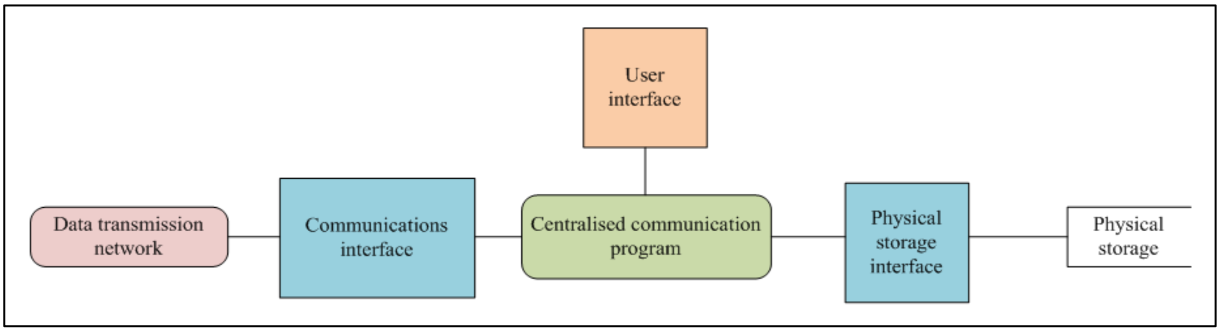


Figure 3-11: Centralised communication program

Figure 3-12 shows the interfaces of the data integration and optimisation program. This program requires access to the physical storage of the centralised server to allow movement and storage of files, such as the file which contains the Swanepoel model for the plant. It also requires an interface to interact with the simulation model, and the different optimisation engines present.

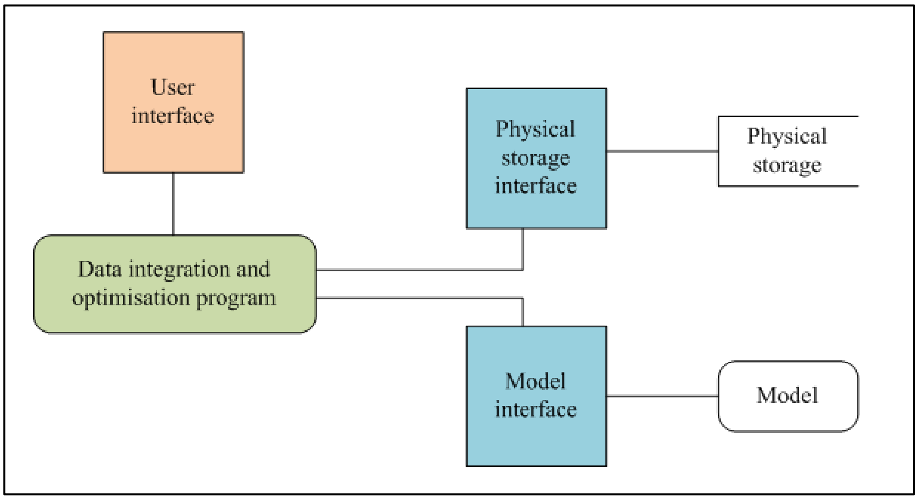


Figure 3-12: Data integration and optimisation program interfaces

3.4.2 Detail data flow and processing

Figure 3-13 shows the simple, first step, the data logging program uses to periodically log data. This data is the instantaneous value of the different tags available through the OPC interface. This data is typically logged once every two minutes in a simple comma delimited text file.

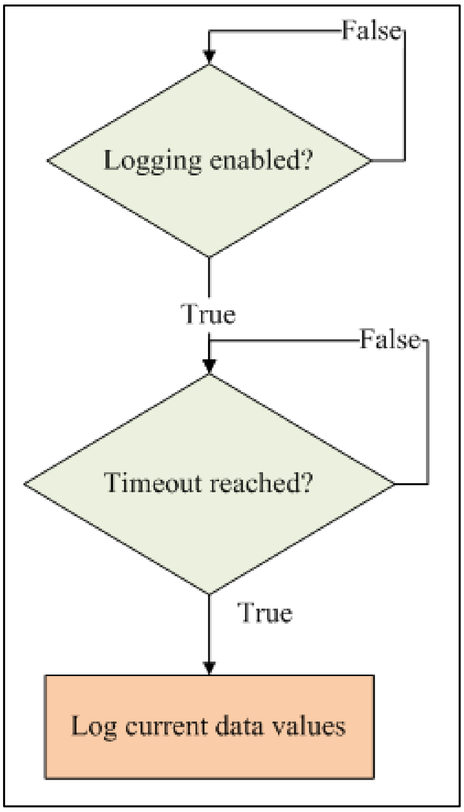


Figure 3-13: Flowchart of data logging program process

Figure 3-14 shows the process followed by the on-site communication program. This program, when enabled, will check for incoming and outgoing data in programmed intervals, which would usually be set to every 15 minutes. When incoming information arrives, it is in the format of updated schedules. This is then transferred to the user interface program. At certain intervals, the logged data is despatched to the centralised server for processing.

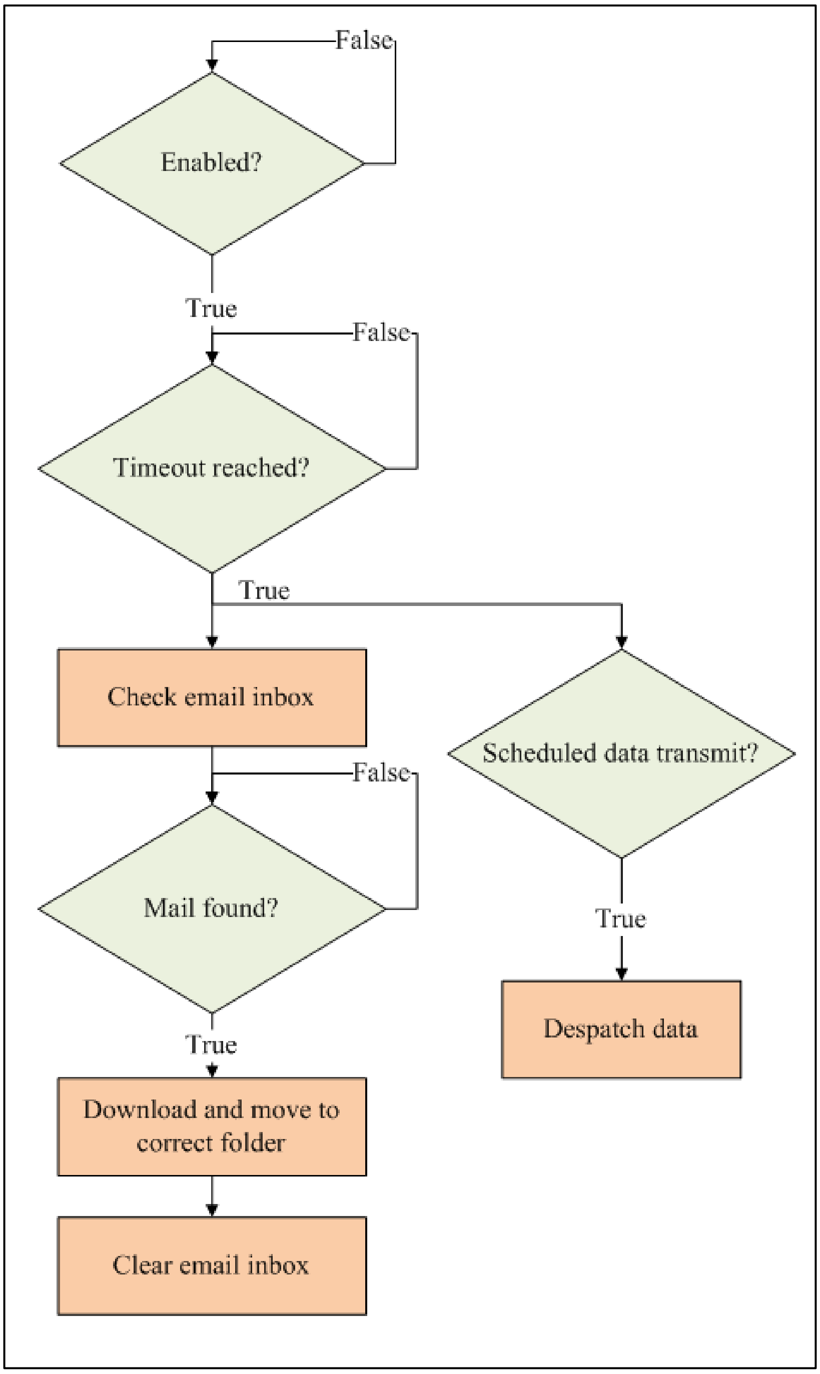


Figure 3-14: Flowchart of on-site communication program process

Figure 3-15 shows the process followed by the centralised communication program. Although similar in operation to the on-site version, this program requires several additional logical decisions. Whenever data is received, it is important that this data is sorted and stored in the correct incoming folder. Similarly, schedules placed in a specific outgoing folder must be sent to a specific on-site system. At this stage, data from multiple sources needs to be sorted. For instance, the maintenance and production data for a project may originate from different sources, but have to be stored in the same folder.

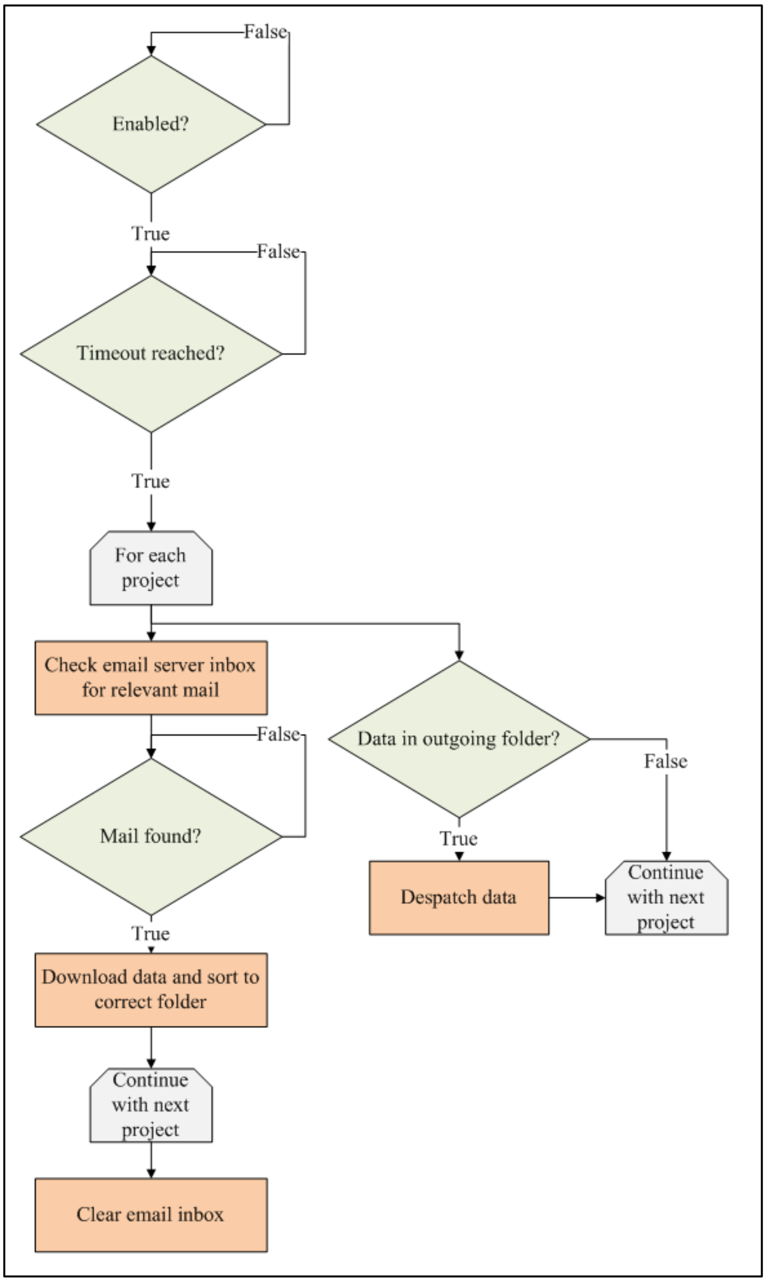


Figure 3-15: Flowchart of centralised communication program process

Figure 3-16 shows the data integration process of the data integration and optimisation program. When enabled, this program continually checks the incoming data folders for new data. When new data arrives, the program must first identify the data type. This could be logged data, worksheet data or user input data. Depending on the data type, a specific function is applied to process and integrate the data.

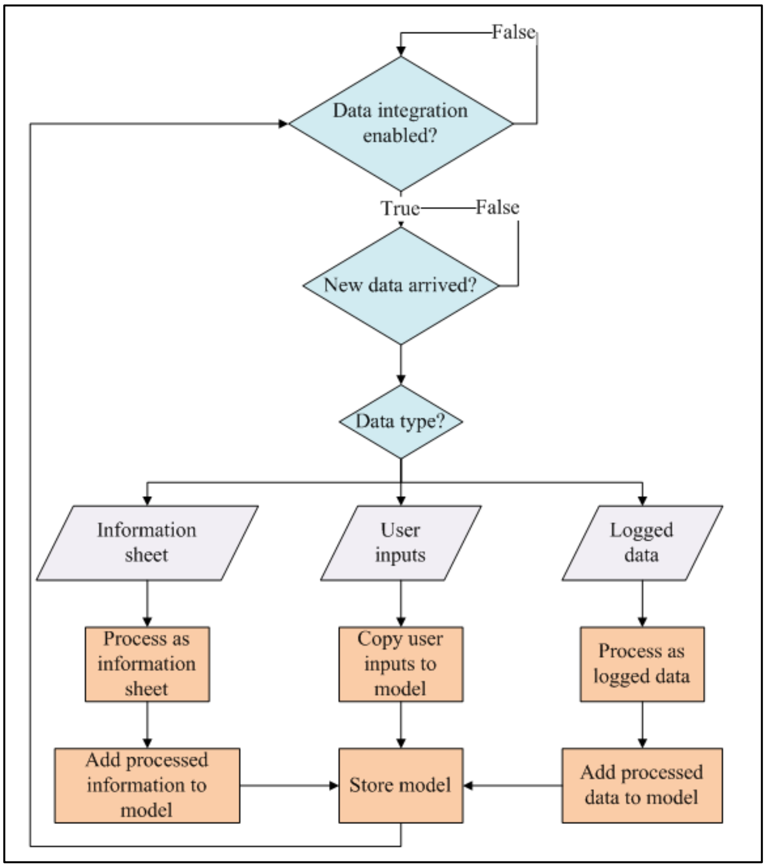


Figure 3-16: Flowchart of data integration process overview

Figure 3-17 shows the data processing step in greater detail. In the case of information sheets or user inputs, the process is simplified. The program checks whether a map sheet has been created to instruct it on where incoming sheet information or user inputs need to be placed. This sheet can be fully customised to allow user flexibility in the integration of incoming production and maintenance information.

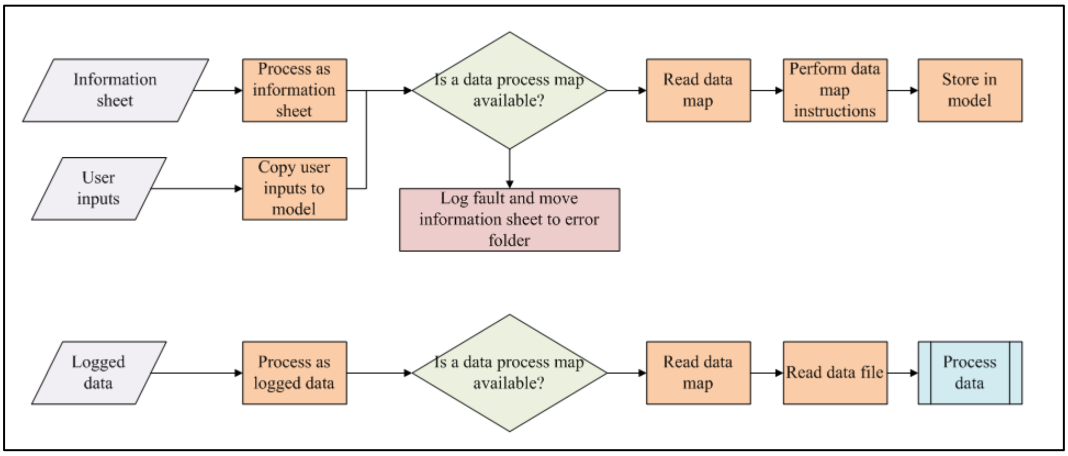


Figure 3-17: Flowchart of breakdown of data processing step

Figure 3-18 shows the steps taken to process logged data. Again, a data map is used to determine how the logged data is to be processed. The raw data logged on-site has a very high resolution which needs to be reduced. However, different data types cannot be reduced in the same way. For instance, the electricity demand of a component should be averaged per hour so that the electrical energy consumption for that hour can be calculated. On the other hand, when working with silo levels, it is beneficial to use the silo level at the end of the hour.

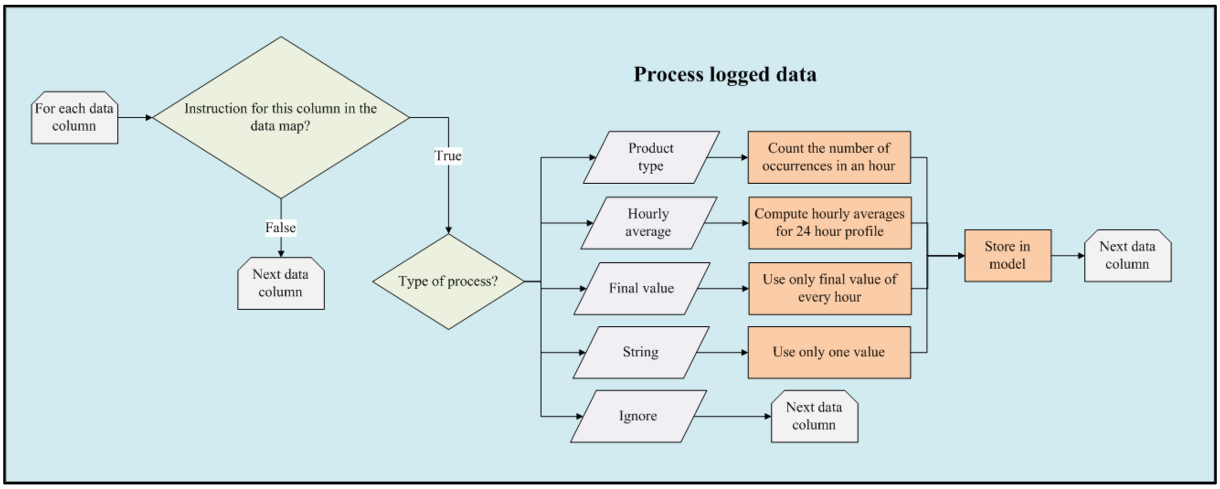


Figure 3-18: Flowchart of logged data processing steps

Another type of logged data that needed to be incorporated was the production status of cement mills. As this was subject to change several times per hour, a new notation was developed to present this data. This notation is in the format *Offline*:*Product 1*:*Product 2*: *etc*. In this format, the number of observations of each state within an hour is given. This would indicate to the user what percentage of time within each hour was spent manufacturing each product. A potential flaw of this solution was that it was not possible to determine in which order each product was made. However, this flaw is easily overcome by checking the data of the preceding and succeeding hour.

Figure 3-19 shows the process followed by the optimisation program. Instead of implementing a fixed process within the program, the optimisation step was implemented as a script run within the model workbook. This allowed for greater flexibility in the optimisation process.

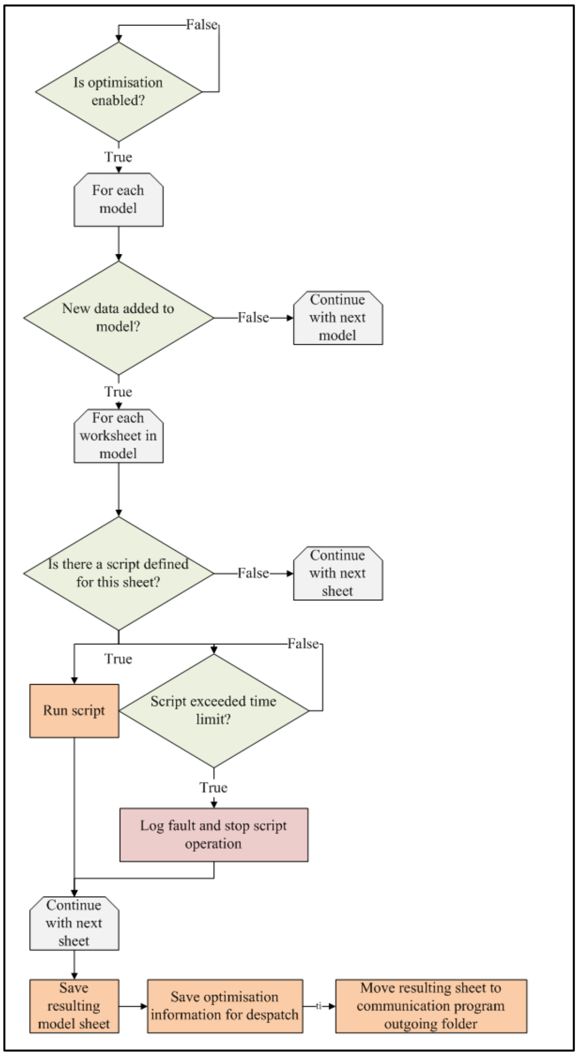


Figure 3-19: Flowchart of optimisation process

The standard implementation of this script was to run a third party optimisation engine on the model, as defined by Swanepoel [11]. This engine would vary the production hours of different plant components and attempt to solve for minimum costs. The constraints of the model were set to be the same as those of the plant, to force the optimised model to always fall within operating constraints. A typical implementation is shown in Figure 3-20. When implemented, the Swanepoel defines every plant component as a unique step in a mathematical equation. Using starting values based on plant data, the model can be used to simulate the behaviour of the plant for various operational plans. By applying an optimisation engine to run through the different operational plans, an optimal solution can be found. Further details regarding the workings of the model can be found in [11].

