



NORTH-WEST UNIVERSITY
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Modelling for integrated energy optimisation in cement production plants

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23390484

Dissertation submitted in partial fulfilment of the requirements for the degree
Master of Engineering in Mechanical Engineering
at the Potchefstroom campus of the North-West University

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November 2012



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ABSTRACT

Title: Modelling for integrated energy optimisation in cement production plants
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Cement production is an energy intensive process. In South Africa the cost of energy increased since 2006, while cement sales have dropped dramatically. It has become important to focus on methods to optimise energy consumption to achieve cost savings in the cement industry. Various methods of reducing production cost by improving energy efficiency are available, but require extended installation periods and high initial capital expenditure. Other methods such as operational optimisation can reduce production cost, but offer limited savings.

The aim of this study is to integrate the optimisation of multiple component operations to improve savings and reduce interruption during implementation. Although integrated optimisation models have been developed, no literature could be found on the application of these models in the cement industry.

This thesis reports on the development and implementation of an energy management system at four South African cement plants. The total electricity costs were reduced without installing costly infrastructure upgrades. The results summarise the success of the improved production planning. A conclusion regarding the feasibility of this implementation is compiled by comparing the savings achieved by the implementation of the energy management system to other energy saving methods. Recommendations are also made for further study and the implementation of the energy management system in similar industries.

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

OPSOMMING

Titel: Modelling vir geïntegreerde energie-optimalisering in sementproduksieaanlegte
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Die produksie van sement is 'n energie intensiewe proses. In Suid-Afrika het die koste van energieverbruik sedert 2006 gestyg, terwyl sementverkope skerp gedaal het. Dit het belangrik geword om op die verbetering van energieverbruik te fokus om kostes te bespaar. Verskeie metodes is beskikbaar om energie in die sementindustrie meer doeltreffend te verbruik om produksiekostes te verlaag, maar dit vereis verlengde installasietydperke en die aanvanklike uitgawes is hoog. Ander metodes, soos produksie-optimalisering, bied beperkte besparingsmoontlikhede.

Die doel van hierdie ondersoek is om te bepaal of 'n geïntegreerde optimalisering van veelvoudige komponente energiebesparing kan bevorder en onderbrekings gedurende die implementering daarvan kan verminder. Alhoewel daar reeds geïntegreerde optimaliseringsmodelle ontwikkel is, is daar geen literatuur beskikbaar wat die toepassing van hierdie modelle in die sementindustrie beskryf nie.

Hierdie verhandeling beskryf 'n ondersoek na dié modelle en die toepassing daarvan (energiebestuur) in vier Suid-Afrikaanse sementaanlegte. Die doel van die toepassing is om die totale elektrisiteitskoste van sementproduksie te verminder, sonder om duur infrastruktuuropgraderings te doen. Die elektrisiteitsverbruik van die vier sementaanlegte is bereken en gebruik om die kostebesparing, wat die toepassing van die energiebestuurstelsel bewerkstellig het, te bereken.

Die bevindinge oor die sukses van die verbeterde produksiebeplanning word saamgevat. 'n Gevolgtrekking aangaande die toepaslikheid van die stelsel word gemaak deur die resultate van hierdie toepassing met dié van ander energiebesparingsmetodes te vergelyk. Laastens word voorstelle in verband met die toepassing van die energiebeheerstelsel in soortgelyke industrieë gemaak.

Sleutelwoorde: geïntegreerde energiemodel, sementaanleg, energiebestuurstelsel

PREFACE

This dissertation is presented in the form of a research article, with a consolidating preceding discussion. The consolidating discussion provides more detailed information to better contextualise the article. The research article is presently under review by the ISI accredited journal, *Applied Energy* (impact factor = 5.11). The unpublished manuscript and the editor's letter are attached (see Annexure A). The co-authors are Prof E.H. Mathews, Prof L. Liebenberg and Dr J.C. Vosloo.

The article focuses on a newly developed energy management system to manage the operations of a cement production plant. This energy management system was developed in accordance with present energy management standards and implemented in four South African cement plants. The effect of optimising operations schedules and the application of these schedules on the day to day operations of the industrial plants was determined during a three month trial period.