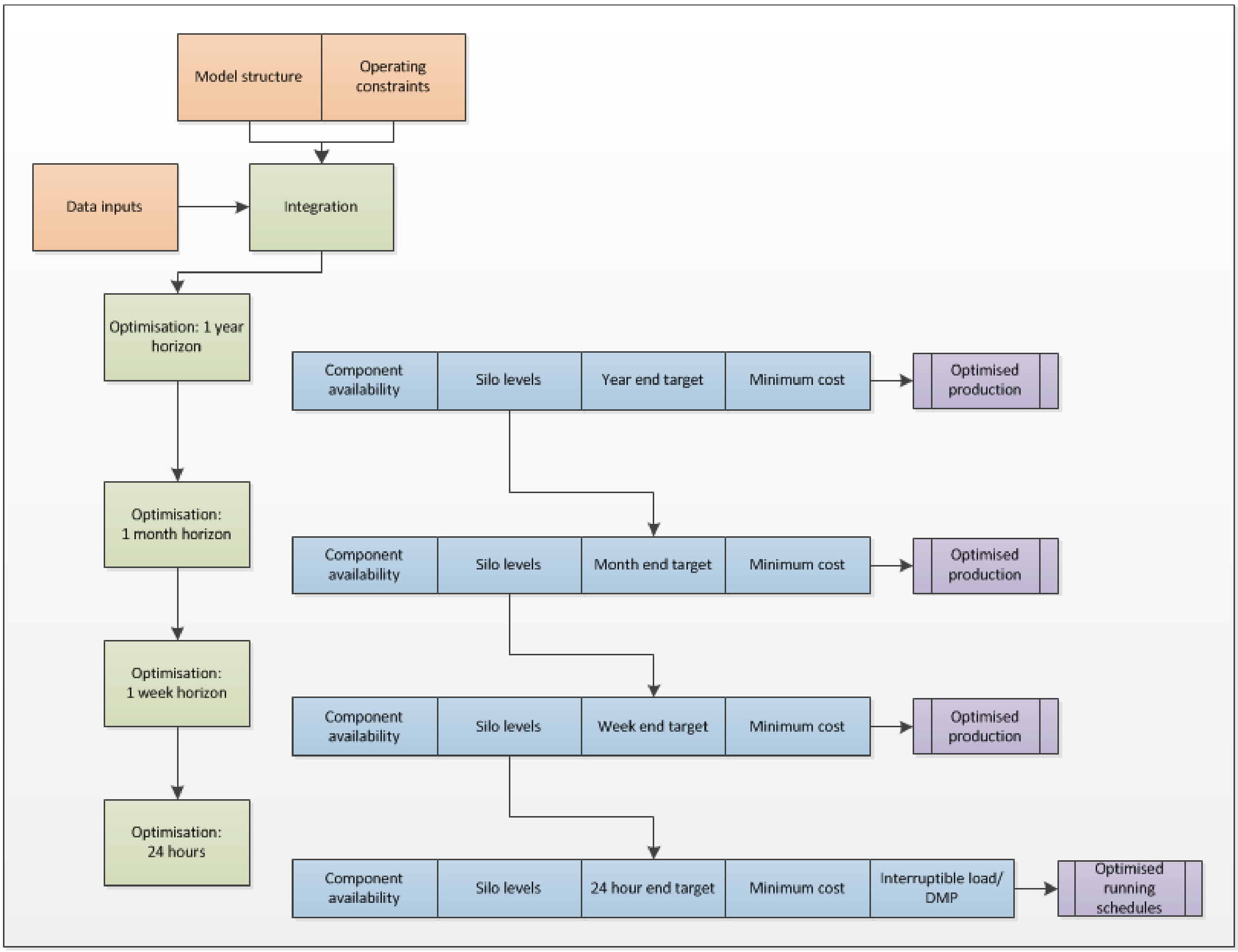


Figure 3-20: Typical function of optimisation model

An important aspect of the Swanepoel model as implemented in the workbook was that multiple time periods were often simulated. In such cases, separate optimisations needed to be performed on both yearly, monthly, and sometimes, daily level. Each level could take up as little as 30 seconds or as much as 45 minutes to reach an optimal solution on the centralised server (technical specifications appended as Table A-6). As several different plant models needed to be catered for, the amount of time required to solve each model to optimality could potentially exceed the available hours and result in a backlog.

As a result, the optimisation engine could not always be allowed to continue running until optimality was reached for each optimisation model. Therefore, the system was set to monitor the optimisation time for each model, and halt the process after 55 minutes. Although this would seem counterproductive, it should be remembered that individual models could be solved several times per day. As such, each time new data arrived, the model would be solved closer to optimality by using the previous result as a starting point.

In some cases, it was found that the optimisation engine did not behave satisfactorily, or was not suitable to the optimisation problem to be solved. In these cases, the results of applying the optimisation engine would not fall within the given constraints, or would provide no solution at all. The most common cause was determined to be faulty data from the plant SCADA.

It was possible to use a programmed expert control philosophy developed by an engineer instead. The engineer responsible for implementing the project would create a control philosophy. This philosophy would consider the silo or stock levels only to make a decision regarding the necessary running hours. Although this solution did not result in minimum operating costs, it closely reflected the decisions that would be made by engineers attempting to reduce electricity costs in real-time.

After completing the optimisation process, the resulting optimised schedule is saved in the project specific Swanepoel model file. A copy of this model file that excludes the optimisation software is then saved in the outgoing folder relevant to the project.

3.5 Implementation

A server computer was purchased to host the centralised programs. As the optimisation engine was resource intensive, an expensive server was chosen with high processing ability. For each implementation of the system at a cement factory, an additional computer was purchased. These computers had less intensive tasks, and cheaper models could be chosen. All computers were loaded with the Microsoft Windows Server 2008r2® operating system.

The data integration and optimisation program was developed in the Microsoft VisualBasic.NET® environment to make use of previous code that had been developed in this environment. The programming philosophy used was modular design, meaning that the program possessed several modules. Each of these modules had a distinct function, such as reading data from binary files, or interacting with the optimisation engine.

Both communication programs[29] were developed in the Microsoft C#.NET® environment. Available code libraries were used to reduce completion time.

The data logging program[30] was developed using Borland Delphi®, as a version of this program had already been developed in Delphi and could simply be modified.. This program made use of a third party plug-in to enable communication through OPC.

[29] Acknowledgement to Mr. S.W. van Heerden for the development of the communication programs.

The on-site user interface was developed in the Microsoft VisualBasic.NET® environment to make use of Visual Basic Powerpacks to improve appearance. The programming philosophy used was Object Oriented Design. Several generic types of input and output screens were programmed. These screens could then be used for virtually every type of input and output the system would need to handle.

3.6 Conclusion

In this chapter, a computerised system was developed to implement an optimisation model at a cement plant. This system was designed to overcome specific previously identified challenges, the bulk of which dealt with information integration and system automation. Although the system design was completed in this chapter, the objective of developing the aforementioned system cannot be deemed completed until results have been generated, and these results have been validated and verified.

[30] Acknowledgement to Mr. J.N. du Plessis for the development of the data logging program.

Chapter 4 System verification and validation

4.1 Preamble

This chapter will evaluate the system that was designed and implemented. During the verification process, system processes were tested to observe if quality criteria were met. For validation, the four case studies are introduced and discussed. The result of the DSM-project based implementation of the system is also discussed. The names of the factories where case studies were conducted are withheld for confidentiality reasons.

4.2 System evaluation

4.2.1 Introduction

In Chapter 3, a set of criteria for the evaluation of the design of the system were identified. These criteria were developed to ensure that the system had all the necessary characteristics to implement an optimisation model and realise electricity cost savings. In this section, the methodology of this testing as well as the results will be presented. From these results, it will be determined whether the system has met quality criteria.

The verification tests were performed by making use of a computer that had been installed on a cement factory. A server computer was put in place at the central location, and communication was established both through a wireless router and an e-mail service, as described in Chapter 3. The wireless router was placed on a Virtual Private Network, restricting access to authorised personnel. The wireless router could be used to log in on the computer remotely, while data was transmitted via the e-mail service. The various programs that had been developed were setup on the respective computers, and configured to perform their tasks as normal. For the purpose of verification, artificial stimuli were introduced to test the behaviour of the system.

4.2.2 Testing and results

User interface for inputs and outputs

The system was designed with multiple user interfaces. Only one of the interfaces was designed to be used specifically by site personnel. The rest of the interfaces were designed for configuration of programs and maintenance, should this be required.

An interface was developed for the data communication program. The controls of this interface allow users to enable and disable the program. The rest of the interface provides feedback to the user with regards to the status of the optimisation process. Text lines are provided as feedback. When new data files were placed in a project's incoming folder; they were integrated to optimise the model. The inspection method was used to determine whether this user interface provided sufficient feedback and control to allow proper monitoring and maintenance of the software.

An interface was also developed for the centralised communication program. This interface also allows users to enable and disable the program. In addition, this interface allows users to configure the program. This program has to be configured with the incoming and outgoing e-mail addresses for each project. It also has to be configured to send and retrieve data e-mails.

Figure 4-1 shows two parts of the on-site user interface. This interface allows plant personnel to access and modify the system constraints. It also allows access to the various graphs, tables, and information sources. The figure shows only a single part of the interface.

The methods used to verify this interface included demonstration of the inputs and outputs to a panel of peers. Qualitative measurement of the usability of the interface was evaluated through inspection. In both cases, minor improvements were requested, where after the system was accepted.

Figure 4-1: On-site user interface program.

An important part of the functionality of the on-site user interface was to make plant personnel aware of their electricity use during different tariff periods. An example of this is shown in Figure 4-2.

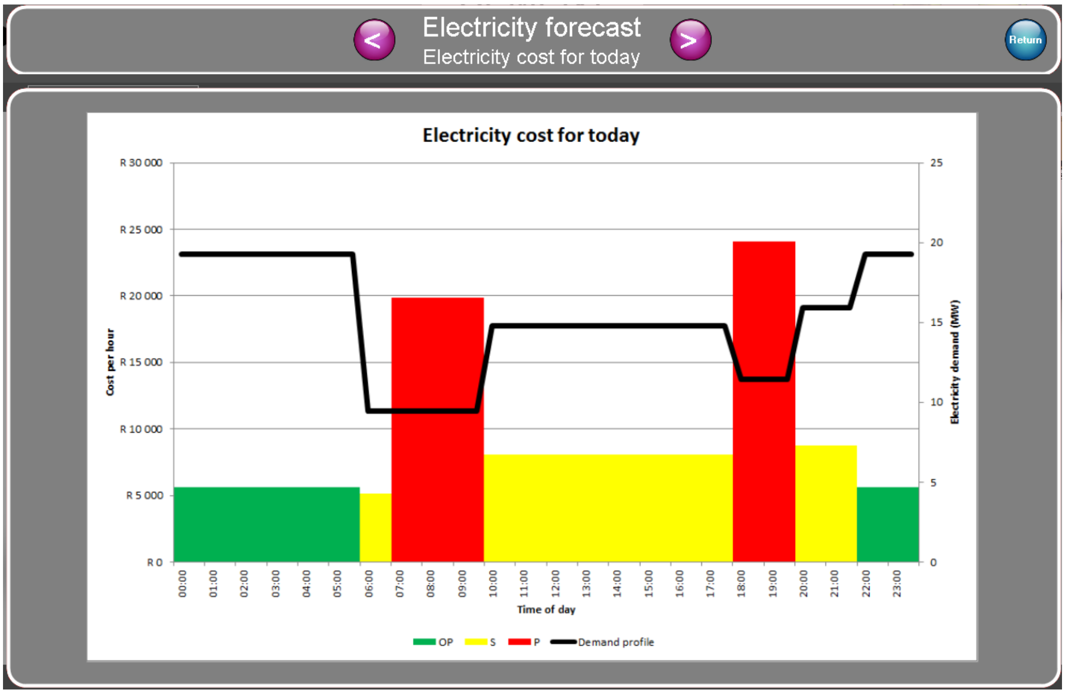


Figure 4-2: On-site user interface showing electricity demand at different tariff periods.

A user interface for the data logging program was also developed, and is shown in Figure 4-3. This interface allows users to configure an OPC connection to a computer on the plant network, allowing data access and recording. The data can then be grouped by component, to be logically sorted in the log files.

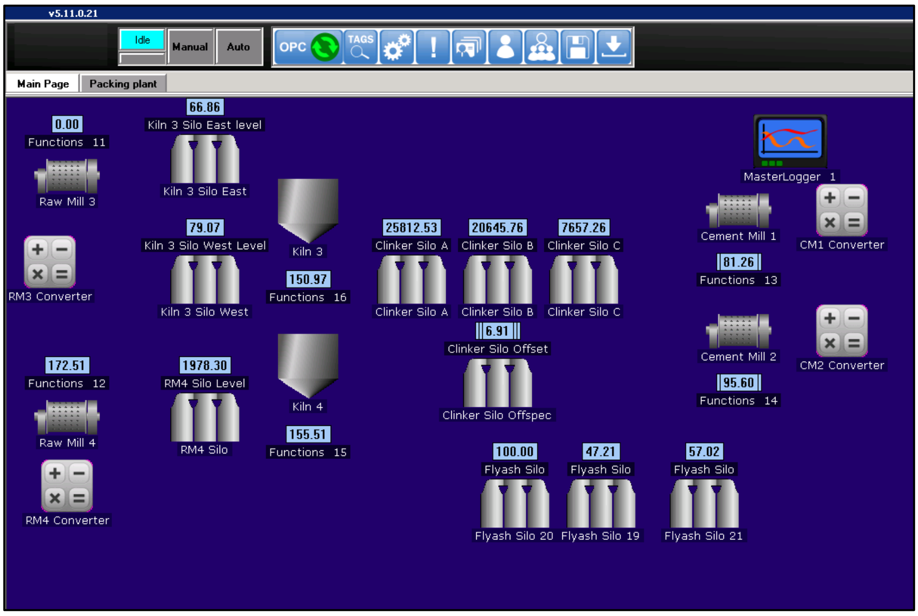


Figure 4-3: Data logging program user interface

Data logging

The data logging program was based on a previously developed energy management program. Initial tests indicated a fault with the program. It was found that, due to a rounding off error, certain large values had the number of significant figures in the data reduced. After this fault was corrected, the program functioned as required during system tests.

Testing of the data logging program was conducted on-site. The program was configured with an OPC connection, and tasked to record the data for the various plant devices. The logged data was compared to the data shown on the plant's own SCADA system, and found to be correct.

After the system tests were completed, the complete system was implemented. At this point, reliability problems were identified. The program functioned correctly for long periods, but approximately once every three months it ceased to log data. Maintenance personnel discovered this fault only the following working day when they noticed that no data had been received. It was often a time consuming task to recover lost data, as it had to be retrieved manually from plant personnel. This fault was rectified through corrective maintenance of the software code of the program to remove the cause of the error.

Collection of data

The program primarily concerned with the collection of data was the on-site communication program. This program functioned by transmitting and receiving data through electronic mail. Initially, this program had severely limiting reliability problems. The program was prone to either stop working completely, or to function in a way other than configured. When the program stopped working, users would have to completely reset it. Remote access made this maintenance easier to perform, but it still wasted time. After several system tests, the causes of these faults were identified as programming errors. The program was revised and the reliability improved.

The data collection functionality was tested by scheduling data transfers and checking that the data was transmitted. The data was compared to data transferred manually and found to be the same. Transfers also adhered to schedule, but it could take up to an hour to transfer data via the communication network. The cause of this behaviour was that the system had to rely on the e-mail servers of the client network, which had heavy workloads at times. This had no effect on the operation of the system, however.

Processing and integration of data

The system was implemented on four plants within three different companies, each with different report templates. Therefore, the system was designed with configurable 'map' files to allow project engineers to change the way data was processed for different file types. This mapping configuration reduced the time required to implement every new report template received from a different plant or company, because it allowed each project engineer to customise the map file to incorporate new data. If this had not been implemented, it would have been necessary to alter the data integration program every time the data format changed.

The processing and integration of data was tested by introducing data from different sources through the system, and verified by manual calculations. In all cases, these tests were successful. The only notable fault with this system occurred when plant personnel changed the template of reports. This only occurred twice during the nine month period following the implementation of the system. Until the map file was manually updated, the data integration was incorrect. However, importantly, it did not affect other data files or projects. The system would continue to function as normal, while logging the error in a file for attention.

Implementation of optimisation engine

The automated implementation of the optimisation engine was tested next. The system was designed in such a way that the optimisation engine would run when new data was successfully integrated to update the schedules automatically.

To test the automation of the optimisation engine, the system was tasked with new data from several different models. These models were also optimised manually. After completion of the test, it was found that the optimisation engine implemented through software performed as well as manual optimisation. To prevent overloading the system, a time constraint was enforced. In some cases, it resulted in preventing the optimisation engine to reach optimality within the allotted time. However, the conducted tests showed that the optimisation engine never produced a result outside of 5% of optimum. Results were typically much closer to optimal. Potential for always reaching the optimum solution will be discussed in Chapter 5.

Table 4-1 shows the results of the testing of the optimisation system. Four tests were conducted with the same initial values. Three tests were run with the system in automated mode, while the fourth was run manually as a benchmark. The automated tests were set with a 5 minute time limit per level of optimisation. The system was setup to run an optimisation of the Swanepoel model on a system with two cement mills manufacturing two different products. The optimisation model was tasked to produce yearly, monthly, and weekly schedules.

Table 4-1: Summary of optimisation system test

Optimisation test results				
	Run time:	Yearly result:	Monthly result:	Weekly result:
Automated optimisation test 1	16:14	154 667	140 644	3 918
Automated optimisation test 2	15:56	154 667	140 630	3 202
Automated optimisation test 3	16:30	154 667	140 670	3 504
Manual optimisation test	37:42	154 666	140 615	3 185

The values shown are the results of the cost function that the model attempted to minimise. These cost values are unit-less values that give a value reflection of the total electricity cost, as well as certain penalty costs that are built into the optimisation models. Due to the different ways that results are determined for different time periods, these values cannot be directly compared. For further detail on the working of the Swanepoel model, see [11].

Lowering this value produces a schedule with lower electricity costs and closer to the constraints of the plant. The run time column shows the number of minutes the engine took to optimise the three time periods together. The yearly results column shows that in all cases a similar, near optimal solution was found. The monthly and weekly results columns show that the time limited automated optimisations could not reach optimal solutions. No time limits had been set for the manual optimisation and optimisation continued until no further improvements could be made. Therefore, it showed better results than the automated tests.

As the table shows, the automated results performed on par with the manual results. The manual system also showed that, when no time limit was enforced, the optimisation engine could take a lot of time to produce only marginally better results. With no set time limit, the manual optimisations took twice as long to produce results that were only slightly improved from those that could be achieved in five minutes. As the time available for the system was limited, it was decided that this was an acceptable result.

Communication of resulting schedule

Upon completing the optimisation process, the system is tasked with communicating the resulting schedule to plant personnel. Three different methods were implemented to do so:

1. Updating of schedule on the on-site user interface.
2. Updating of schedule on control room user interface.

3. Mailing of scheduling report to plant personnel.

The first method formed part of the system test. The integration and optimisation program was triggered by inserting new data for a test model. After integration and optimisation was completed, the resulting optimised model was transferred to the outgoing folder of the centralised communication program. During the next triggered transfer event of this program, the optimised model was successfully transmitted.

The on-site communication program was monitored until the incoming schedule was received. This schedule automatically replaced the outdated schedule within the on-site user interface folder. The user activated the on-site user interface and navigated to the schedule page, which showed the new, updated schedule. En example of this schedule is shown in Figure 4-4.

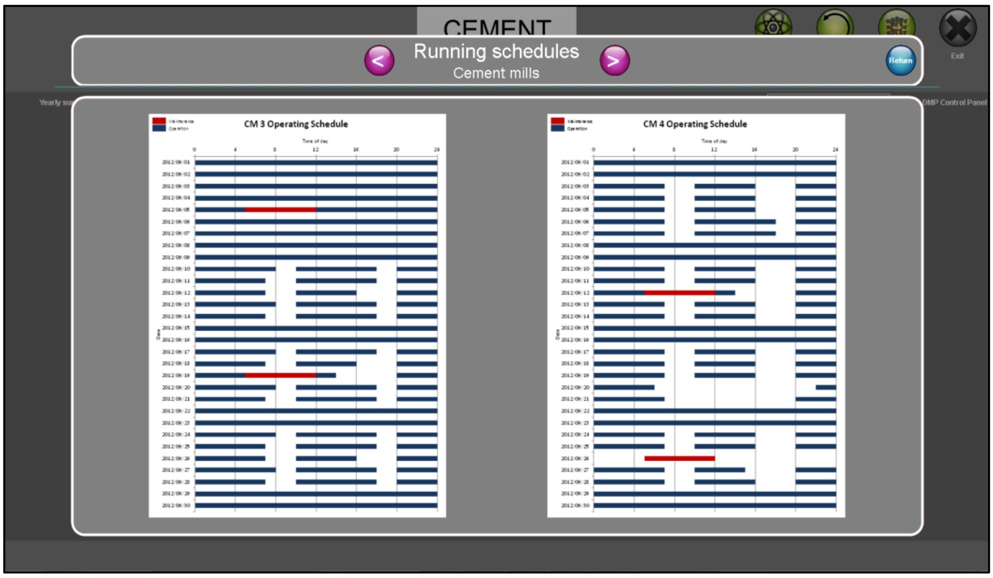


Figure 4-4: On-site user interface showing updated operating schedules

As the control room interface did not form part of the original system design, it was tested by inspection. This interface simply extracted the schedule from the optimised model, meaning that whenever the on-site user interface was updated, this schedule was updated as well. The scheduling report was implemented manually, and it was not tested.

4.2.3 Evaluation of verification results

The results presented in this section indicate that the system fulfilled the criteria described in Chapter 3. A summary of the obtained results are given in Table 4-2. These results indicate that the system tests were performed and that the system was verified against the set criteria. The results also indicate the importance of the integration tests. For example, the data communication program functioned correctly during unit tests. It was only during system testing that some of the faults were identified.

Table 4-2: Summary of system evaluation results

Verification Method				
1	Inspection			
2	Demonstration			
3	Analysis			
4	Test			
Requirement:	Verification results:			
	1	2	3	4
1. User interface for inputs and outputs	Each user interface inspected.	User interface reviewed by project engineers through demonstration.		Each user interface tested for functionality. Configurations tested.
	Passed	Minor changes requested.		Passed
2. Data logging	Data logging program inspected.	Data logging program demonstrated to project engineers.	Implementation of data logging program analysed to show that correct functionality was implemented.	Data logging program tested on-site.
	Passed	Passed	Passed	Passed
3. Collection of data	Data communication programs inspected during development.	Data communication programs demonstrated.		Initial system tests showed poor reliability. Revised program developed and tested.
	Passed	Passed		Passed
4. Processing and integration of data		Data processing algorithms demonstrated.	Data processing algorithms analysed to ensure mathematical correctness.	System tests showed data processing and integration to work as expected compared to manual process.
		Passed	Passed	Passed
5. Implementation of optimisation engine		Optimisation engine controls demonstrated.	Analysis of algorithms conducted.	Tested against manual process.
		Passed	Passed	Shown to produce marginally worse results in less time. Considered an acceptable result.
6. Communication of resulting schedule		Schedules displayed on user interface demonstrated.	Analysis of communication process conducted.	Automated schedule communication tested.
		Passed	Passed	Passed

4.3 Case study result measurement

Before the case studies are introduced, the method to measure the performance of the system must be presented. The case studies in this document will be evaluated according to the primary goal of this study – the financial savings that were achieved. Due to the difference in cement demand from year to year, and even month to month, the results cannot be measured by comparing electricity bills from before and after implementation.

To determine the savings achieved, the measured electricity consumption prior to the implementation of the system was used to calculate a baseline. As the goal of this project was to deliver financial savings based on the concept of shifting load to cheaper periods, it was assumed that the net electricity consumption would remain constant. Thus, the baseline should be scaled so that the total electrical energy use of the baseline is equal to that of the profile after implementation. This scaling would ensure that changes in production levels due to increasing cement sales would not influence the results.

Figure 4-5 shows an example of the baseline scaling process. In this figure, the green line represents the baseline prior to implementing the system. The blue line shows the profile after implementing the system. However, as the total electrical energy consumed after implementing the system has risen, the resulting profile cannot be directly compared to the baseline. The baseline was scaled so that the total baseline electrical energy consumed would be the same as the actual electrical energy consumed. A new baseline is drawn, represented by the red line. The area under the red and blue curves is now the same, indicating an energy neutral equation.

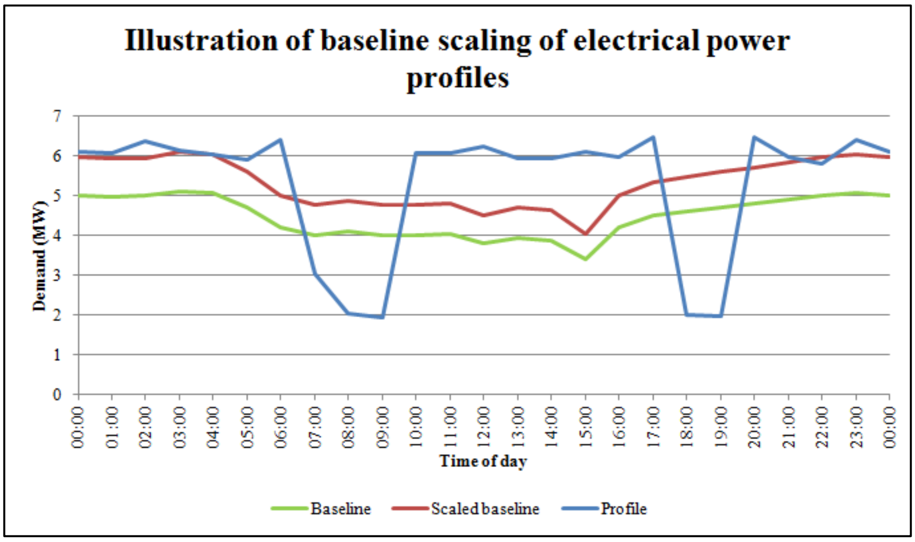


Figure 4-5: Illustration of baseline scaling

As a result, the electricity cost of the scaled baseline can be compared with the load shift profile to determine if electricity cost savings were achieved. However, the reason for the overall consumption increasing or decreasing should be identified, to ensure that the system did not cause an adverse degradation in production efficiency. Possible reasons for consumption changes are the rise or fall of cement sales, and annual maintenance. Variations in the overall reliability of equipment could also cause changes in overall demand.

4.4 Case study one

4.4.1 Introduction

In the first case study, the system was implemented on a cement production plant in the North West Province. This plant has the highest production capacity of any single plant in Southern Africa, with three clinker production lines and two cement mills on site.

Raw materials are sourced from a quarry approximately 45 km from the plant, crushed and transported via rail. The raw limestone is stored in two modern blending beds, which continually homogenise the stock. From there, the stock can be fed to bins preceding the raw mills on the plant, whilst some material can be directed to bins feeding the cement mills.

The plant has three production lines. The oldest of these is not in operation due to reduced demand for cement. This line features an older, dual chamber ball mill for raw milling, which is preceded by a hammer mill. The kiln feed is blended in two small silos before being stored. Material that is not of kiln feed specification can be stored in a separate silo until kiln feed of sufficient quality can be produced to blend with this material. From the storage silo, kiln feed is passed to the production line’s pre-heater tower. After pre-heating and pre-calcining, the material is fed into the kiln.

The second production line is a newer line with more modern technology. This includes a central discharge ball mill for kiln feed preparation, along with two large storage silos. The pre-heater, pre-calciner and kiln used on this line are also more modern, and more energy efficient. This line is currently the third largest clinker production line in South Africa.

The third line was commissioned in 2009. Although it has less production capacity, it is more energy efficient. This line also has a central discharge mill for kiln feed preparation, and a modern kiln feed silo with automated homogenisation. This silo is fed by a central discharge ball mill with less production capacity than the mill on the second line.

The clinker from the kilns is housed in one of three large storage silos with a combined capacity of approximately 85 000 tonnes. From the clinker silos, the clinker is fed through a high-pressure roller press. This press pre-crushes the clinker prior to feeding it into the mill, improving overall efficiency [reference]. The crushed clinker is then fed into one of two cement mills along with additives and milled in a closed loop until fine. This plant produces three different cement blends of varying quality. The finished cement is stored in one of four silos. A layout of the plant is given in Figure 4-6. A legend for each component on the layout is provided in Table 4-3.

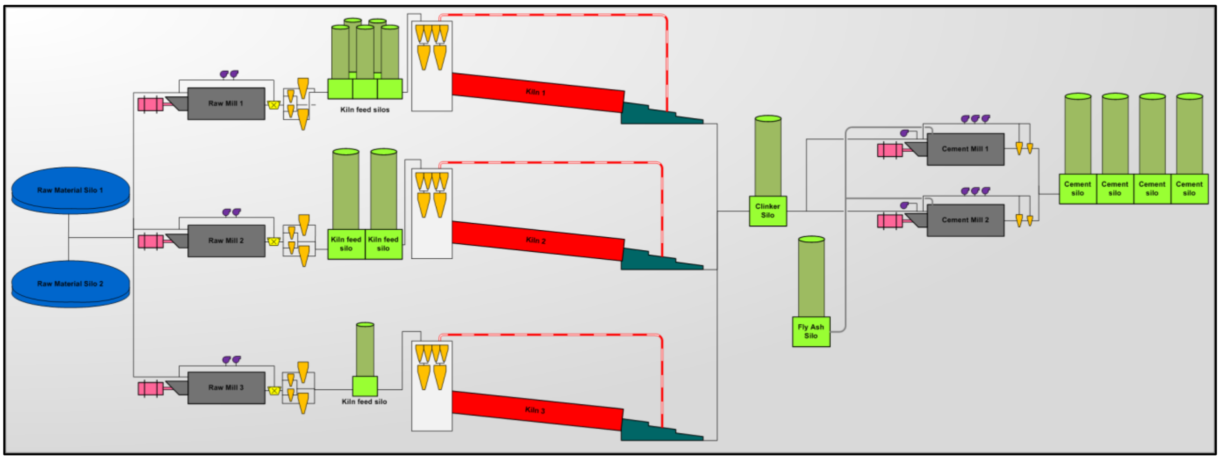
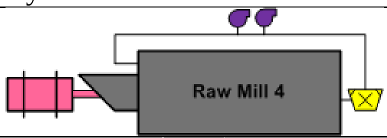
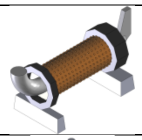
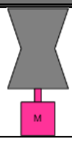
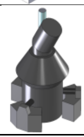
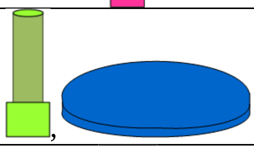
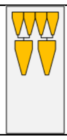
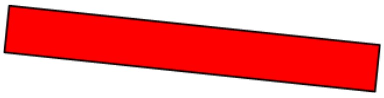
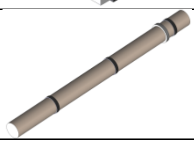
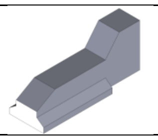


Figure 4-6: Case study one plant overview

Table 4-3: Legend of plant layout and user interface layout components

Component:	Layout icon	User interface icon
Ball mill		
Vertical roller mill		
Silo		
Pre-heater tower		
Kiln		

Clinker cooler		

4.4.2 Implementation

The system was implemented as part of a DSM project, with capital costs covered by Eskom. A computerised system was put in place as discussed in Chapter 3. The user interface for the plant personnel is shown in Figure 4-7. In addition to logged SCADA data, the system also had to incorporate sales data from an Excel daily distributed log sheet. The maintenance input was done manually by plant personnel, as no template was available to retrieve the information.

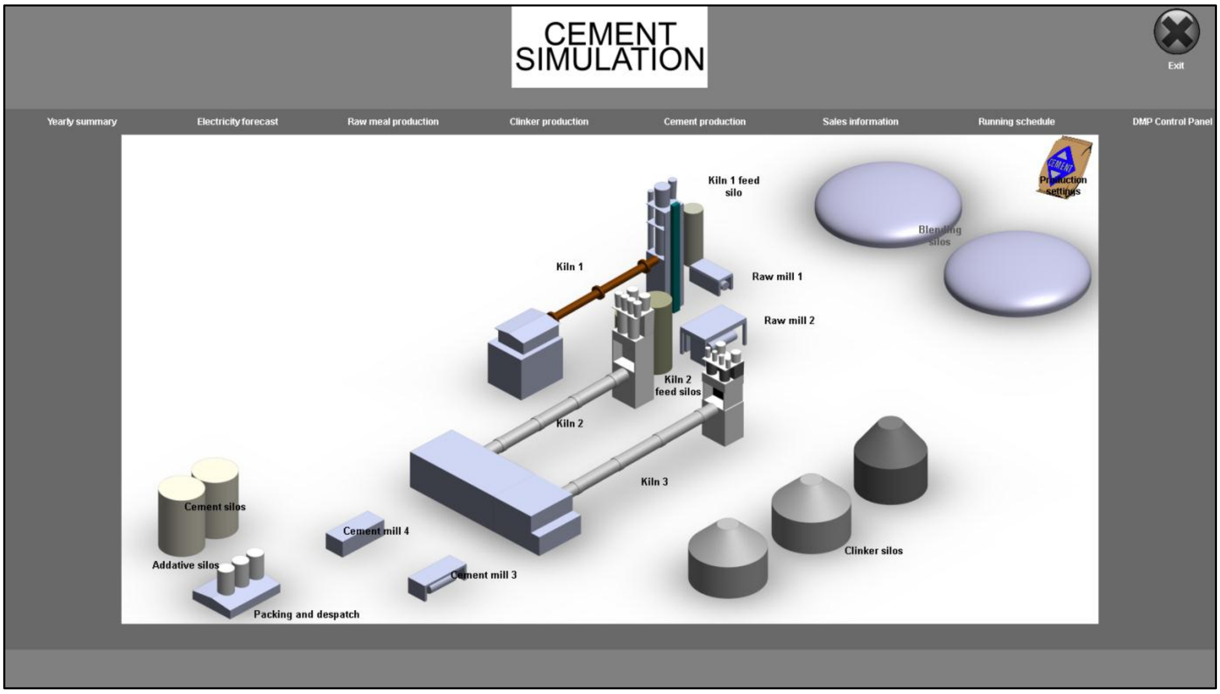


Figure 4-7: Case study one user interface

This implementation proved to be one of the most challenging, as the plant already participated in the Eskom DMP programme when the project started. However, no strategy was in place to manage DMP. A strategy was needed to ensure that the implementation of a DSM project would not reduce DMP performance.

The system also had to implement a control interface to assist plant personnel with DMP. As reported by Vosloo *et al.* [21], DMP at cement plants can be implemented by managing the mills. As the Swanepoel model would already manage the mills, it was decided to integrate DMP into the system.

To do this, a user driven interface was programmed into the on-site user interface. Plant personnel were provided with controls on the user interface where DMP event details could be entered. The system would then generate a recommendation regarding plant operation. The system also automatically calculated the CBL and estimated the results of the recommended action. In this way, plant personnel would immediately know whether the reduced load was in line with Eskom's event request. This user interface is shown in Figure 4-8.

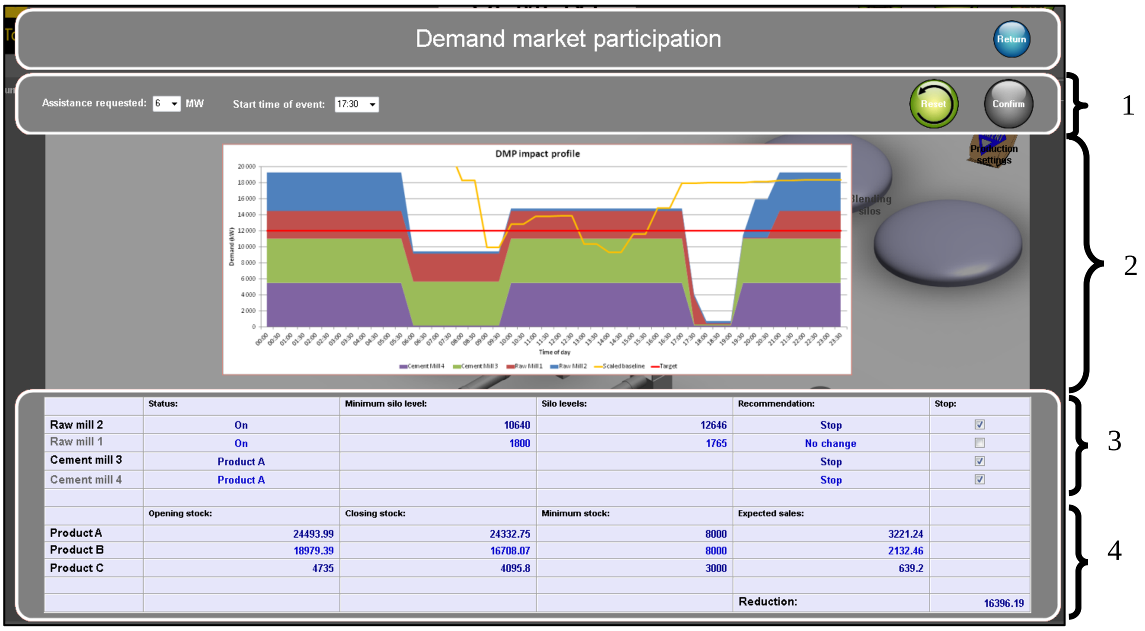


Figure 4-8: Case study one Demand Market Participation interface

The components of the DMP interface shown in Figure 4-8 are:

1. DMP event controls – Plant users input DMP event times and the amount of electricity demand (MW) to reduce.
2. DMP impact profile – A visual representation of the plant electricity demand throughout the day. The calculated CBL and the target for the DMP event are also displayed.
3. Recommendation – This section shows the actual operating status of every component considered, and provides a recommendation regarding the safety of a shut down.
4. Results – This section shows the results of shutting down according to the given recommendations. This includes the resulting silo levels, and the expected load reduction.

The plant personnel involved in this case study requested customised reporting. Two daily reports were required. The first would be sent daily at 16:45 to update personnel on the schedules recommended by the system at that time. This report would be generated manually. An example of the scheduling report is given in Appendix B. The second report was a customised savings report, which would report daily on operational cost savings. This report would be generated daily before 06:00. A staff member was assigned to check this report, before sending it to plant personnel. An example of this report is attached as Appendix C.

4.4.3 Results

The system implementation was completed in February 2012. Initially, the focus of the system was exclusively on a single raw mill. Plant personnel had committed this raw mill as part of a DSM project to shift an average load of 2,5 MW out of Eskom's evening peak. For the period February to May, this objective was achieved, with an average weekday impact of 2,55 MW.

From June 2012, the system included both raw mills and the cement mills of the plant. Figure 4-9 shows the impact of the system for June to October 2012, where all plant components were included in the project. The cumulative savings for this period was R2 392 000. Although an improvement over previous operation, the results showed that a significant amount of R1 017 000 of possible savings was not achieved. Three causes were identified: equipment breakdowns and under-performance, schedule faults and schedules not being followed.

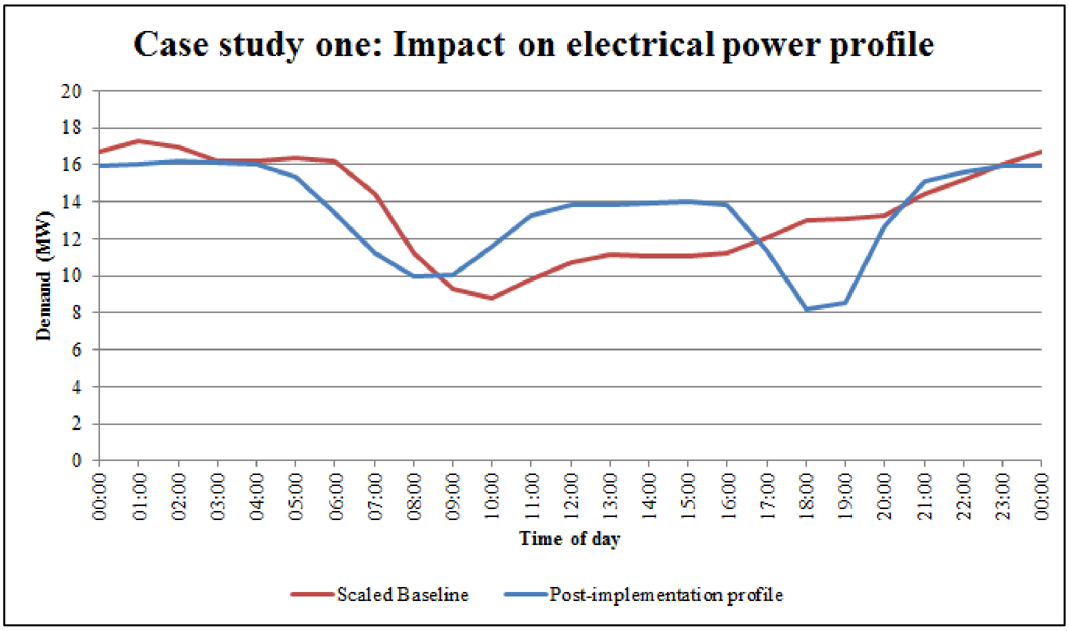


Figure 4-9: Baseline and resulting profile for Case study one

Equipment breakdowns would typically lead to several hours of down-time. By the time repairs had been completed, the silo levels had fallen, and mills would need to be operated continuously to ensure that silo levels returned to constrained levels. In July and August, the cement mills on the plant suffered numerous failures. This resulted in reduced savings because the optimised schedules could not be followed.

Schedule faults occurred due to data or communication faults. These faults resulted in schedules that were either not optimal, or did not include updated data. Plant personnel were also prone not to follow the provided schedules, and opted to shut down whenever the opportunity presented itself. This behaviour reduced the achieved savings, as it often resulted in future missed load shift opportunities that operators could not foresee.

Figure 4-10 shows the consumption and cost distribution of plant operations both before and after the project was implemented. The baseline cost used in this case study was higher than others, as a larger portion of winter peak was considered in these results. These figures show a considerable impact on the operating costs of the plant, although peak period electricity consumption was still the biggest electricity expense.

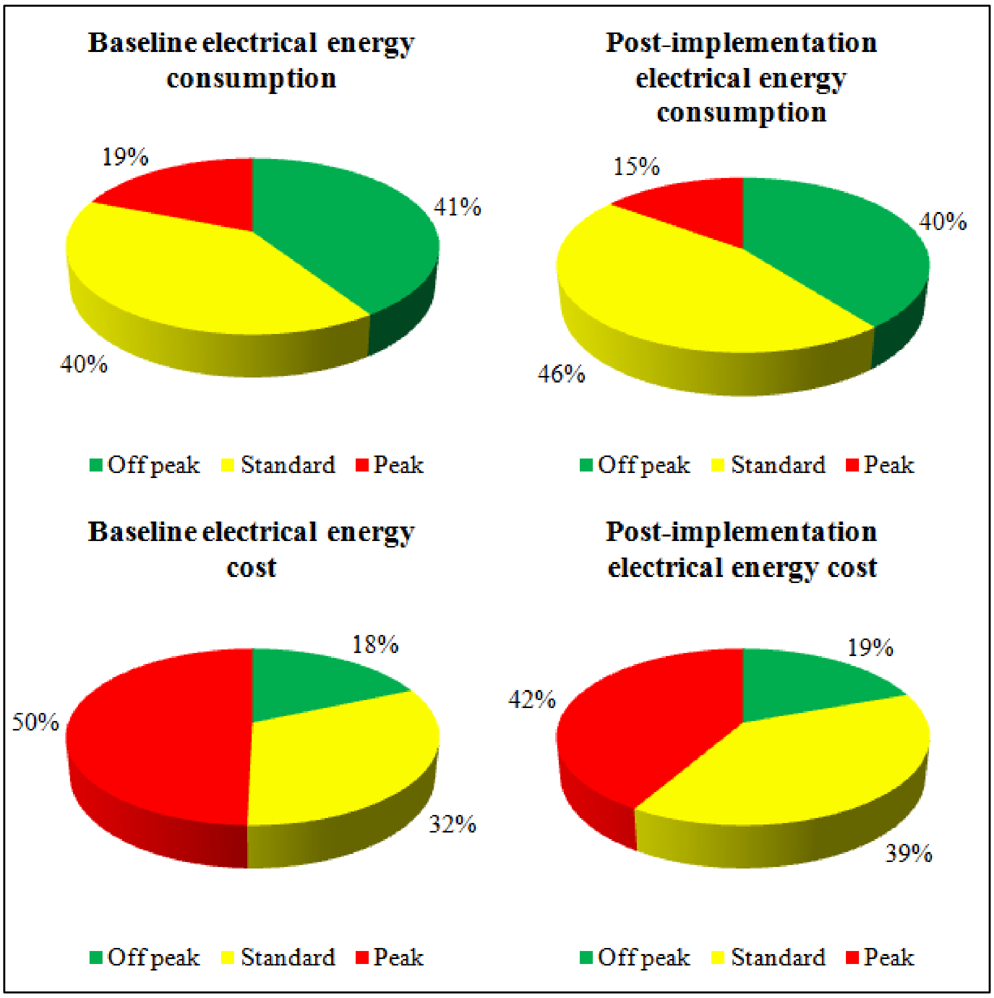


Figure 4-10: Case study one electrical energy consumption and cost distribution

4.5 Case study two

4.5.1 Introduction

In the second case study, the system was implemented on a cement production facility in the Limpopo Province. Again, the computerised system was implemented as discussed in the previous chapter. This production facility has two clinker production lines and a single cement mill. Raw materials are sourced from a nearby quarry that is operated as part of the plant. A layout of the plant is given in Figure 4-11.