ACKNOWLEDGEMENTS

- I would like to thank the Lord my God for the opportunities granted me and the ability to seize these opportunities. I do so in humble praise as to showcase His glory.
- I would like to thank Prof E.H. Mathews and TEMM International (Pty) Ltd for giving me the opportunity and means to complete the study documented in this thesis.
- I would like to thank Prof L. Liebenberg for his invaluable guidance and assistance.
- I would like to thank the members of the team who assisted during the development and implementation of the energy management system that serves as topic for this study. In particular Dr. J.C. Vosloo for his guidance and support, R Maneschijn for his dedication and hard work and all other project engineers involved in the implementation of the four considered case studies.
- I would like to thank my parents for motivation, support and love.

CONTENTS

| | |
|---|------|
| Abstract..... | i |
| Opsomming | ii |
| Preface | iii |
| Acknowledgements..... | iv |
| Contents | v |
| List of Figures | vii |
| List of Tables | viii |
| Nomenclature | viii |
| Abbreviations: | viii |
| Glossary:..... | ix |
| 1. Cement production in South Africa..... | 2 |
| 1.1. Preamble | 2 |
| 1.2. Aims of the study | 4 |
| 1.3. Basic assumptions..... | 5 |
| 1.4. Research question..... | 5 |
| 1.5. Scope of the study | 6 |
| 1.6. References | 7 |
| 2. Cement production and important concepts..... | 10 |
| 2.1. Cement plant layout and components..... | 10 |
| 2.2. Energy consumption in a cement plant | 11 |
| 2.3. References | 18 |
| 3. Motivation and relevance | 20 |
| 3.1. Energy consumption in the cement industry..... | 20 |
| 3.2. Emissions in the cement industry..... | 21 |
| 3.3. Present energy savings measures for the cement industry | 22 |
| 3.4. Integrated modeling of plant operations for energy constraints | 24 |
| 3.5. Energy management standards ISO 50 001, DIN EN 16 0001 and PAS 55..... | 25 |

CONTENTS (CONTINUED)

| | |
|---|----|
| 3.6. References | 28 |
| 4. Method and analysis | 31 |
| 4.1. Modeling | 31 |
| 4.2. System development and Implementation | 33 |
| 4.3. References | 40 |
| 5. Application and results | 42 |
| 5.1. Case 1: Time of use tariffs with parallel components | 42 |
| 5.2. Case 2: Utilising storage capacity for extended periods of time..... | 45 |
| 5.3. Case 3: Dynamically fluctuating electricity cost | 48 |
| 5.4. Case 4: Raw materials cost | 50 |
| 5.5. References | 53 |
| 6. Summary and conclusion..... | 55 |
| 6.1. Summary of case studies..... | 55 |
| 6.2. Conclusion..... | 56 |
| 6.3. Recommendations..... | 57 |
| 6.4. References | 59 |
| Apendices | 61 |
| Annexure A..... | 61 |
| Writer requirements for articles submitted to Applied Energy | 61 |
| Annexure B..... | 76 |
| Swanepoel R., Mathews E., Vosloo J., Liebenberg L., 2013, "Integrated energy optimisation models for the cement industry", Applied Energy, in review..... | 76 |