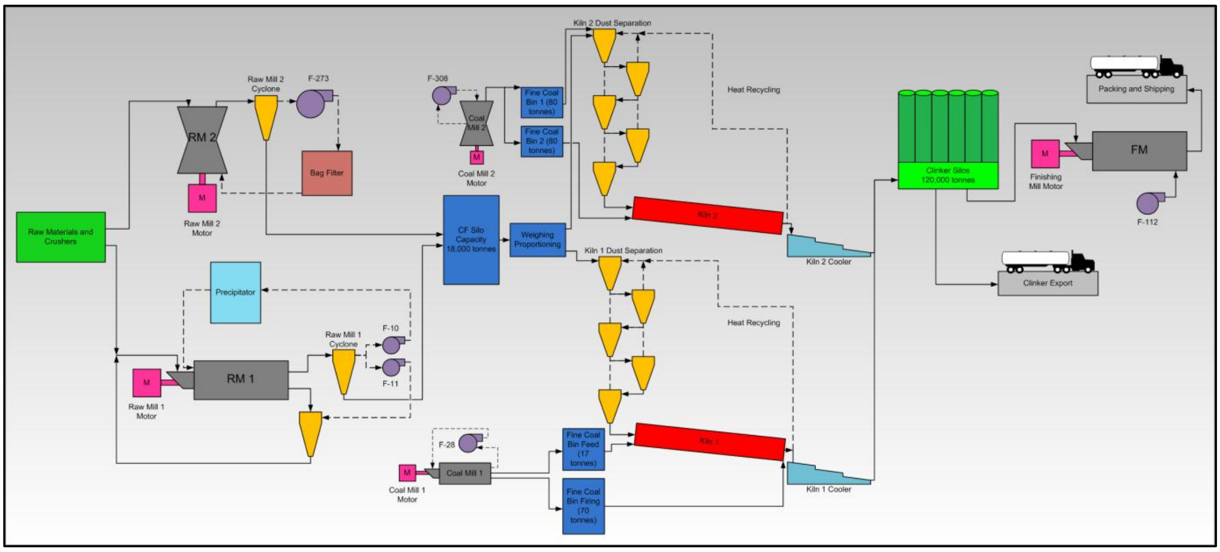


Figure 4-11: Case study two plant overview

As shown in the figure, the plant has two raw mills feeding into a communal silo. This single, large silo feeds both kilns. The two raw mills are different. The older one is a ball type mill, while the newer one is of the vertical roller mill variety. The second mill is more efficient, consuming 60% less electrical energy per tonne of raw meal produced.

Both kilns are preceded by pre-heater towers and pre-calciners, and succeeded by grate coolers. From the coolers, clinker is fed to a set of communal clinker stores. As the plant only has a single cement mill, the majority of the clinker produced is exported to other production facilities within the company.

4.5.2 Implementation

The target of the optimisation process for this case study was the two raw mills, the finishing mill, and the two coal mills. This case study was the only case in which the scope included coal mills, as there was sufficient capacity in the feed bins to supply the kilns with the required fuel while the coal mills were shut down during peak periods.

As part of this project, two customisations were requested by plant personnel. The first was to design the system to allow users to manually request new, optimised schedules. This was implemented with an additional control on the user interface. Due to the design of the rest of the system, only the on-site interfaces needed to be changed.

A second request was a user interface specifically for the control room. The existing interface had specifically been designed for high-level operations managers. A simpler, straight forward interface was required to allow control room operators to easily determine whether they were operating according to schedule.

Finally, the engineers implementing the project requested the system to be modified to allow use of the Swanepoel model without implementing the standard optimisation engine. This request was due to difficulties experienced with reliability of the engine on this specific project. Again, the system had been designed and implemented so that custom optimisations could easily be implemented without changes to the software. As such, the engineers scripted an expert control philosophy to manage production.

4.5.3 Results

The system was implemented as part of an Eskom DSM project. The project was completed in February of 2012, and has been in operation since then without failures. The cumulative savings achieved by the project to date is R1 804 000. The resulting profile is shown in Figure 4-12.

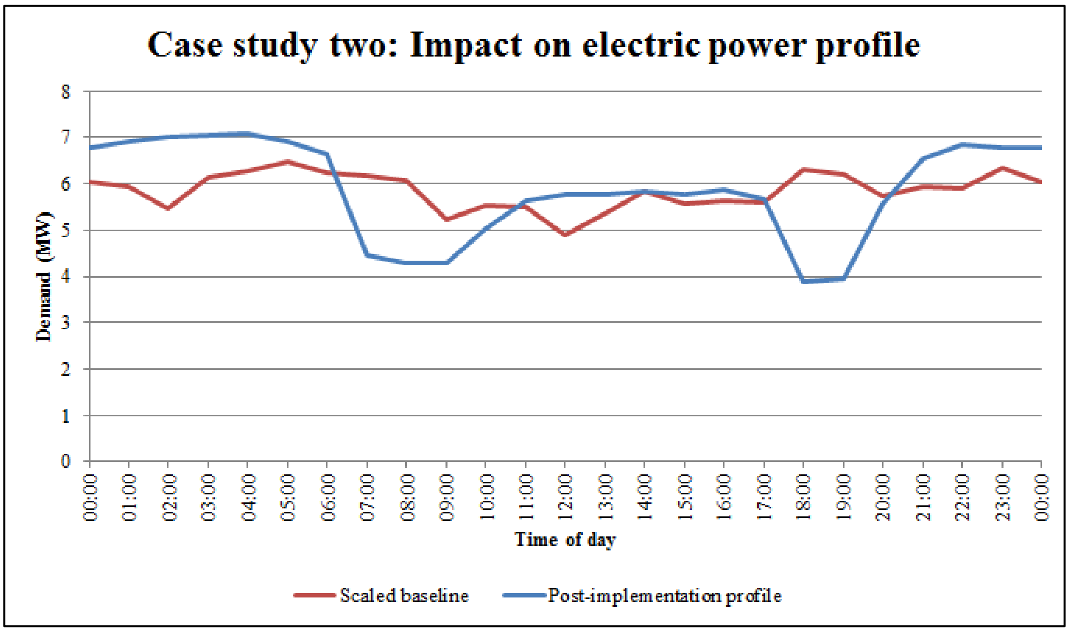


Figure 4-12: Baseline and resulting profile for Case study two

Figure 4-13 shows the distribution of electricity consumption and costs for Case study two. These figures indicate that electricity consumption was redistributed to cheaper standard and off-peak periods. This results in lower overall electricity costs.

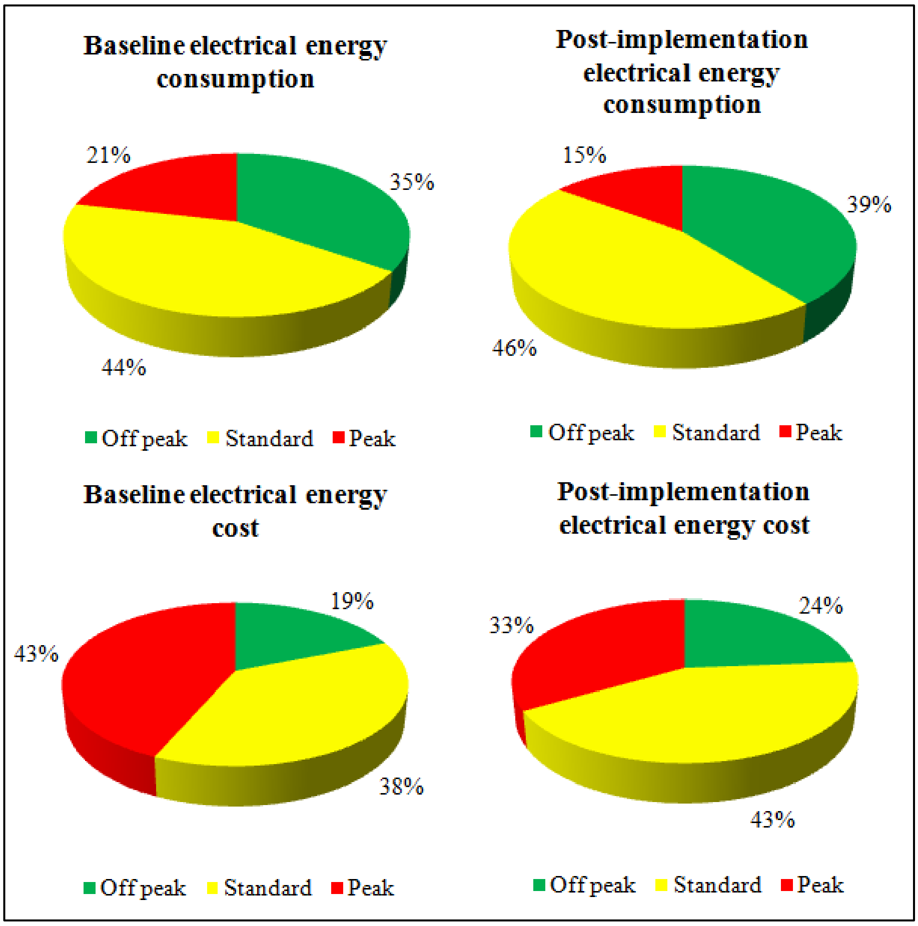


Figure 4-13: Case study two electrical energy consumption and cost distribution

4.6 Case study three

4.6.1 Introduction

In the third case study, the system was implemented on a cement production plant in the Northern Cape. This facility currently hosts the single largest kiln (measured by production) in South Africa, although an even larger one is currently under construction in the country.

Kiln feed is supplied by a single vertical roller mill. The pyroprocessing system includes a pre-heater tower and a pre-calciner, as well as a grate cooler. Clinker is stored on site, to be used later to produce cement in one of the two cement mills on the facility. The two cement mills are both ball mills, although one is fitted with a more effective classifying device in the mill return feed loop. The layout of the plant is given in Figure 4-16.

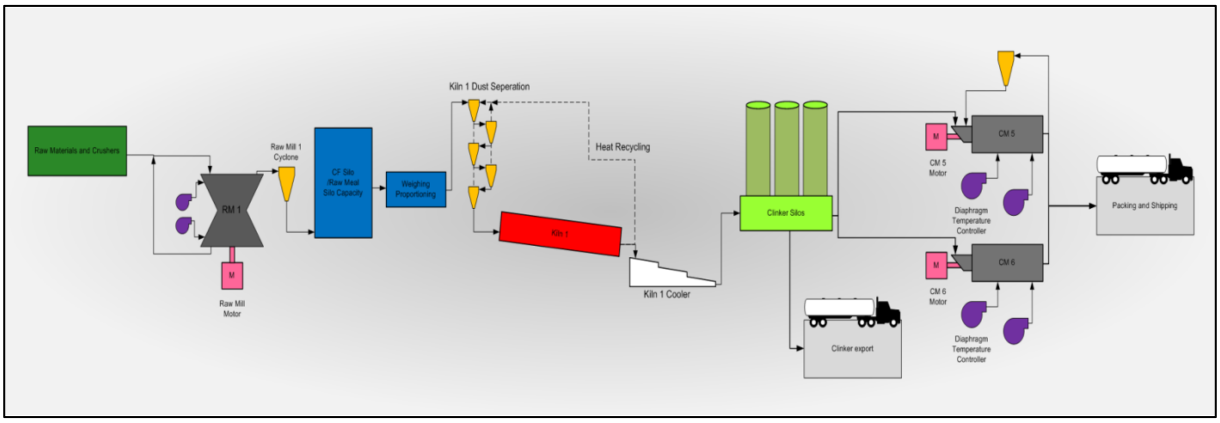


Figure 4-14: Case study three plant overview

4.6.2 Implementation

The scope of this implementation was the raw mill and both cement mills. On this project, a control room interface identical to that presented in Case study two was requested. Additionally, plant personnel asked for an indicator to be added to the interface to show the prevailing cost of electricity. This modification was implemented and is shown in Figure 4-15.

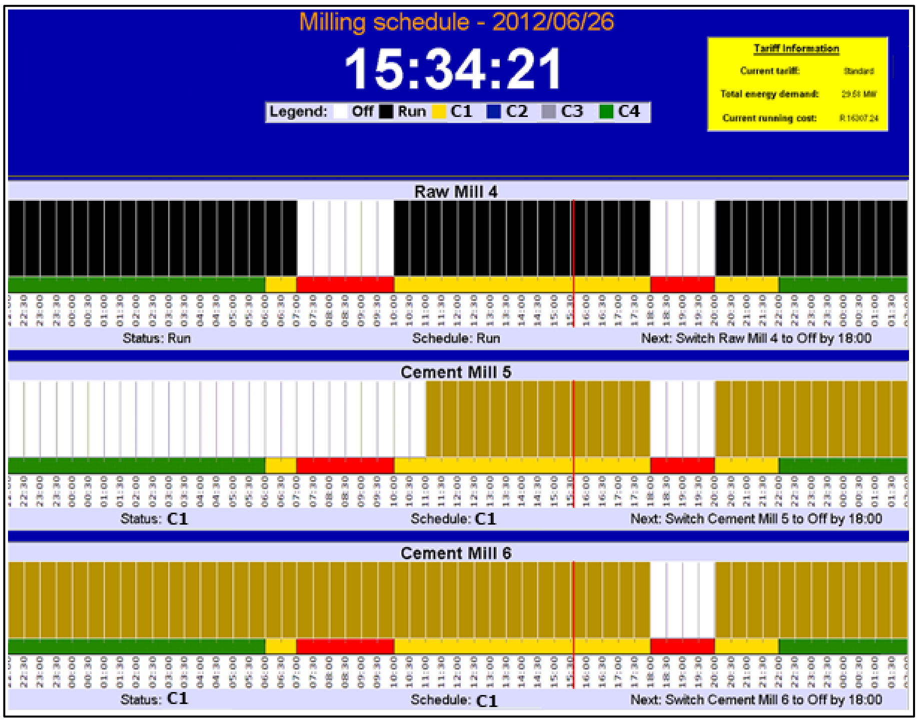


Figure 4-15: Control room schedule viewer showing current tariff period

4.6.3 Results

Figure 4-16 shows the scaled baseline and the post-implementation demand profile of Case study three. This figure shows that a significant impact has been made in morning and evening peak periods. The change in the demand pattern resulted in a cost saving of R3 140 000 for the period February to October 2012.

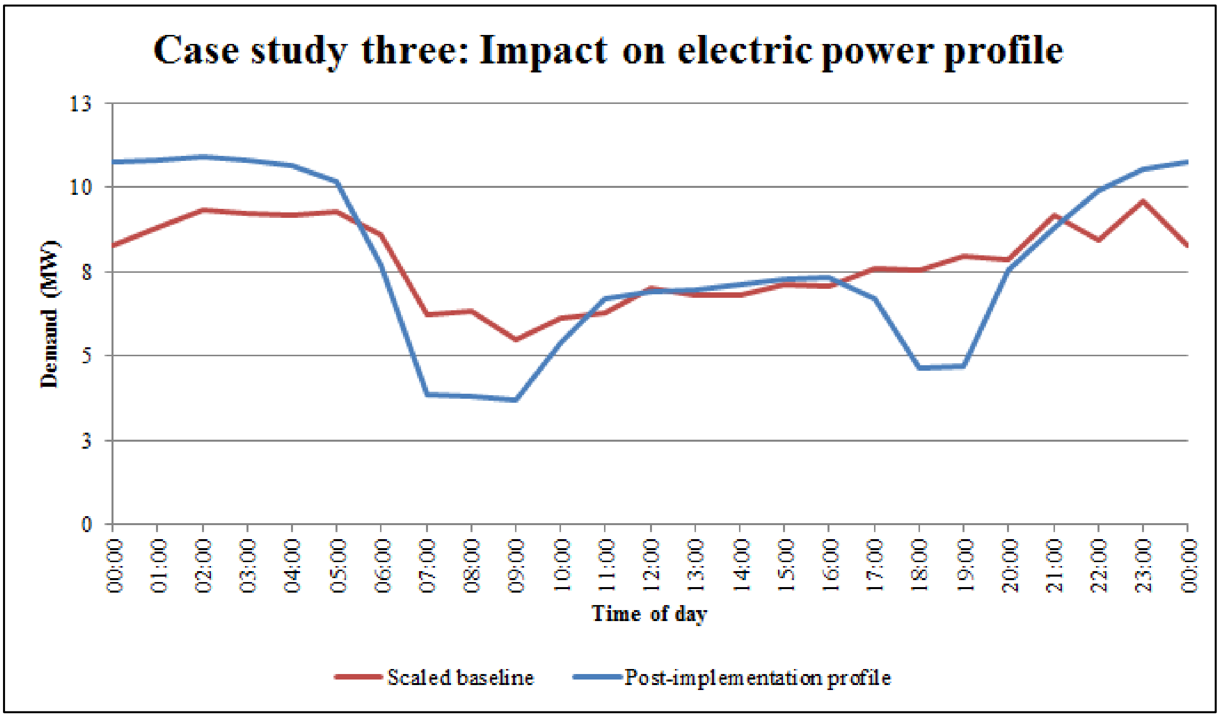


Figure 4-16: Baseline and resulting profile for Case study three

Figure 4-17 shows the electrical energy consumption and cost distribution of Case study three both before and after implementation. The post-implementation cost distribution shows a marked improvement over the baseline cost. A significant amount of electricity previously consumed during peak periods was shifted to off-peak periods, which had a significant impact on electricity costs.

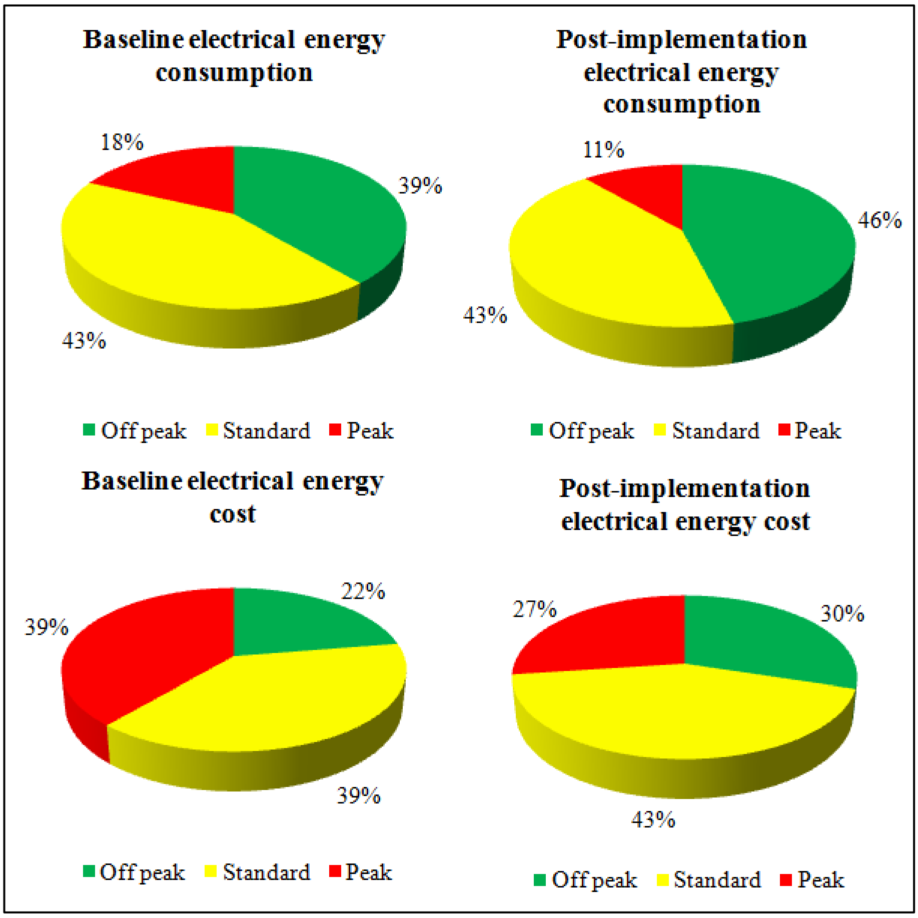


Figure 4-17: Case study three electrical energy consumption and cost distribution

4.7 Case study four

4.7.1 Introduction

In the final case study, the computerised system was implemented on a cement production plant near Mafikeng in the North West Province. This plant is the oldest one included in this study. The plant sources raw materials from a nearby quarry. These raw materials are fed into two parallel crushing lines. Each crushing line has a jaw crusher as the primary device. This is followed by a secondary and tertiary cone crusher. The crushing plant layout is presented in Figure 4-18.

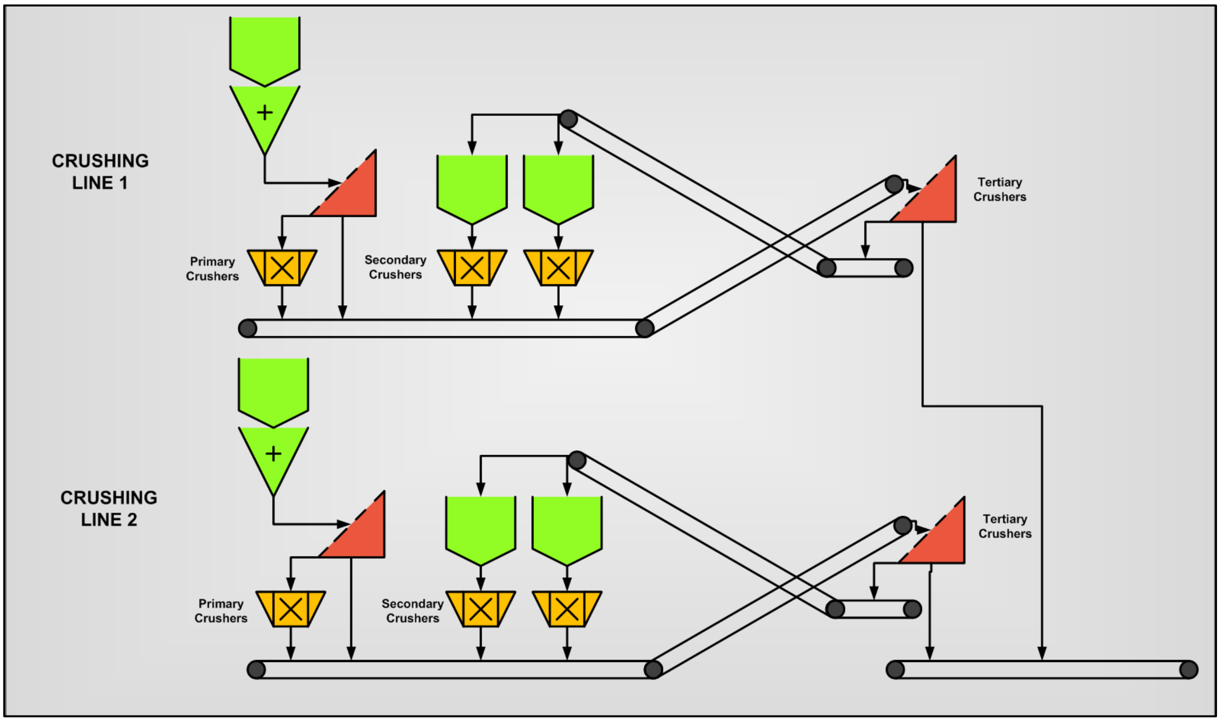


Figure 4-18: Case study four crushing plant layout

A diagram of the plant is given in Figure 4-19. This plant has four clinker production lines, all of them of an older variety. Two of the kilns are of the long dry type and do not have pre-heating. These kilns are currently not in production, but may be brought online if needed. The third include a pre-heater, but not a pre-calciner. The fourth production line possesses both. All four kilns are equipped with planetary clinker coolers, which are less efficient at recovering waste heat.

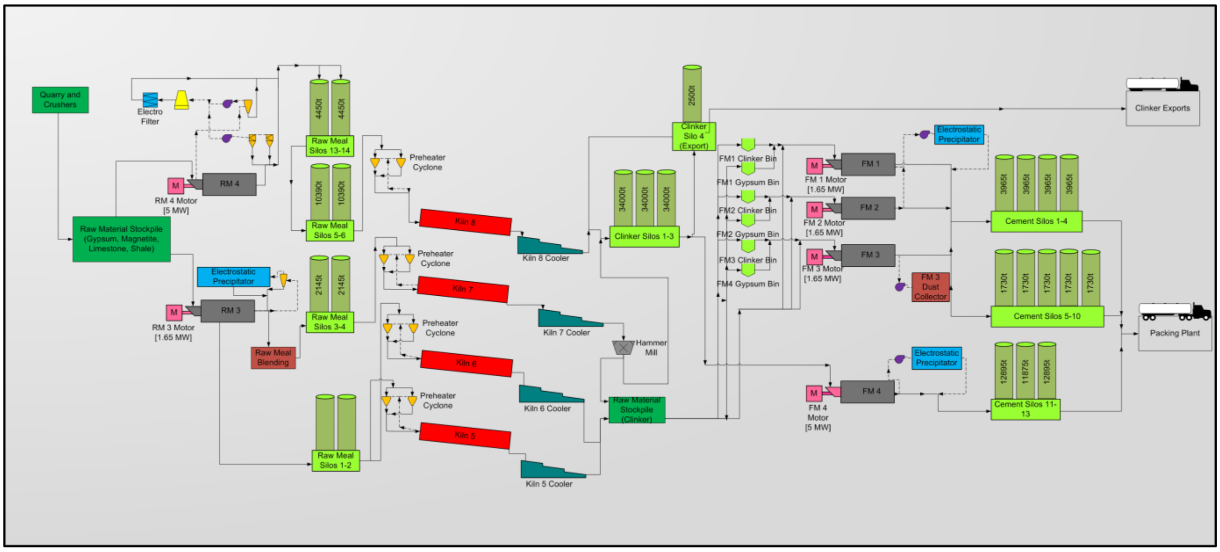


Figure 4-19: Case study four plant overview

The plant has four raw mills, although two have been permanently decommissioned. A third is currently not in use, but may still be required in future if production increases. These three raw mills are of an older configuration, and are not fed by waste gasses from the kilns. Instead, a furnace must be operated to provide heated air for these mills. The fourth mill is of a newer type, and is supplied with waste gasses from the fourth kiln.

The plant hosts four cement mills of the ball mill variety. Three of these mills are of older design, and only capable of producing a basic product. The fourth mill is newer and larger, and capable of producing the company’s premium product.

4.7.2 Implementation

During project implementation, plant personnel requested attention to be given to the crushing section of the production line. This was the only case study in which the crushing plant was considered as part of the system. To implement a solution for the crushing plant, a customised optimiser needed to be implemented. Again, as in Case study two, this was done without any significant system changes.

The system was also implemented so that it would still function correctly should the kilns currently not in use be started. However, this would be dependent on users updating the information in the system to reflect this.

4.7.3 Results

The results of Case study four show a far poorer performance of the project when compared to the other case studies. Several months after implementation of the project, the system was removed from the on-site network. As a result, the system could not be updated with recorded plant data. As maintenance of this project was neglected for several months, the project underperformed for a considerable period of time.

Even so, while the system was operational, reasonable savings were achieved, as shown by the results (see Figure 4-20). A total cost saving of R1 292 000 was achieved during the period from 1 April 2012 to 30 September 2012.

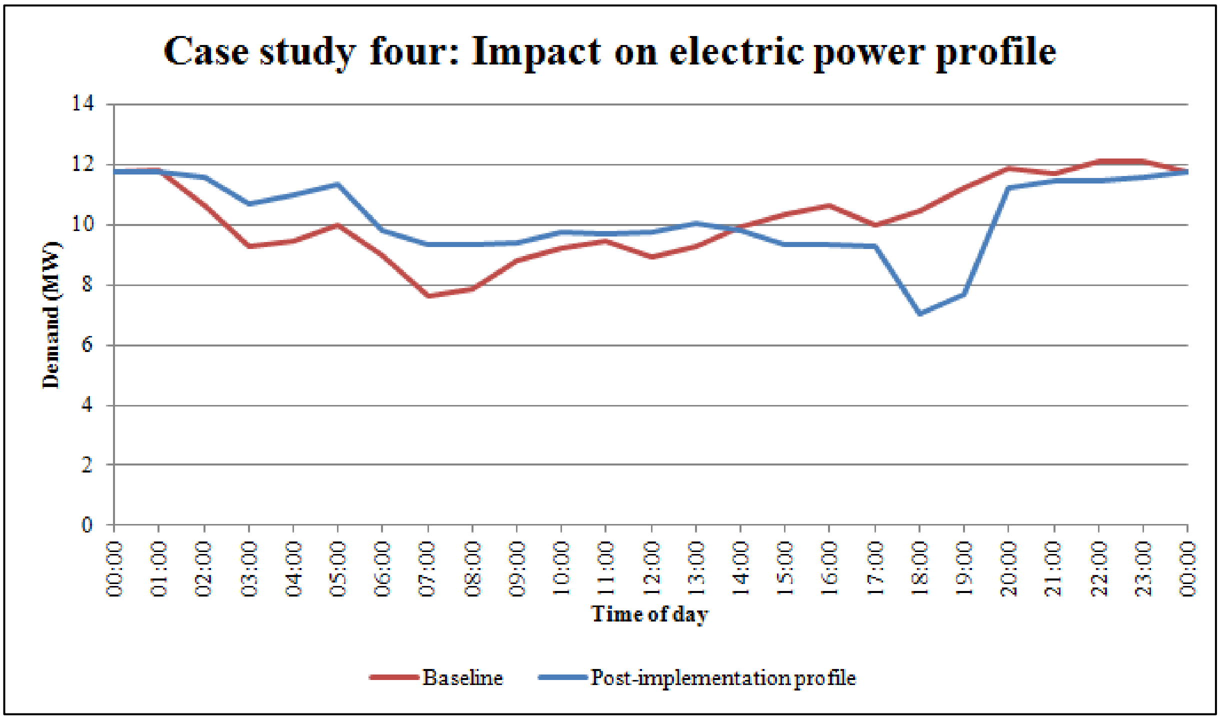


Figure 4-20: Baseline and resulting profile for Case study four

Figure 4-21 shows the electrical energy consumption and cost distributions according to Time-of-use periods. These graphs indicate that Case study four was less successful at achieving results compared to the other case studies. After implementation, a large proportion of weekday electricity costs are still allocated to peak time usage.

As previously discussed, the system implemented in Case study four had notable maintenance issues. A part of the poor performance of this case study can be apportioned to this shortfall, as the Swanepoel model could not be used effectively as long as the data was not updated. Another contributing cause for the poor results was the lack of accessibility to the schedules. Only a single member of plant personnel had access to the system, which meant that any human error or absence on his part would render the system ineffective.

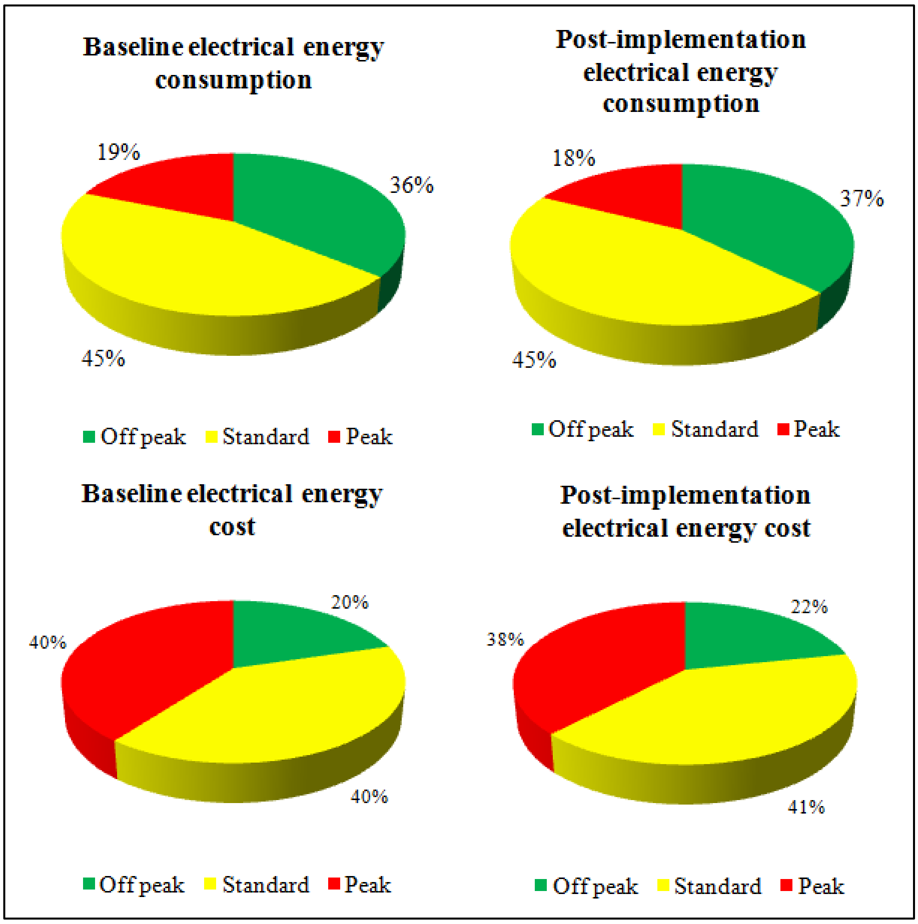


Figure 4-21: Case study four electrical energy consumption and cost distribution

4.8 Assessment of results

4.8.1 Overview

An important goal of this study was to show how a system can be used to achieve electricity cost savings. The case studies showed that this goal was achieved by implementing the Swanepoel model, as made possible by the developed system. These savings have been achieved over a period of several months, indicating the sustainability of the system. However, as Case study four showed, both poor maintenance of and inadequate access to the system can significantly reduce the cost savings achieved.

One important concern is that a significant amount of possible savings have not been realised. A large portion of these missed savings was caused by equipment failure and delays in the expected raw material shipments, which cannot be predicted or prevented by the system. A portion of these missed savings was caused by operators not following schedules. As the aim of this project was to achieve previously unrealised savings, these missed savings are of significant concern. The system is responsible for providing clear and effective instructions to operators so that maximum savings can be achieved.

Several techniques were implemented to educate and inform plant personnel to monitor and obey schedules. In Case study one, a scheduling report was generated on a daily basis and sent electronically to production personnel from 1 June 2012. This resulted in improved savings. In Case study two and Case study three, a separate user interface was provided so that control room operators would always have optimal schedules available on screen. An example of this is shown in Figure 4-22.

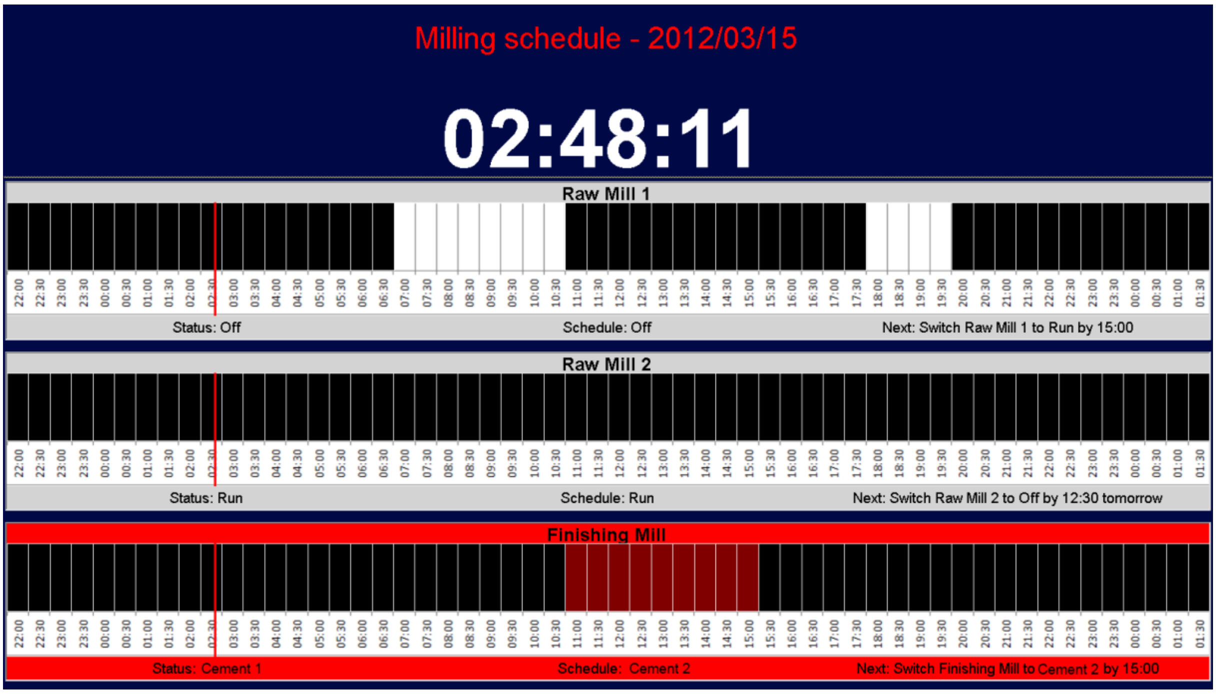


Figure 4-22: Control room interface indicating that the finishing mill schedule is not being followed

4.9 Conclusion

The results of implementing the research described in Chapter 3 were presented, discussed, and evaluated in this chapter. The system passed all quality assurance tests. In certain cases, minor modifications to the software programming were required. For validation, the system was implemented as part of DSM projects at four South African cement plants. Each DSM project was successful, and produced electricity cost savings.

The case studies also address the wide range of applicability of the system. The system was tested on a range of plant components, from as little as one raw mill to a plant with six mills. Due to the varied nature of the factories where the system was implemented, as well as the different operating procedures found within each company, it can be concluded that the system is adjustable for various different users.

Chapter 5 Conclusions and recommendations

5.1 Preamble

This section will conclude the study. Firstly, a brief summary of the research process followed will be given. The benefits of the research will be discussed and the conclusions developed from the results of the research will be presented. Finally, this chapter will make recommendations on future avenues of research within this field of study.

5.2 Summary of research

The overall aim of this research was to realise cost savings in cement plants by implementing an optimisation model. Several researchers had shown the potential for cost savings in cement plants, but none of these had yet been realised. A survey of available literature revealed that certain cement plant components were particularly suited to be managed around Eskom TOU tariffs. It was also found that various solutions had been suggested to optimise the production schedules in cement plants, but these had not been implemented yet.

Based on the analysis of the requirements of one such model, it was found that the barriers preventing its implementation were the data and information requirements. To implement a model manually would have been a time consuming task, therefore a computerised system was designed and implemented.

During the design phase, a system verification test was developed. A conceptual design was conducted, and the various tasks to be performed were reviewed. This allowed for a decision to be made regarding the functional layout of the intended system. Finally, a detailed design was performed to translate the conceptual design into tasks a programming team could implement.

The resulting system was verified by the tests established during the design phase. Following this, validation was performed by implementing the system at four cement factories in South Africa. This resulted in a combined cost saving of R8 628 000 at the four cement factories where case studies were conducted. Non-adherence to schedules and equipment failures contributed significantly to the loss of potential savings.

5.3 Benefits of the research

The chief beneficiaries of the study were the cement factories where the system was implemented. Awareness of different electricity tariffs at different times was increased among plant personnel. This encouraged them to attempt to improve cost savings where possible. Improved communication channels between the plant personnel of different departments were established as a direct result of this project. For example, after the maintenance schedule was updated on the system, production personnel would immediately be aware of which days certain production components would be unavailable.

Another benefit was regarding resource management. Swanepoel's model was capable of showing, on a day to day basis, what raw materials would be required to maintain production. Furthermore, by monitoring the stock levels of various resources, the model also assists in risk management. Users were able to follow the rate of consumption of material and predict when stock would be depleted.

When all system constraints were incorporated, users were also able to quickly and accurately determine what the effect of component changes and upgrades would be. If a different management system was introduced on a component to improve production, the system could automatically simulate what the cost benefits would be.

The user friendly interface encouraged users to utilise the system. As in the case of most computer systems, learning to use these systems is enhanced when the users are actively busy using these systems. After new parameters were entered, monitoring and scheduling was carried out automatically. The sophisticated, yet simple control mechanism also encouraged the use of the system.

A key benefit to project engineers was the ease with which the system could be customised. Most of the case studies were implemented by a third party optimisation engine. Two case studies however required either partial or full support of script based optimisation. Due to the nature of the system, this requirement could be easily implemented.

With the system only restricted to certain inputs and outputs when absolutely necessary, it was also very easy to customise it. New types and formats of inputs could be added easily, and changes to existing data inputs could be implemented easily and efficiently. Outputs of the Swanepoel model could also be modified and expanded as required without significant additions to the underlying software.

Another beneficiary of the research was Eskom. The sustained savings achieved by the system coincided with an average demand reduction of 10,5 MW during evening peak hours. The net impact of the system is shown in Figure 5-1. This load reduction assists Eskom in maintaining a stable supply network.

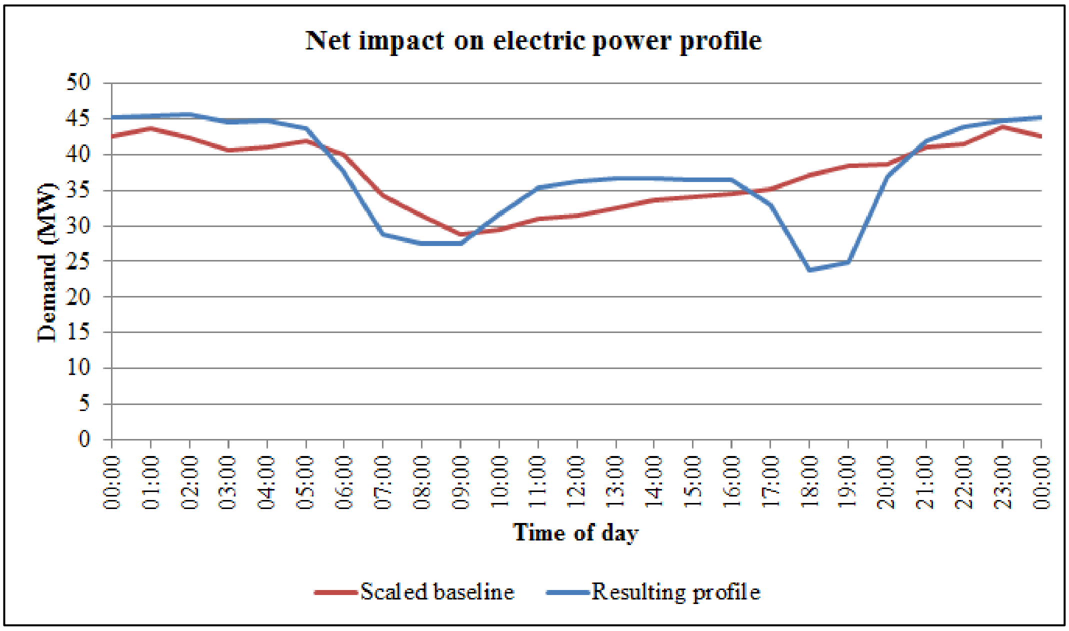


Figure 5-1: Net impact on electrical power profile

5.4 Conclusions

In Chapter 2, it was discovered that production optimisation was a field of intense research. Both locally and internationally, much work on the subject had been presented. Notably, however, this research had been largely restricted to the theoretical level. Although some researchers had conducted simulations and pilot studies, none had yet presented a way to implement such research.

It was unusual that in such a popular research field, no efforts had been made previously to develop a system to implement an optimisation model. Possible causes of this could be that researchers were unaware of the operating conditions at production lines. Plant personnel are generally overburdened, and do not have time to learn how to apply a theoretical solution. As such, a study that only shows that optimisation is possible, but does not produce an easily implemented, tangible means for doing so, is ineffective. Although the cost of production losses would exceed the gains from energy cost savings with present electricity prices, the baselines for the chosen projects showed that excess capacity was available.

By studying one such optimisation model in depth, it was found that the principle problem with implementing such an optimisation solution was the amount of work required to gather the required data and information. The age old principle that states *the quality of the inputs determines the quality of the output* was very applicable. The models would only be effective when sufficient amounts of the correct information were available.

An important aspect to consider when judging the results of this study is the role of *staff awareness*. As the study progressed, it became clear that plant personnel were either partially or wholly unaware of the differences in electricity costs at different times of day. It would appear that most plant personnel were only aware that costs were increasing, but not that certain costs were increasing more than others.

The greatest shortfall of the system was its reliance on plant personnel to implement the provided schedules. The primary barriers preventing full control of the plant are the prohibitive cost of automation infrastructure, as well as the unwillingness of plant personnel to entrust production to new and unproven software. Although it is understandable that plant personnel might be reluctant to relinquish control to a computer system, the benefits could be considered to outweigh such concerns. Reliable operation over time would also serve to alleviate concerns.

This problem also prevented any further research into bringing the system solution closer to optimality. As the results available were not being achieved due to both the practical constraints and poor cooperation from plan personnel, it was not believed that the improved solution would increase savings. If nothing else, the decision making process should be improved so that a single person could be held accountable for missed savings. By taking responsibility for such losses, it would be much easier to encourage plant personnel to cooperate when schedules are provided.

The most important lesson of this dissertation is that of realising that energy efficiency technology is not the only way to improve a factory’s performance towards responsible energy usage. While the cement industry is very concerned with technology that can reduce the kWh consumed per tonne of cement produced, the electricity cost per tonne produced while keeping the kWh constant does not receive much attention. Improved management and scheduling is often ignored, even though significant cost savings can be realised this way. These savings coincide with improved stability of the electricity supply grid, to the benefit of all parties involved.