LIST OF FIGURES

| | |
|---|----|
| Figure 1: South African electricity charges trend | 2 |
| Figure 2: International coal cost per short ton | 2 |
| Figure 3: South African cement sales trend | 3 |
| Figure 4: South African electricity demand profile | 4 |
| Figure 5: Dry process cement production flow diagram..... | 11 |
| Figure 6: Jaw crusher operation..... | 12 |
| Figure 7: Jaw crusher..... | 12 |
| Figure 8: Horizontal ball mill..... | 13 |
| Figure 9: Vertical roller mill..... | 13 |
| Figure 10: Preheater tower | 14 |
| Figure 11: Preheater tower operational diagram | 14 |
| Figure 12: Schematic of a precalcining kiln | 15 |
| Figure 13: Rotary kiln for the cement industry | 16 |
| Figure 14: Energy distribution of cement manufacturing equipment | 20 |
| Figure 15: Structure of integrated asset management as described by PAS-55..... | 25 |
| Figure 16: Energy management system characteristics | 26 |
| Figure 17: Case study of a processing stage with multiple component..... | 31 |
| Figure 18: Discrete modelling compared to aggregate modelling | 31 |
| Figure 19: Optimal storage and production profiles during application in the cement industry | 32 |
| Figure 20: Schematic of PTB system integration and functionality | 33 |
| Figure 21: Variables considered in the integrated system, and the resultant system outcomes and capabilities..... | 35 |
| Figure 22: Model accuracy without calibration..... | 36 |
| Figure 23: Model accuracy with continuous calibration (daily)..... | 36 |
| Figure 24: Daily operations schedule plan (APC = All-Purpose Cement, RHC = Rapid Hardening Cement, HSC = High-Strength Cement) | 37 |
| Figure 25: South African average daily electricity demand profile in 2008 | 42 |
| Figure 26: Time of use tariff structure implemented by electrical utility, Eskom | 43 |
| Figure 27: Schematic representation of Case Study 1 with two different raw mills operating in parallel. ("RM" = raw mill; "F" = fan) [5.1]..... | 44 |
| Figure 28: Power consumption with load-shift and energy efficiency trend during the implementation of PTB in Case 1 [5.1] | 45 |
| Figure 29: Power consumption trend for weekly load shift of Case 2 [5.1]..... | 47 |

| | |
|--|----|
| Figure 30: Storage utilisation (i.e., silo usage) to reduce annual electricity cost | 48 |
| Figure 31: DMP performance before and after implementation of the PTB System (Case 3) | 49 |
| Figure 32: Production component schematic indicating two finishing mills in parallel, with different separators. | 50 |
| Figure 33: Cost comparison of raw materials cost to electricity cost of operation | 51 |
| Figure 34: Example layout of a typical gold plant | 57 |
| Figure 35: Example layout of a typical platinum concentrator plant | 58 |

LIST OF TABLES

| | |
|--|----|
| Table 1: Typical emissions for coal-fired electricity supply | 22 |
| Table 2: Summary of savings achieved during the implementation of the ENMS | 52 |
| Table 3: Summary of savings achieved during the implementation of the ENMS | 55 |

NOMENCLATURE

ABBREVIATIONS:

| | |
|-------|--|
| APC | Advanced Process Control |
| APC | All Purpose Cement |
| BAT | Best Available Technologies |
| DMP | Demand Market Participation |
| DMP | Demand Market Participation |
| DSM | Demand Side Management |
| EE | Energy Efficiency |
| ENMS | Energy Management System |
| HSC | High Strength Cement |
| OLE | Object Linking and Embedding |
| OPC | OLE for Process Control |
| PDCA | Plan, Do, Check, Act |
| RHC | Rapid Hardening Cement |
| SCADA | Supervisory Control and Data Acquisition |
| TOU | Time of Use |
| VRM | Vertical Roller Mill |

VSD

Variable Speed Drive (Alternative: Variable Frequency Drive)

GLOSSARY:

Short ton:

A unit of weight representing 2000 pounds in the United States of America.

One

Background and Introduction

Chapter One

This chapter summarises the background of the study, states the aims and scope of the study and also includes the research goal.

1. CEMENT PRODUCTION IN SOUTH AFRICA

1.1. PREAMBLE

The production of cement is an energy intensive process, with 20% to 40% of the total costs allocated to energy and 17% to electricity [1.1, 1.2]. Due to the rapid increase of the cost of electricity in South Africa (see Figure 1) and the international coal cost (see Figure 2) – disproportional to inflation – production cost is increasing. In addition to the overall increase of the cost of cement production, South African cement sales dropped dramatically since 2006/2007 (as shown in Figure 3). These two factors have motivated an in depth study of feasible projects that can be implemented to decrease energy cost during the production of cement.