5.5 Future work and recommendations

Although the objectives of this research have been met, it is clear that there are still several shortfalls in academia with regards to optimising production lines where complex electricity tariffs prevail. As such, more work needs to be done in this field.

This study identified several areas where further research is recommended. The first area was identified by the literature survey. It showed that some commercial software packages which might have been suited for the purposes of this study, was available. However, quite importantly, it was discovered that academically reliable literature related to these software packages was lacking. It is therefore recommended that efforts should be made within the academic community to identify cases where such technology has been implemented in practice, and to present the results that can be achieved by using these software packages.

Another key area for future research was identified by the shortfalls of this study. As the previous chapter showed, the system is still wholly dependent on plant personnel and their willingness and capability to follow the schedules supplied by the system. A logical further step in the research process would be to develop a more comprehensive automated system. Savings were lost directly as a result of human error. As such, a system should be developed where the supplied schedules can be implemented by an automated system.

Another area for potential further study is that of international markets. Internationally, efforts to reduce operating costs on production facilities are ongoing, especially as economies seek to recover from the global recession. Certain developing countries, such as India and Brazil, are also currently facing significant problems to meeting the electricity demand. Both utilities and plant operators can benefit by implementing the system developed in this dissertation along with the optimisation models as defined by Swanepoel to reduce production costs and sustain a stable electricity supply in developing countries.

The system is also ideal for implementation in other industries. As the type of model and optimisation engine implemented can be customised, the system could potentially be used with simulation models already developed for other industries. Research would first need to be done to indicate which fields currently lack such software.

On cement plants specifically, the potential for load management on coal mills in semi-direct firing lines still holds scope for investigation, as well as the crushing plants. As discussed in Chapter 2, coal mills are often capable of producing fuel faster than the kiln can consume, and could potentially be shut down during peak periods. The impact of stopping a coal mill on the energy efficiency of the kiln it is feeding has not been adequately investigated. It is possible that this would reduce the energy efficiency of the kiln, which would negate any possible cost saving that could be realised by improved load management. On the crushing lines, the prohibitive cost of increasing storage capacity makes implementing load shifting unfeasible.

Another potential area for research is the regional, national or global supply and demand network of industries. By incorporating several plants in a region, along with the sales and demand for product in the region, production can be optimised to minimum cost for the company.

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Appendix A: Model information tables

Table A-1: 'Constant' information inputs.

Physical constants			
	Data type	Example	Unit
1. Crusher			
1.1. Crusher type	String of characters	"Jaw"	-
1.2. Feed rate	Real number	140	Tonne per hour
1.3. Electricity demand	Real number	500	Kilowatt
1.4. Reliability	Percentage	95	Percentage (%)
2. Stockpile			
2.1. Maximum stock	Real number	20 000	Tonne
2.2. Minimum stock	Real number	0	Tonne
3. Raw mill			
3.1. Mill type	String of characters	"Vertical roller"	
3.2. Feed rate	Real number	326	Tonne per hour
3.3. Electricity demand	Real number	3 300	Kilowatt
3.4. Reliability	Percentage	95	Percentage (%)
4. Kiln feed silo			
4.1. Maximum capacity	Real number	20 000	Tonne
4.2. Minimum capacity	Real number	8 000	Tonne
5. Kiln			
5.1. Kiln type	String of characters	"Long dry"	-
5.2. Feed rate	Real number	200	Tonne per hour
5.3. Mass conversion factor	Real number	0.64	-
5.4. Coal feed rate	Real number	25	Tonne per hour
6. Coal mill			
6.1. Mill type	String of characters	"Vertical roller"	-
6.2. Feed rate	Real number	25	Tonne per hour
6.3. Electricity demand	Real number	600	Kilowatt
6.4. Reliability	Percentage	95	Percentage
7. Clinker silo			
7.1. Maximum capacity	Real number	100 000	Tonne
7.2. Minimum capacity	Real number	0	Tonne
8. Finishing mill			
8.1. Mill type	String of characters	"Vertical roller"	

8.2. Products	Array of strings	[“CEM I”;”CEM II”]	-
8.3. Feed rates	Array of numbers	[50,150]	Tonne per hour
8.4. Electricity demand	Real number	5 300	Kilowatt
8.5. Reliability	Percentage	95	Percentage (%)
9. Cement silos			
9.1. Product name	String of characters	“CEM I”	-
9.2. Maximum capacity	Real number	8 000	Tonne
9.3. Minimum capacity	Real number	1 500	Tonne

Table A-2: 'Variable' information inputs.

Variables			
	Data type	Example	Unit
1. Crusher			
1.1. Status	Boolean	True	(True = running)
1.2. Actual feed rate	Real number	125	Tonne per hour
2. Stockpile			
2.1. Stock	Real number	6 000	Tonne
3. Raw mill			
3.1. Status	Boolean	False	-
3.2. Actual feed rate	Real number	0	Tonne per hour
3.3. Actual electricity demand	Real number	125	Kilowatt
4. Kiln feed silo			
4.1. Level	Real number	15 000	Tonne
5. Kiln			
5.1. Status	Boolean	True	-
5.2. Actual feed rate	Real number	60	Tonne per hour
5.3. Actual coal feed rate	Real number	10	Tonne per hour

6. Coal mill			
6.1. Status	Boolean	True	-
6.2. Actual feed rate	Real number	22	Tonne per hour
6.3. Actual electricity demand	Real number	590	Kilowatt
7. Clinker silo			
7.1. Level	Real number	55 000	Tonne
8. Finishing mill			
8.1. Status	Integer	1	1 = CEM I, etc.
8.2. Actual feed rate	Number	48	Tonne per hour
8.3. Actual electricity demand	Real number	5 212	Kilowatt
9. Cement silos			
9.1. Product name*	String of characters	"CEM I"	-
9.2. Level	Real number	3 250	Tonne

Table A-3: 'Constraint' information inputs.

Logical/operational constraints			
	Data type	Example	Unit
1. Crusher			
1.1. Maximum number of stops/starts per day	Integer	3	-
1.2. Minimum time between stop and start	Integer	30	Minutes
1.3. Minimum time between start and stop	Integer	120	Minutes
2. Raw mill			
2.1. Maximum number of stops/starts per day	Integer	2	-

2.2. Minimum time between stop and start	Integer	30	Minutes
2.3. Minimum time between start and stop	Integer	60	Minutes
3. Kiln feed silo			
3.1. Dead stock	Real number	1 000	Tonne
3.2. Minimum reserve stock	Real number	500	Tonne
4. Coal mill			
4.1. Maximum number of stops/starts per day	Integer	1	-
4.2. Minimum time between stop and start	Integer	10	Minutes
4.3. Minimum time between start and stop	Integer	40	Minutes
5. Clinker silo			
5.1. Dead stock	Real number	1 000	Tonne
5.2. Minimum reserve stock	Real number	10 000	Tonne
6. Finishing mill			
6.1. Maximum number of stops/starts per day	Integer	3	-
6.2. Minimum time between stop and start	Integer	30	Minutes
6.3. Minimum time between start and stop	Integer	60	Minutes
6.4. Product change quality delay	Integer	90	Minutes
7. Cement silos			
7.1. Dead stock	Real number	3 250	Tonne
7.2. Minimum reserve stock	Real number	1 000	Tonne

Table A-4: Component data types.

	Data type
1. Crusher	
1.1. Maintenance schedule	Start time and date, duration
2. Raw mill	
2.2. Maintenance schedule	Start time and date, duration
3. Kiln	
3.1. Maintenance schedule	Start time and date, duration
4. Cement mills	
4.1. Maintenance schedule	Start time and date, duration
5. Raw material	
5.1. Surveyed stock	Real number
5.2. Deliveries	Time, date, quantity
6. Sales	
6.1. Predicted sales	Date, quantity
6.2 Actual sales	Date, quantity, format
7. Tariffs	
7.1. Weekday tariffs	Time of day, cost
7.2. Seasonal adjustments	Months, times, cost
7.3. Public holidays	Date, tariff schedule followed

Table A-5: Output graphs.

	Output format
1. Crusher	
1.1. Operating schedule	Bar graph
1.3. Stockpile	Level simulation graph

2. Raw mill	
2.1. Operating schedule	Bar graph
3. Raw meal silo	
3.1. Silo level	Level simulation graph
4. Kiln	
4.1. Operating schedule	Bar graph
5. Clinker silos	
5.1. Silo level	Level simulation graph
6. Cement mills	
6.1. Operating schedule	Bar graph
7. Sales	
7.1. Sales to date	Column graphs
7.2 Expected sales	Area graph
8. Stock	
8.1. Stock change balance	Table of stock levels

Appendix B: Example contents of scheduling report

PTB DAILY MILLING SCHEDULE FOR THURSDAY, 26 JULY 2012

1. DEMAND MARKET PARTICIPATION

1.1. Scheduling

Today's event:	**None**
Eskom status:	**248 MW**
Tomorrow's standby:	**None**

1.2. Month to date performance

Events:	6
Performance percentage:	109%

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2. POWER PLANNING

2.1. Raw mill 3

Next stop: Tomorrow from 18:00 to 20:00

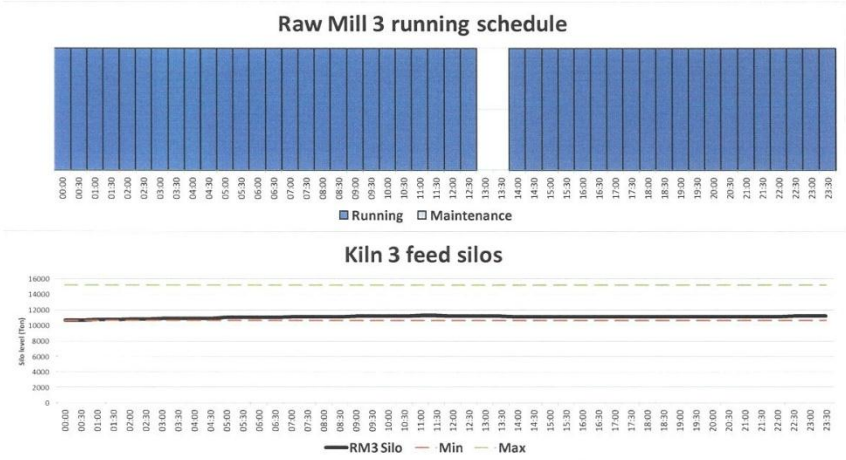

Figure 1: Raw mill 3 running schedule and silo levels for today

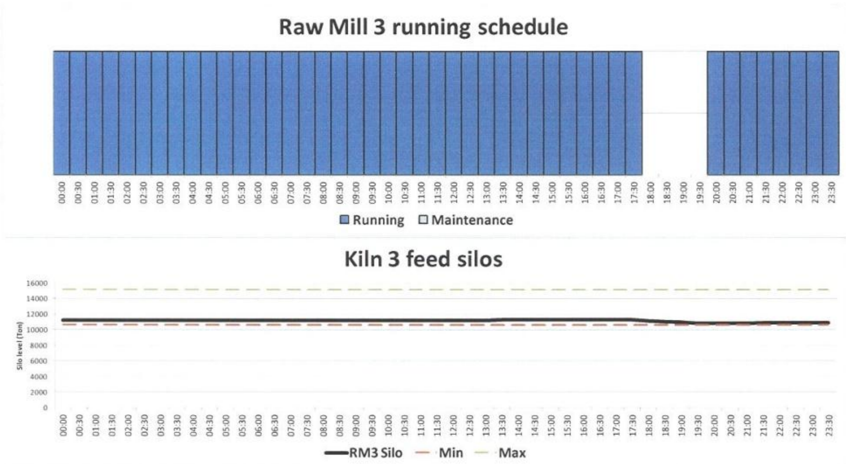

Figure 2: Raw mill 3 running schedule and silo levels for tomorrow

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2.2. Raw mill 4

Next stop: -

Figure 3: Raw mill 4 running schedule and silo levels for today

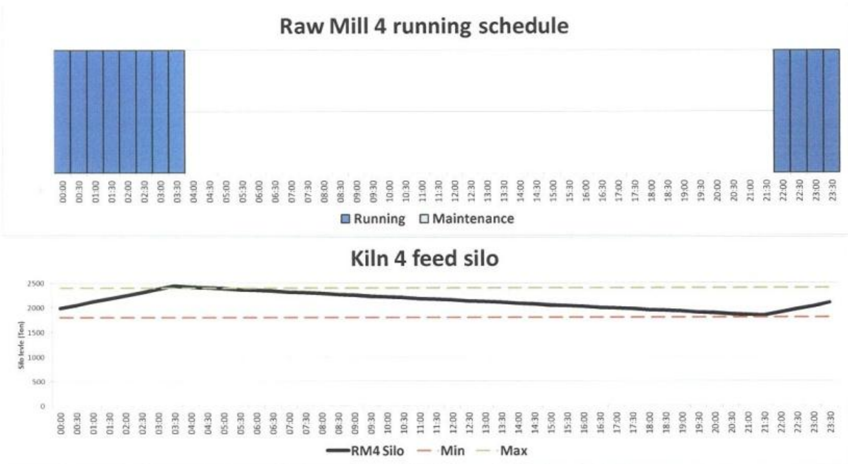

Figure 4: Raw mill 4 running schedule and silo levels for tomorrow

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2.3. Cement mill 1

Next stop: -

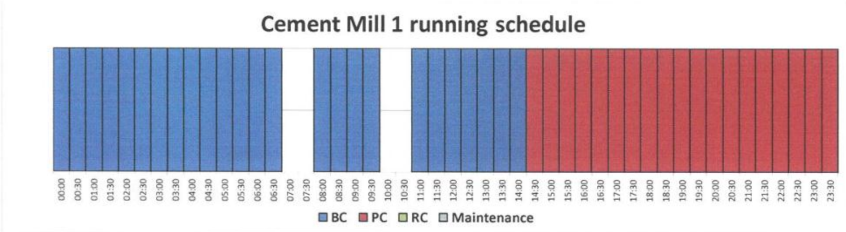

Figure 5: Cement mill 1 running schedule for today

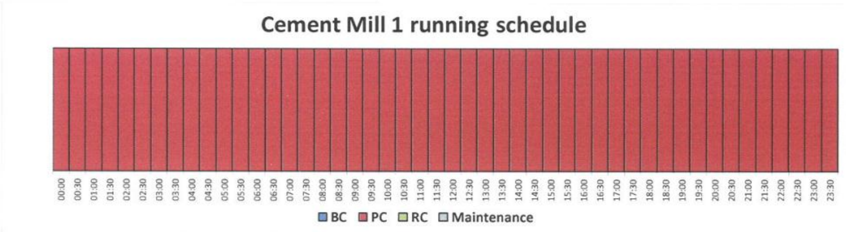

Figure 6: Cement mill 1 running schedule for tomorrow

2.4. Cement mill 2

Next stop: -

Figure 7: Cement mill 2 running schedule for today

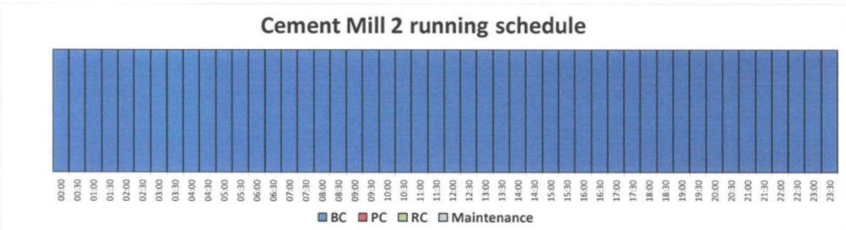

Figure 8: Cement mill 2 running schedule for tomorrow

Appendix C: Example contents of savings report

Daily report for

23 August 2012

Generated on 24 August 2012

1 Project information

Project name:

Tariff structure: MEGAFLEX

2 Day performance* (Thursday, 2012/08/23)

Peak period reduction: 68.20 MWh

Cost saving: R 116 019.94

Remaining potential: R 50 678.06

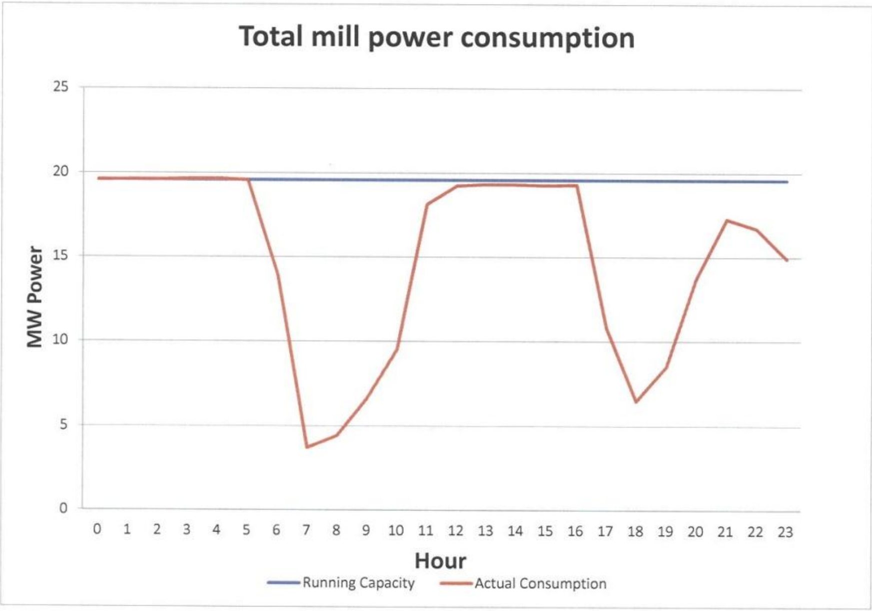

Figure 2-1: *Power profile and baseline for 23 August 2012*

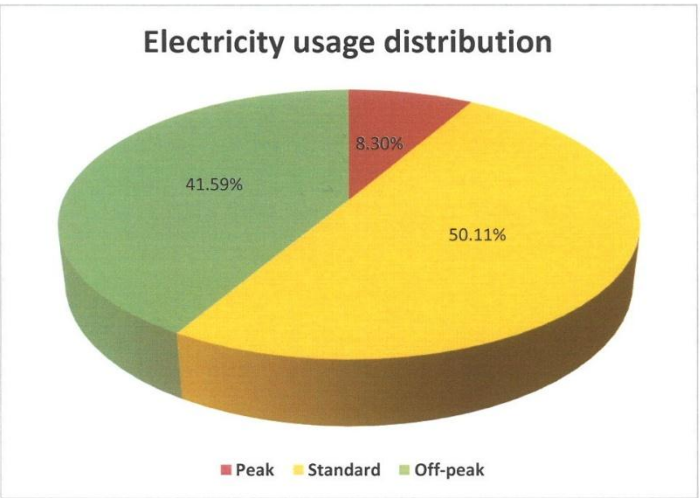

Figure 2-2: Weekday usage distribution – 23 August 2012

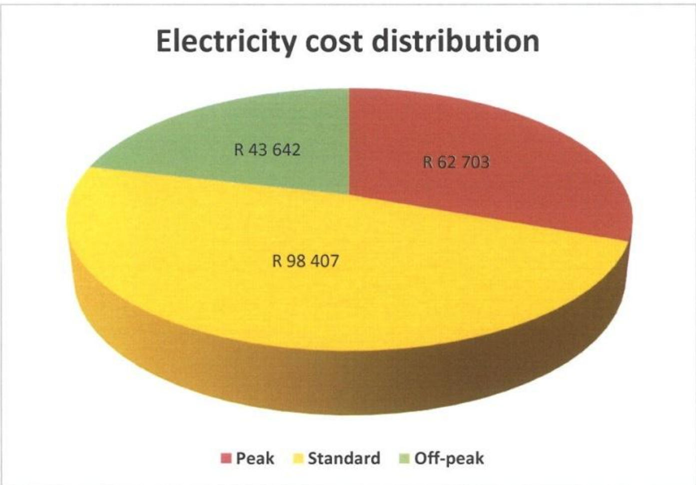

Figure 2-3: Weekday energy cost distribution – 23 August 2012

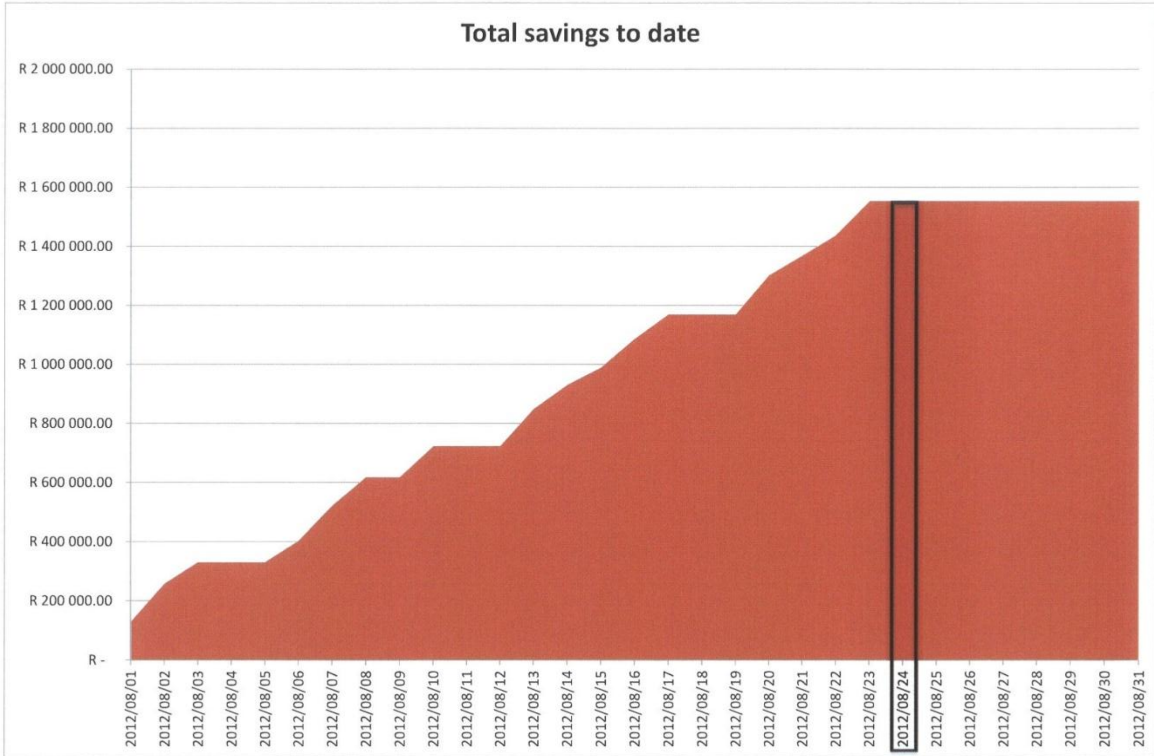

Figure 2-4: *Total savings to date – 24 August 2012*

Appendix D: Unpublished article

The following article is attached in electronic format:

R. Swanepoel, E. Mathews, J. Vosloo and L. Liebenberg, "Integrated energy optimisation models for the cement industry," 2012.

Appendix D

INTEGRATED ENERGY OPTIMISATION MODELS

FOR THE CEMENT INDUSTRY

Riaan Swanepoel, Edward Mathews, Jan Vosloo and Leon Liebenberg

Center for Research and Continued Engineering Development, North-West University (Pretoria campus), and consultants to TEMM Intl. (Pty) Ltd and HVACI (Pty) Ltd.,
Suite no. 93, Private Bag X30, Lynnwood Ridge 0040, South Africa

Corresponding author: Leon Liebenberg
E-mail: LLiebenberg@researchtoolbox.com; Tel: +27 (0)12 809-0995

ABSTRACT:

Energy costs play a major role in the cement production process. As much as 60% of total cost is allocated to energy and 17.75% to the consumption of electrical energy. Historically, energy cost savings were achieved by large infrastructure upgrades. These upgrades are often costly and lead to interruptions in production. In this paper the operation of all the energy intensive components of the cement production process are identified, modelled, integrated and optimised for minimum operational costs while meeting production targets. This integrated approach allows for simulation of the collective effect of individual system components. The model incorporates constraints such as maintenance, production and dynamic energy costs. No published research could be found where these constraints are combined into a single operational modelling system and implemented. The system was implemented on four different cement plants and a total energy cost saving of 7.1% was achieved.

Keywords: integrated energy model, cement plant, energy management system

1. INTRODUCTION

A large portion of the total financial expenditure in the production of cement is allocated to cost of energy [1, 2] which is increasing in some instances at a more rapid rate than inflation [3 - 8]. As a result, the proportion of cost allocated to energy in cement production is increasing. This highlights the importance of decreasing cost in a competitive market that is under pressure due to increasing energy costs [9]. Figure 1 shows the layout of a typical dry cement production process.

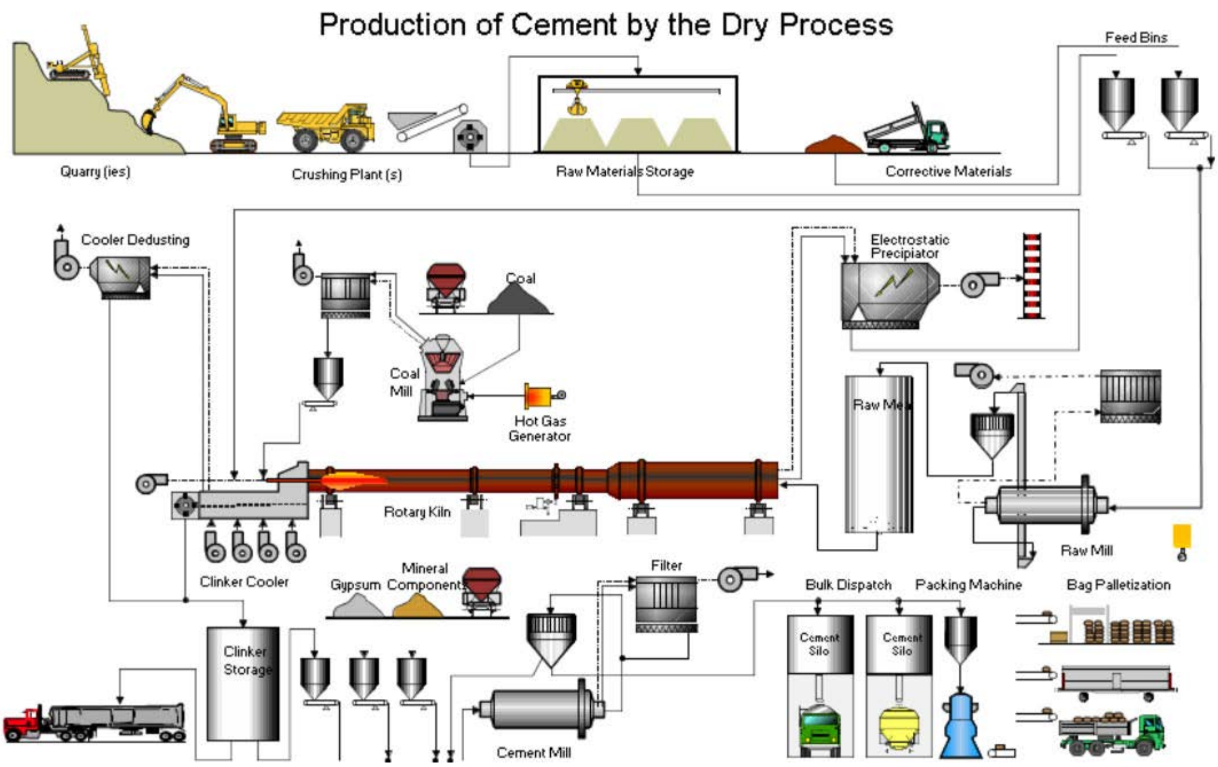

Figure 1 – Basic layout of a dry cement production process [10]

Limestone is the primary raw material that is used in the production of cement. It is mined in large open cast mines, through blasting. The unprocessed limestone has large variations in particle size and therefore passes through a crushing process. This process incrementally reduces the particle size of the limestone by systematically crushing, screening and re-crushing the limestone. From the crushing plant, the crushed limestone is transported via an overland conveyor transport to a large stockpile [11]. The crushers, screens and conveyor transport are all driven by electric motors.

From the stockpile, the raw limestone is reclaimed and transported to a milling circuit where the particle size of the limestone is reduced to a finely monitored powder, known as raw meal. This milling circuit is referred to as the raw mill. In the raw mill, various other raw materials are added to obtain the correct chemical composition of the raw meal. Keeping the raw meal at a constant fineness and accurately controlled chemical composition is crucial to the quality of the final product. Various types of mills are used as raw mills; these include ball- and vertical roller mills. The milling circuit usually consists of one or two raw mills with various separators, precipitators or bag filters. These components require a controlled draught of air induced by fans and blowers that utilise electric drive motors, making them one of the primary consumers of electric energy of the cement plant [11].

The raw meal is then transported to a raw meal silo via airlift or *fluxo*-pumps, air-slides or bucket elevators. From the raw meal silo, the raw meal passes through a pre-heater that consists of a series of cyclone-separators in which heat generated from the kiln is transferred to the raw meal. The draught needed for the operation of the separators is obtained from the kiln in which large fans create airflow to assist the calcination process as well as pre-heating process. The main function of the pre-heater is to recapture the lost thermal energy from the kiln and heat the raw meal before it enters the calcination process. Another function of this component is to separate grinding fines from the raw meal in order to obtain the correct consistency for calcination to take place. This fine dust and emissions from fossil fuel burnt in the kiln is then expelled into the atmosphere through a smoke stack [11].

A more modern design and addition to the pre-heater and separator is the so called pre-calciner. In this process, fossil fuels are burnt to heat the raw meal before it enters the kiln itself. This reduces the total amount of coal required in the kiln and since the pre-calciner heats the raw meal more effectively than the kiln, it offers a reduction in fossil fuels used [11].

The calcination process typically takes place in a large rotating horizontal ceramic lined metal cylinder called a kiln which has a fixed diameter, usually between two and six meters. The length of these cylinders can vary between 40 to 80 meters. In the centre of the latter end of the cylinder is a fuel burner that forms the only heat source in the kiln. The raw meal enters the kiln at the opposite end to the burner and moves slowly along the cylinder allowing sufficient time for heating to a temperature of up to 1400°C. This activates a chemical process in the raw meal called calcination and forms clinker which is the base material used in the making of cement. The pyro-process also removes volatile substances from the raw meal [11].

The final process in the production line is known as finishing milling. Similar to raw milling, this milling process is used to grind clinker and other raw materials to a very fine powder called cement. The active component of cement is clinker. To obtain different final characteristics of the finished product, such as rapid hardening or high strength, different raw materials such as gypsum and fly-ash are added. This final milling is accurately controlled to ensure quality and consistency. It is also necessary to accurately control the temperature and fineness of the final product to ensure reliable and predictable cement quality. To do this, the finishing milling process also consists of a milling circuit with accurate separators and classifiers. This process is also dependant on draft air which is induced by large electrical fans. [11]

The major energy consuming components in the production of cement can be subdivided into four categories as shown in Figure 2.

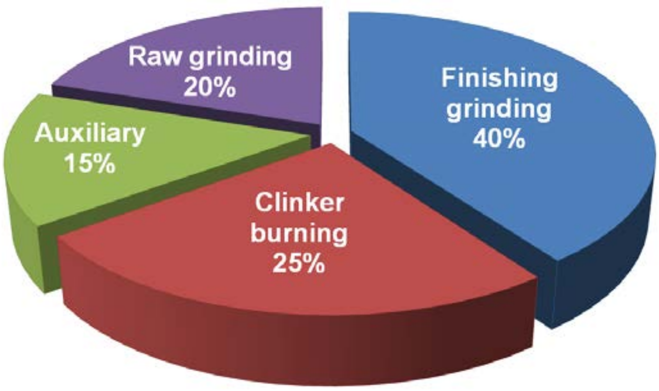

Figure 2 – Energy distribution of cement manufacturing equipment [11]

Figure 2 shows that approximately 60% of the energy is consumed by the grinding circuits. These circuits consume both thermal energy, provided by coal fired kilns, and electrical energy to power the drive motors, conveyor transport systems and fans. Modern cement plants consume an average of 100 kWh - 120 kWh per ton in the grinding circuits [11, 12].

Electrical auxiliary systems of the grinding circuits include air compressors, conveyor transport, water- and oil pumps, and various large fans. The combined electrical energy consumption of grinding systems can constitute up to 75% of all energy used in the cement industry [2, 11]. This corresponds to a total production cost component of 50% - 60% for energy of which 17.75% - 42.6% is allocated to electricity alone [2]. The fairly large variation is attributed to different pricing structures and electricity costs in different areas in the world.

In addition to energy costs, environmental conservation in terms of reducing carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions is a global concern [13]. Thirty-three per cent of global emissions are directly linked to the use of energy [14, 15] of which the cement industry contributes up to 7% of global CO_2 emissions [14, 15].

South Africa's primary electricity utility, Eskom, produces 95% of the electricity consumed in South Africa. Ninety-three per cent of this electricity is generated in coal-fired power plants and the remaining 7% produced by hydro-, nuclear-, gas turbine- and pumped storage generation [16]. Reducing electricity demand of cement plants in South Africa will therefore serve to reduce CO_2 emissions. Managing the demand of the cement industry will also assist in creating a more uniform daily demand distribution and eliminating peaks and valleys in the demand profile. Detrimental gas emissions from coal fired power plants have been quantified by Mann and Spath [17] as indicated in Table 1.

Table 1 – Typical emissions for coal-fired electricity supply [17]

Emissions for coal fired electricity supply	
	Air Emission (g/kWh)
Carbon Dioxide	1018.00
Carbon Monoxide	0.30
Non-methane Hydrocarbons	0.20
Methane	0.90
Nitrogen Oxides	3.30
Nitrous Oxides	0.00
Particulates	9.20
Sulphur Oxides	6.70

The additional CO_2 emissions indirectly emitted as a result of the use of electricity is estimated to be between 101.8 kg and 122.2 kg CO_2 per ton cement produced. This is fairly large when compared to the 137 kg CO_2 per ton cement produced that is directly emitted by the production plant and reported by Velderrama [18].

Various new technologies are available that allow the cement manufacturing industry to operate more efficiently [2]. These technologies are available for various components including mills, kilns, and conveyor transport [2, 19]. Most of these technologies require the installation of new equipment and offer average electrical energy savings of between 1 kWh and 5 kWh per ton [20-22]. In a life-cycle assessment, Valderrama [18] reported that the implementation of best available technologies (BAT) reduced the electricity consumption of clinker production from 76 kWh to 69 kWh per ton. These installations are however costly and require extended production down time [11, 12]. The payback period for these installations is often longer than 10 years [21].

Another technique for achieving energy savings is improved control systems. These systems optimise specific component operation, thus ensuring stable, optimal operation [23]. Savings of between 1.4 kWh and 6 kWh per ton can be realised [20-23]. Valderrama [18] reported a 4% reduction in CO_2 emissions by implementing BAT. Reduction in NO_x, SO_2 and dust emissions of 20.5%, 54% and 84% respectively are also possible.

No literature publications on the application of management and computerised modelling systems that simultaneously integrate the numerous production components could be found in literature. A new modelling system is proposed that provides a solution for reducing emissions and energy consumption by integrating various production components. An integrated model was developed and implemented for this energy management system. Four existing South African cement plants were investigated. Reports on the financial savings achieved during the implementation are also given.

2. INTEGRATED MODELLING

Public awareness and sensitivity to energy consumption and noxious gas emissions have increased in recent years. Benchmarks and regulations have been proposed and documented to help create a structure in which energy consumption and emissions are monitored [24, 25]. A computer-based model has been developed that predicts and manages cement plant operations. This is achieved by integrating various characteristics and modelling of production components. This new model has been implemented with a computerised data recording and processing system. The new simulation model operates in a system that conforms to the "Planning", "Doing", "Checking" and "Acting", or PDCA structure as set out in ISO 50001 [25]. The energy management system (ENMS), referred to as the *Process Tool Box* (PTB), includes an integrated modelling system.

Figure 3 is a schematic representation of PTB. The Roman numerals in the figure indicate which component of the PDCA structure is represented, as described in the sections that follow.

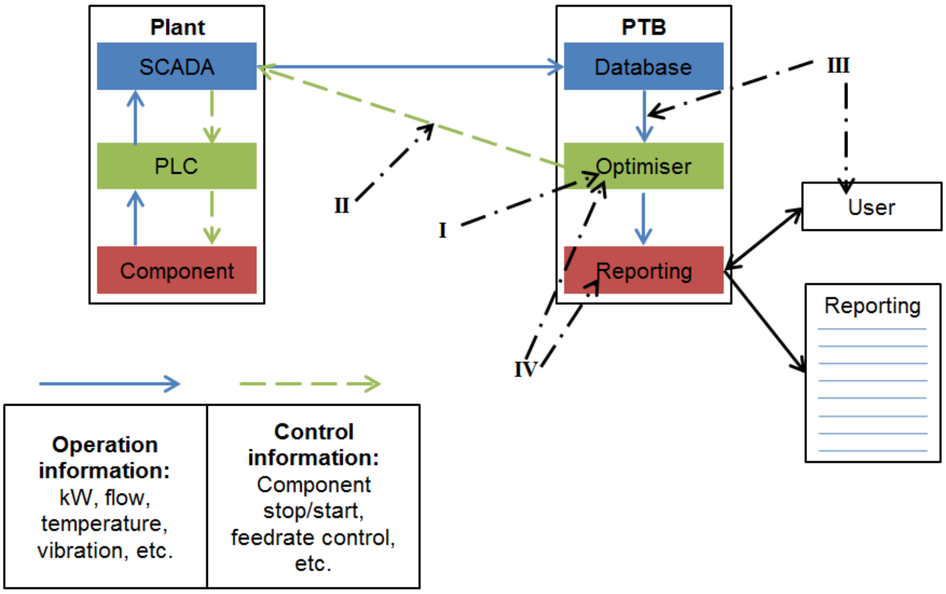

Figure 3 – Schematic of PTB system integration and functionality

In Figure 3, the block labelled "Plant" represents existing control and metering systems installed at the cement plant. PTB extracts required data from the *Supervisory Control and Data Acquisition system* (SCADA) using an *OLE Process Control* or *Object Linking and Embedding Process Control* (OPC) connection and stores the relevant recorded data in a database. PTB's optimiser then accesses the recorded data in the database and optimises the operations model for least operational cost. The optimised solution is then returned to the SCADA via OPC for control of the machines. The optimised solution and operations data is also sent to PTB's reporting tool where it can be accessed by plant personnel. The reporting tool also generates performance reports that are used for evaluation, measurement and verification. PTB is discussed further in conformity to the PDCA structure:

I. Planning:

Planning is set out as establishing energy-saving targets, determining the strategy for obtaining these targets, identifying measures and responsibilities, providing the necessary resources to achieve these targets and preparing an action plan [25]. The core of the ENMS is the PTB modelling system that operates within the larger system (refer to section IV for "Acting"). Various production components have an influence on the cost of the final product and on electricity consumption. In most cases these are either directly or indirectly linked to the operation of the plant. The modelling system therefore considers various constraints that were not previously integrated in similar operations models.

Various physical components are integrated in the simulation model. This allows for the accurate prediction of the influence that different components have on the production system and the final product. These components include raw mills, kilns, coal mills, finishing mills, crushers and auxiliary components. They are essentially and functionally different, but are linked by the production process and cost. Using these two modelling properties – production and cost – the components are integrated in a single, consolidating model. This allows for easy analysis of the influence of these components on the complete system.

To be able to construct an integrated model, the constraints of these components have been incorporated into the system. These include the daily constraints of the specific components, such as maintenance, (scheduled and unscheduled), raw materials requirements, production rate, (constant or variable), and energy requirements. This allows the integrated model to be a powerful tool which contributes significantly to accurately predicting and achieving the plant's potential cost and energy savings. The integrated simulation model does not only analyse the specific cost component, (cost per ton), but optimises the total cost, including raw materials-, energy-, storage-, maintenance-, fuel- and various other costs. The methods for modelling as well as the function of the different variables are shown schematically in Figure 4.

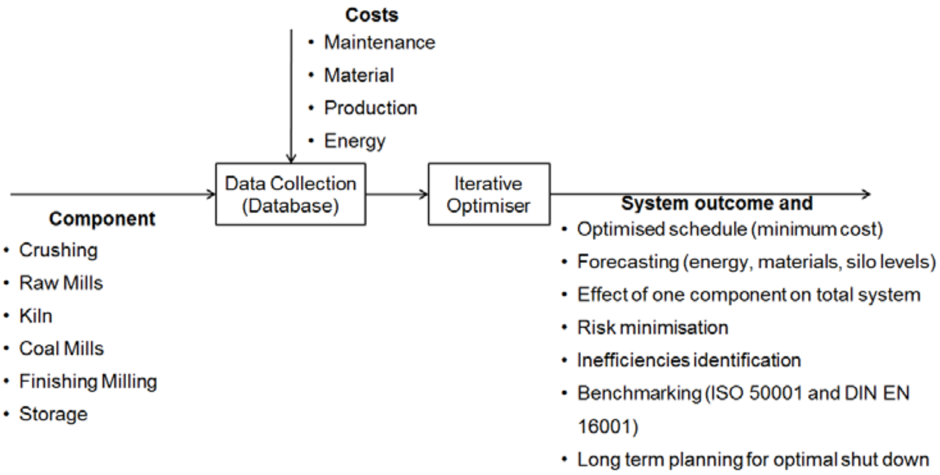

Figure 4 - Variables considered in the integrated system, and the resultant system outcomes and capabilities.

The purpose is to control the operation in order to minimise total production cost and in so doing minimising energy consumption and emissions. To do this, the model makes use of an iterative optimiser that, whilst taking all the variables into account, iterates the operation of the components to obtain the most cost effective solution.

II. Doing:

The "do" clause describes the implementation of the action plan by establishing management structures for maintaining the strategies developed in step I. Implementation also encompasses the actual undertaking of the improvement measures [25]. The output of this model – the optimised operations solution – is then presented in the form of a useful operation and shutdown schedule as shown in Figure 5. This schedule is either implemented by operations personnel (control room operators) or by the system itself through automation, (remote start/stop through programmable logic controller networks).

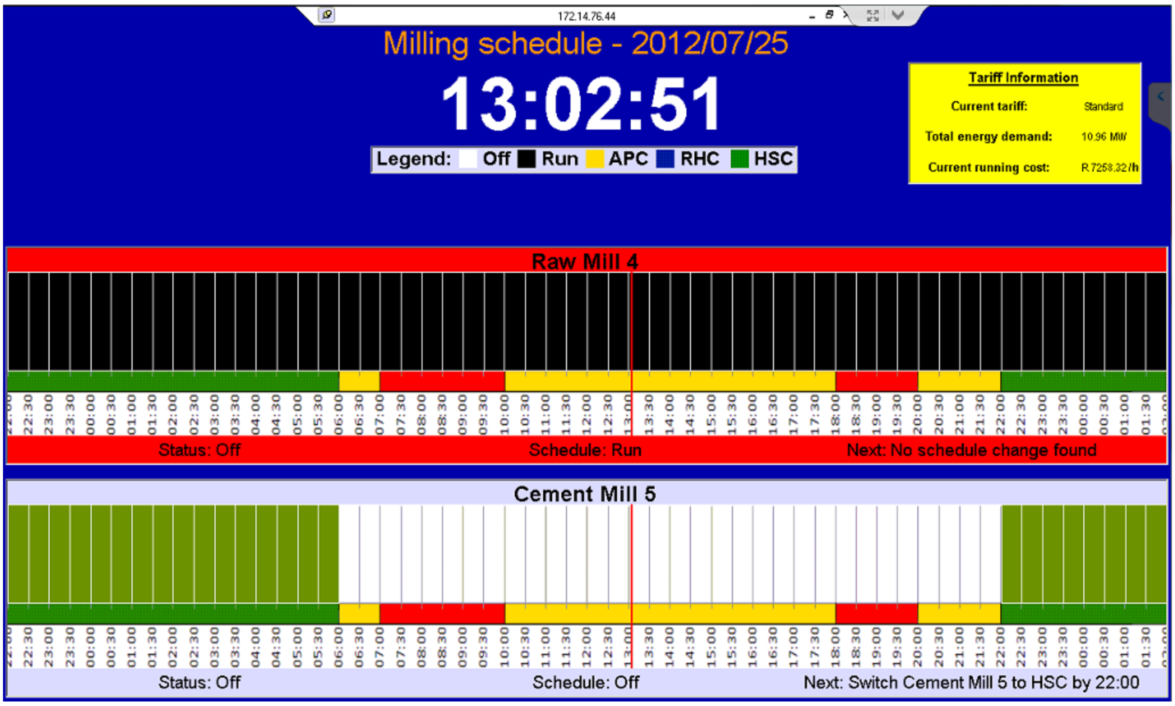

Figure 5 - Daily operations schedule plan (APC = All-Purpose Cement, RHC = Rapid Hardening Cement, HSC = High-Strength Cement)

On this display, as shown in Figure 5, the thin red line represents the prevailing moment. The highlighted blocks represent proposed operating times, colour coded to indicate different products, as seen in the legend in the grey block below the indicated time. The thin green, yellow and red blocks below the schedule indicate the different pricing periods of electricity utility. Once the actual status of the displayed component does not correspond to the proposed schedule, the tab for the component flashes red, as seen with the raw mill tab in Figure 5.