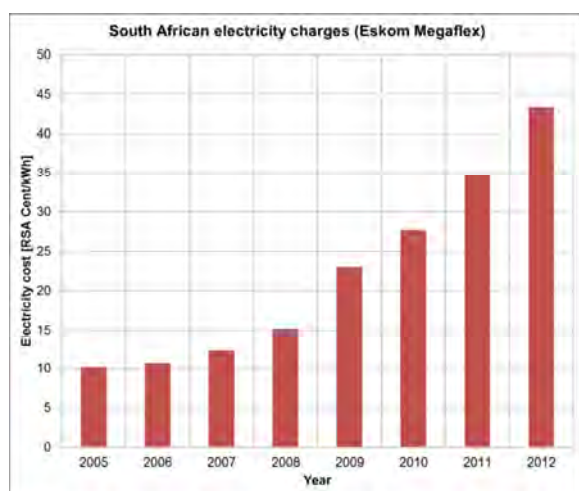


Figure 1: South African electricity charges trend ^a

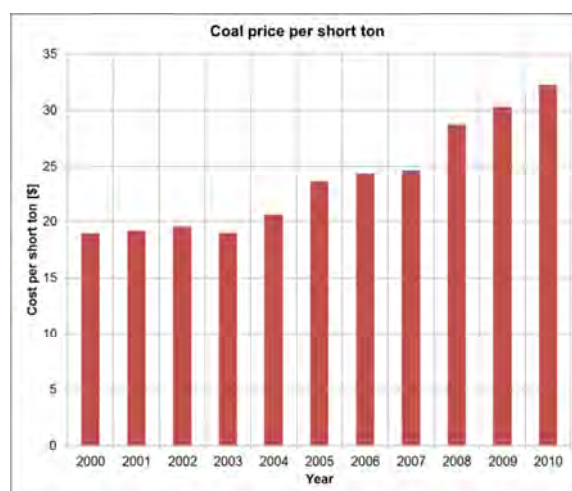


Figure 2: International coal cost per short ton ^b

^a Eskom. Eskom Enterprises (Pty) Limited, Tariffs and Charges, website: <http://www.eskom.co.za/c/article/145/tariffs/> [accessed on 23 June 2012], 2012.

^b U.S. Energy Information Administration, Independent Statistics and Analysis, Annual Energy Review Table 7.9: Coal Prices, website: <http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0709> [access on 11/10/2012], September 2012.

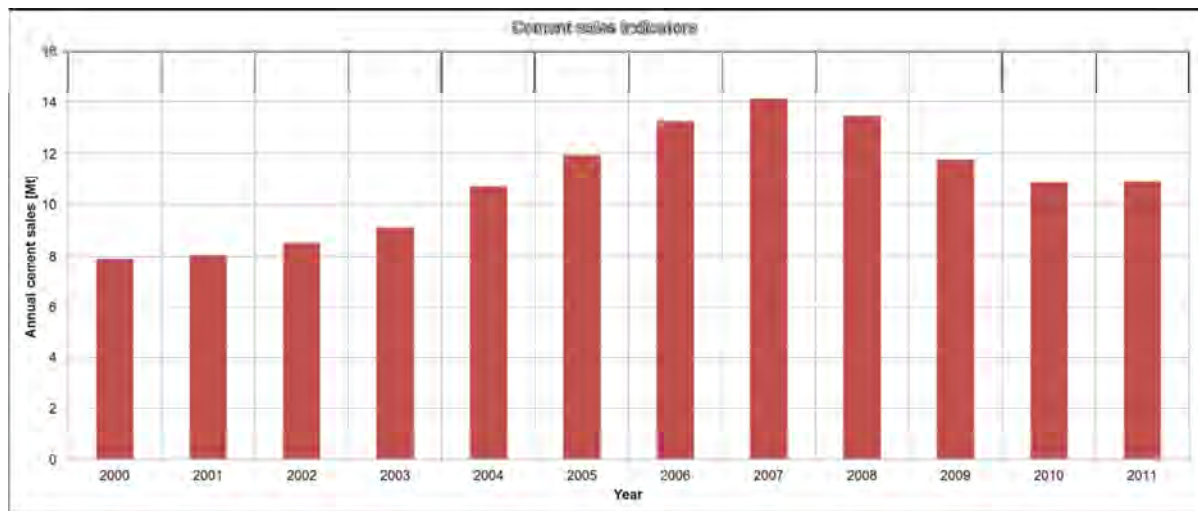


Figure 3: South African cement sales trend ^c

Historically, energy cost savings were achieved by upgrading infrastructure. Swanepoel *et al.* [1.3] state:

“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]...” [1.3].