III. Checking

The third step describes the monitoring of the implemented savings measures. This is done by comparing actual savings with the original target and thus evaluating the effectiveness of the ENMS. A re-evaluation is then made of the original savings strategies and targets as described in step I [25]. Sustainability is a major aspect to consider in the implementation of an optimised solution. For sustainable optimal operation and energy efficiency improvement, a reporting component is added to the PTB system.

The reporting component monitors, tracks and reports the operation and energy consumption of the plant. Operational information is obtained from the database and compared to the optimised operations schedule created by PTB. This information is then processed to provide system response feedback, reporting on savings achieved, maintenance completed and unscheduled downtime. Silo levels, flow rates and other important production information are reported. This provides valuable and accurate feedback to plant and management personnel. A database of relevant information is stored for further use in predictive modelling.

IV. Acting

Using an iterative process, these new savings strategies and targets are implemented. These savings strategies are continuously monitored to maintain and improve the implemented energy-savings measures [25]. Savings and operational reports are generated on a daily, weekly and monthly basis, and sent to key client personnel who monitor and verify the performance of the ENMS PTB.

The PTB model is limited by to the client’s database and instrumentation and updated in real-time. Statistical predictions of the operating storage and production capacities, component reliability and energy consumption are made to account for external variables that cannot be modelled. These variables may include the moisture content of raw materials, mill efficiency, breakdowns, and any other variations in plant characteristics. The system and plant responses can be monitored in real-time, which makes this ENMS robust and versatile. Modelling and forecasting of PTB is accurate and comprehensive due to real-time monitoring and updating of process modelling constants.

The overall benefit of this new system is reflected in the improved performance after implementation. Four different cement production plants in South Africa were targeted; each plant posed different challenges and is discussed in the following sections.

3. CASE 1: TIME-OF-USE TARIFFS WITH PARALLEL COMPONENTS

Electric energy costs can be reduced by operating mills during the less expensive time-of-use, (TOU), periods. The average daily electricity demand profile in South Africa confirms the distinct peaks during morning and evening periods as shown in Figure 6.

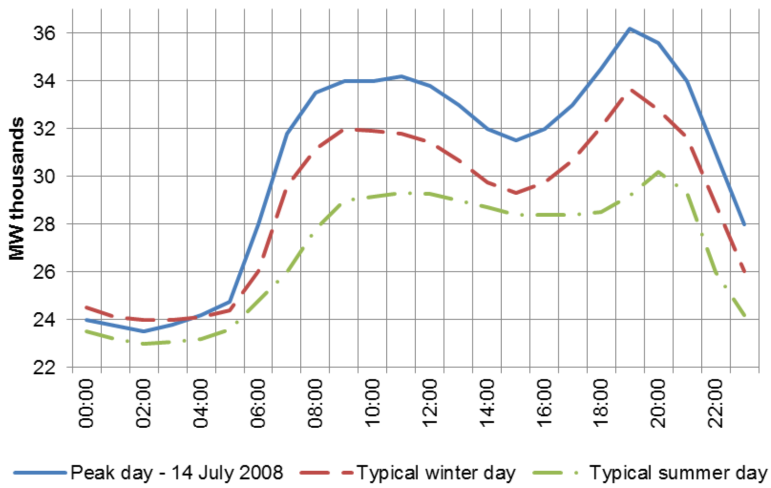

Figure 6 – South African average daily electricity demand profile in 2008 [26]

Loads shifted out of these two peak periods will assist in reducing the maximum supply of the utility. To encourage industries to reduce peak time loads, a TOU billing structure was adopted whereby Eskom applies different tariffs for peak, standard and off-peak periods [8], as shown in Figure 7.

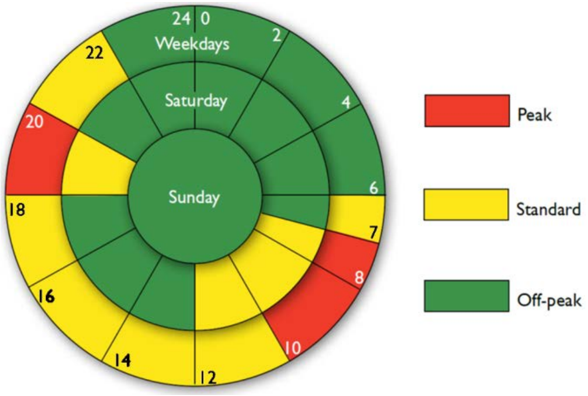

Figure 7 – Time of use tariff structure implemented by electrical utility, Eskom [8]

Optimising costs will ensure that the operation during the most expensive periods is restricted to a minimum. This will not only reduce operating costs for the cement plant but also reduce the power requirement during peak electricity demand periods. Two different cost savings strategies are possible for a cement plant. First the plant operation and cost can be optimised by considering the TOU tariff structure. This can be done by simply restricting operations during the expensive peak periods and, depending on production targets, rescheduling operations to the less expensive periods.

Second, if two components operate in parallel but with different specific electricity consumptions (kWh per ton), as indicated by Figure 8, optimising electricity cost without considering TOU tariffs can also be done. In this case, a horizontal ball mill and a vertical roller mill (VRM) operate in parallel, feeding from the same stockpile and filling the same raw meal silo. It will be more cost-effective to operate the more efficient VRM mill at its maximum availability, and the less efficient ball mill only to essential production requirements. This will be possible when production is lower than the maximum plant capacity. However, in general, the solution in most cases requires a more detailed analysis of components in parallel and taking TOU tariffs into consideration. Analysing the problem now becomes more complex. For instance, it might be more cost-effective to operate the less effective mill during off-peak periods than it is to operate the more effective mill during peak periods (i.e., not operating the more effective mill at its maximum availability as suggested by the second strategy).

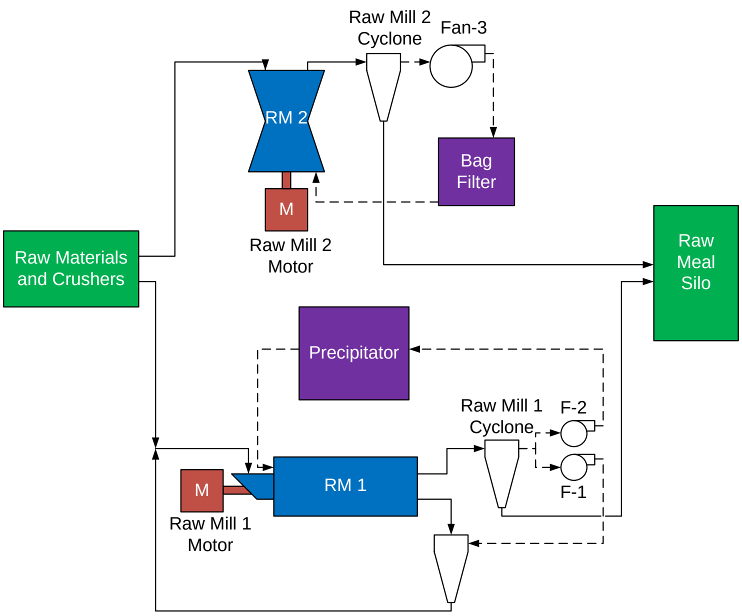

Figure 8 – Schematic representation of Case Study 1 with two different raw mills operating in parallel. (“RM” = raw mill; “F” = fan)

Complexity is increased by the continuously changing production volumes and maintenance requirements, particularly when the number of production components increases. However, by integrating these components in the simulation model, and regularly updating the model, an optimised operations solution is possible. Implementing this ENMS on the circuits as indicated in Figure 8 realised an average 0.97 kWh per ton improvement on the combined electricity consumption of the two mills. Furthermore, 19% of peak electricity usage was also shifted to daily off-peak periods. The combination of these two components of savings resulted in a total saving of 14.8% in electricity costs on the raw milling circuits. Two essential characteristics must however be available to ensure that this operation optimisation is possible. These are reserve production capacity (where production targets are lower than the maximum plant production capacity) and storage capacity. The daily power consumption trend for Case 1 is shown in Figure 9.

Figure 9 – Power consumption with load-shift and energy efficiency trend during the implementation of PTB in Case 1

The trends in Figure 9 are based on three months average production data after implementing PTB. A daily baseline is then compiled using three months average operations data before implementing PTB and scaled with total production volume. This baseline is then further scaled to be energy neutral to the post-implementation power consumption trend. The difference between the production scaled baseline and the energy neutral scaled baseline is considered as the average energy efficiency.

4. CASE 2: UTILISING STORAGE CAPACITY FOR EXTENDED PERIODS OF TIME

Production load-shifting is largely dependent on available storage capacity. Consider for example, a raw meal silo that stores a constant supply of material. If the production rate of the raw mill preceding the silo is greater than the production rate of the kiln, electrical load can be shifted. The silo must however have adequate capacity to supply the kiln with material while the raw mill is shut down. When silo capacity is large enough, more than just a daily load shift is possible. A typical example of this is shifting load from weekdays to weekends where more off-peak time is available. On the plant considered in Case 2 the raw meal silo has a capacity of 36 000 tons. This allows production load to be shifted from weekdays to weekends. The operation during an average week of implementation of the ENMS PTB is indicated in Figure 10.

To evaluate the performance of the implementation, an electrical power consumption baseline was constructed. This baseline is the average electricity consumption profile, taken over a three month period, of normal operation. The baseline is then scaled, based on production volumes, to evaluate the performance of the intervention. From Figure 10, it can be seen that the average demand during standard and peak times is generally lower than the baseline while average demand is increased during weekday off-peak periods and weekends. Due to the dynamic nature of the production process, evaluating the effect of larger or smaller storage capacity on the plant is too complex to solve manually. The obvious solution is to use a simulation model that integrates production rates and storage capacities.

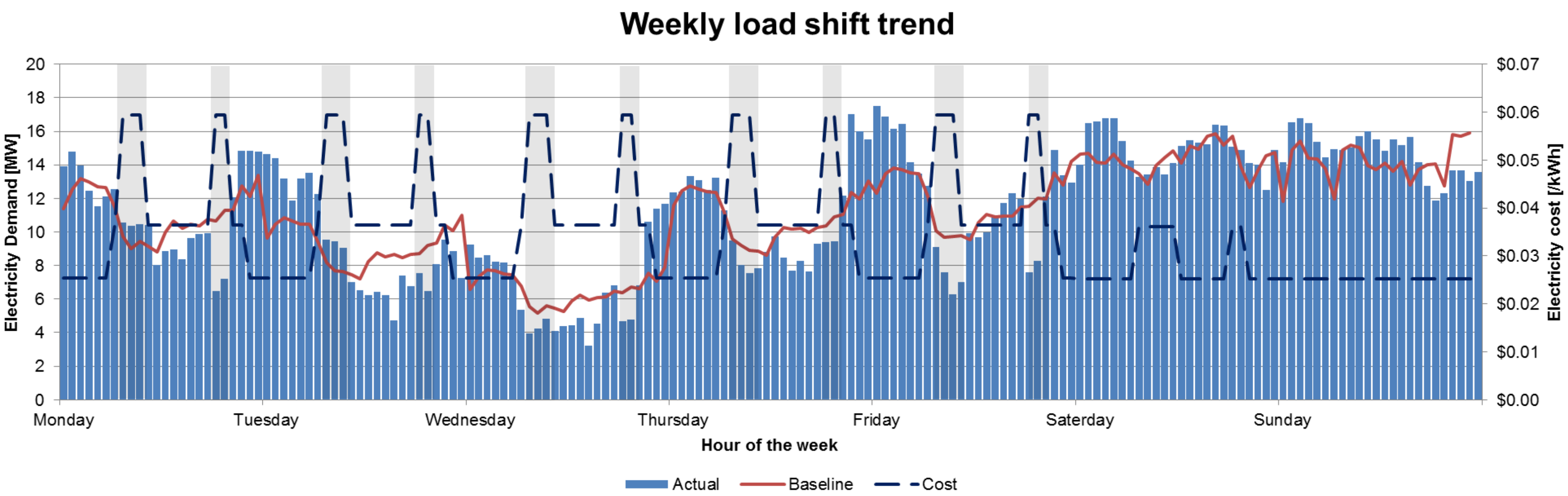

Figure 10 – Power consumption trend for weekly load shift of Case 2

Eskom tariffs are higher during winter months. PTB shows that increased cost savings can be achieved by optimising long-term production to allow for increased winter tariffs, shifting the effective utilisation from winter months to summer months. The total required plant utilisation during winter months is reduced by stocking more material in storage silos during summer months. An example of this storage utilisation is illustrated in Figure 11. PTB indicates that it is in most cases more effective to undertake large annual maintenance events, such as kiln relining, during the more expensive winter months while achieving production and sales targets. It will also specify, depending on the changing production targets, which period during the expensive winter months is the most cost effective to carry out maintenance programs.

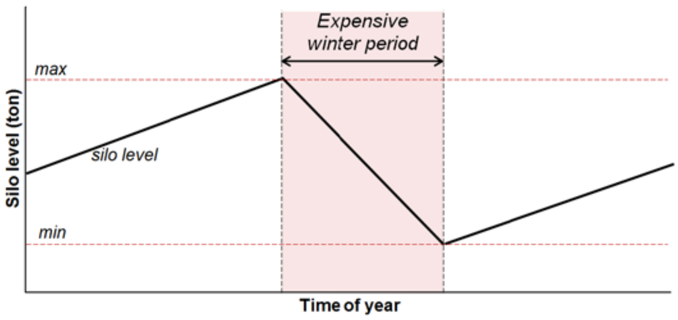

Figure 11 – Storage utilisation (i.e., silo usage) to reduce annual electricity cost

Shifting load out of weekday peak periods to week-day off peak periods and weekends reduced electricity consumption cost by 14.4%, reducing peak electrical demand by 5.6 MW.

5. CASE 3: DYNAMICALLY FLUCTUATING ELECTRICITY COST

Real-time data updates allow PTB to adapt and iterate the operations solution to dynamic variations in energy costs. Reduced reserve supply margins compelled Eskom to introduce an initiative called Demand Market Participation (DMP). This initiative rewards clients for reducing electricity demand on request by the utility. Requests are conveyed on a short-term basis, typically only a few hours before a reduction in demand is required. This short-term notification further complicates optimal operations planning which incorporates DMP.

Frequent data acquisition and iteration of an optimal solution allows the simulation model to allow for these DMP events, (or bids), in the calculation of total electricity cost. Because the financial incentives of these bids vary, the ability to view the effect of a sudden loss of production and its long-term energy cost influence is important in operations planning. An informed decision can thus be made to accept or reject these load reduction requests, depending on whether it is favourable or not to larger-scale cost reduction. The same capability, to frequently update the optimal solution, makes the model ideal for operations in a dynamic energy cost environment, such as an energy market or other dynamic energy cost circumstances.

In Case 3, a total DMP performance improvement of 4.2%, with a total of 3.1 MW of electrical load shifted from weekday peak periods to off-peak periods. A total cost reduction of 5.3% as a result of load shift and DMP performance combined was realised. Figure 12 indicates the DMP performance of Case 3 with a monthly average before and after PTB was implemented.

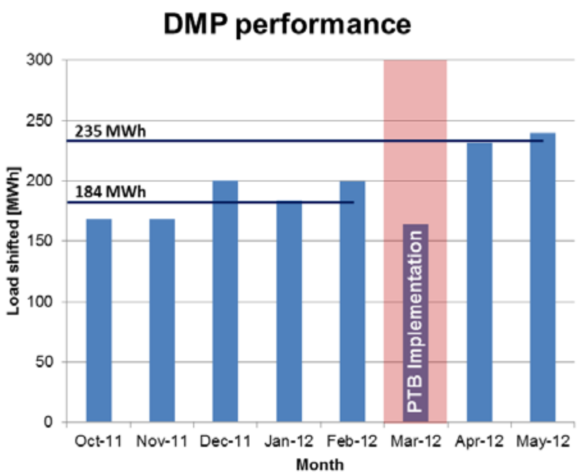

Figure 12 – DMP performance before and after implementation of the PTB System (Case 3)

6. CASE 4: RAW MATERIALS COST

So far, only the energy cost optimisation capabilities of integrated modelling have been evaluated. However energy costs are not the only cost influence that should be considered when optimising component selection and operation. A system with two identical finishing mills, one with a more effective separator, is a good example of this influence. This configuration of components is indicated in Figure 13.

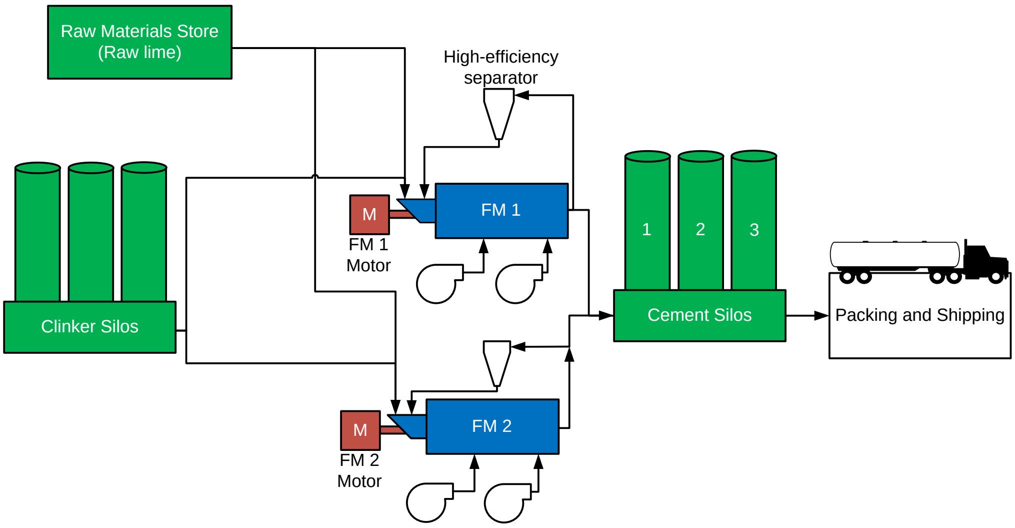

Figure 13 – Production component schematic indicating two finishing mills in parallel, with different separators.

The effect of this increased efficiency separator on the system is that the one finishing mill requires more clinker to produce a final product with the same characteristics. Because clinker is a more expensive material than the alternative raw lime-stone, due to physical characteristics, the one mill requires a more expensive combination of raw materials to produce the same final product.

Once again, as with parallel mills of differing efficiency, it is clear that the production of the more efficient mill (with regards to raw materials cost) should be maximised during normal operation.

However, combining TOU tariffs, raw material cost and dynamic electricity cost influences, this problem also becomes too complex to analyse manually. Figure 14 shows an example of combining the costs of both electricity usage and raw materials cost.

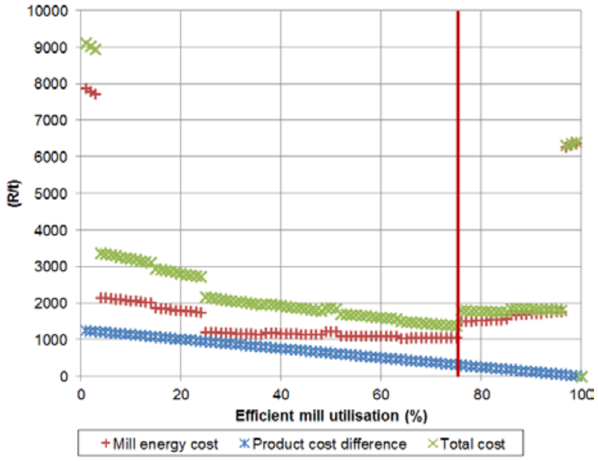

Figure 14 – Cost comparison of raw materials cost to electricity cost of operation

Figure 14 is compiled for a specific cement product and for a specific production target. It indicates the cost spread with increasing utilisation of the more efficient mill and subsequently decreasing utilisation on the less efficient mill. It can be seen that the minimum cost is reached at a 75% utilisation of the more efficient mill and a 25% utilisation of the less efficient mill, instead of the initially assumed full utilisation of the more effective mill. When production targets fluctuate and different constituents are produced, the production costs vary considerably. By integrating each of these influences and rapidly re-evaluating the most cost effective solution, the plant can be operated at the lowest possible cost. In a similar way, the cost of raw materials can be optimised when a pre-determined quantity of coal is added to a raw milling circuit. Implementation of PTB in Case 4 produced a combined saving in electricity cost on the milling circuits and raw materials cost of 8.1%.

7. SUMMARY OF CASE STUDIES

Savings in these various forms combined to achieve the results shown in Table 2. These results were based on a monthly implementation during the less expensive summer months. Integrated modelling allows a production plant to operate more effectively and at a reduced energy cost.

Table 2 – Summary of savings achieved during the implementation of the ENMS

	Actual operations Per annum	**Baseline cost Per annum**	**Savings**	
			Cost	**%**
Case 1	$737 980	$752 694	$14 714	14.8
Case 2	$655 596	$765 793	$96 323	14.4
Case 3	$1 677 552	$1 765 264	$87 712	5.2
Case 4	$2 037 433	$1 872 052	$165 381	8.1
Total	$5 108 562	$5 155 804	$364 130	10.6

8. CONCLUSION

Due to the large initial capital costs and the extended payback period for energy saving infrastructure improvement, a novel approach was followed to effectively obtain energy and emissions savings in the cement industry. All the components used to produce cement on a plant are interlinked. Using this as a starting point, the study found that by modelling the entire system of components and rescheduling their operations, energy savings could be obtained. A computerised operations model was developed that integrated all the components of the cement plant, including each individual constraint. Operational procedures were re-scheduled to optimise for cost savings. This model was implemented by creating an ENMS that conforms to the ISO 50001.

During the investigation, the study found that electricity is the major form in which energy is consumed by the cement industry. The energy analysis was extended to a national electricity demand level. Energy and emission reductions were shown to be possible by changing the load profile of the cement production plants. The TOU tariff structure corresponds to the South African power demand profile. Implementing the developed ENMS resulted in a reduction in peak electricity demand while optimising electricity costs for the cement plant. This new integrated modelling approach, combined with TOU electricity cost saving and system characteristics resulted in an overall energy cost saving. In addition to these savings, frequently updating the modelling constants in real time, these savings can be obtained with dynamically fluctuating energy cost as well.

Optimising cost and integrating different component characteristics meant that raw material costs could also be incorporated in the model. This not only reduces energy costs and emissions, due to lower electricity demand, but total cement production cost is reduced as well. The advantages of an integrated modelling approach allow the cement plants to obtain larger total savings than when the modelling and planning of operations of large components is done individually. Implemented studies clearly revealed the individual benefits of the system. The ENMS combines these benefits to form an integrated solution and showed a 7.1% improvement in operations costs on each milling system on which it was implemented.

The functionality of this new ENMS however is not limited to implementation on only cement production plants. The results suggest that the application of the integrated modelling method and the ENMS in different industries and on different production plants should be investigated further.

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