Another technique for achieving energy savings is to improve control systems. These systems optimise specific component operation, thus ensuring stable, optimal operation [1.7]. Savings of between 1,4 kWh and 6 kWh per ton can be realised [1.4-1.7]. Valderrama [1.8] reported a 4% reduction in CO₂ emissions by implementing the best available technologies (BAT). Reduction in NO_x, SO₂ and dust emissions of 20,5%, 54% and 84% respectively are also possible [1.3].

Electricity costs can be reduced by revising operations schedules [1.9]. The national electricity consumption trend of South Africa (see Figure 4) illustrates two clear peaks in electricity demand. By reducing these peaks of an individual industry, the national maximum

^c PPC. Pretoria Portland Cement Limited, Cement Sales Monitor, website: http://www.ppc.co.za/pages/investor_csm.cfm [Accessed on 27 August 2011], 2011.

demand will also be reduced. This will aid in limiting national emissions. To encourage the reduction of peak demand, the South African electricity utility has employed a time-of-use (TOU) tariff structure.

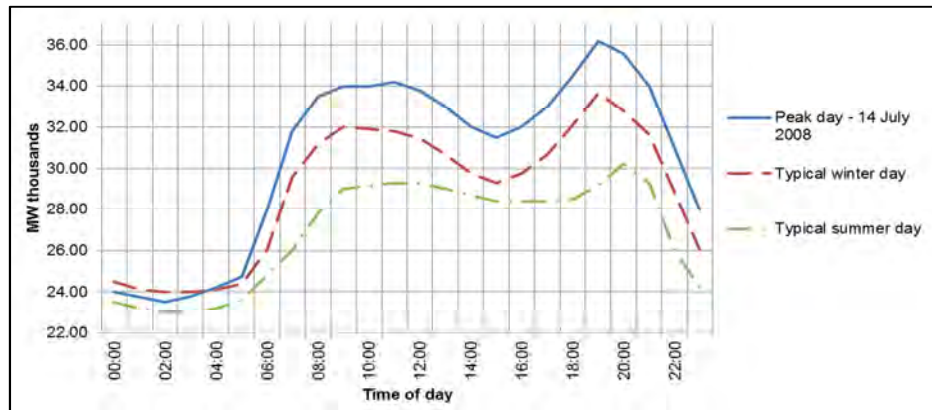


Figure 4: South African electricity demand profile [1.3]

Optimising electricity operations will aid in reducing peak demand and reduce electricity cost. This can be achieved by rescheduling operations and effectively implementing of production *load-shift*. The problem becomes complex due to varying production targets, maintenance schedules, equipment failure, plant production and storage constraints. A possible solution is to observe operational constraints to be able to reschedule operations so that production energy cost can be reduced. This method can support a cost effective implementation without any production stoppages.

Recent literature reports on the development of modelling techniques used by continuous plants where both energy- and electricity constraints were present. The models show that effective operation of a plant can minimise energy cost. However, no literature could be found on the application of these techniques to a production plant (such as the facilities used in cement production). The techniques are also not applied in practice at physical plants to reduce production cost.

1.2. AIMS OF THE STUDY

The aim of this study is to develop a discrete operations model and apply this model by using an integrated Energy Management System (ENMS) to optimise the scheduling of components to minimise operations energy cost during the cement production process. The benefits of an ENMS include:

- Lowering of energy cost of the cement production process,
- No installation of major infrastructure upgrades,
- Integration of maintenance, production and dispatch constraints,
- Lowering of total operation and production cost.

The modelling method presented by *Castro et al.* [1.9] and *Mitra et al.* [1.10] was applied to continuous chemical processes, but never to production planning and scheduling environments. The goal of this study is to develop a method for modelling the operations of a production plant, and to apply this method on industrial production plants in the cement industry. To enable the application of this modelling concept, a different modelling approach will be explored to achieve an optimal scheduling solution as discussed by Castro [1.9] and Mitra [1.10].

1.3. BASIC ASSUMPTIONS

The following basic assumptions underpin the study:

- Integrated modelling of the operation of a production plant can reduce energy cost,
- The use of an ENMS to implement this modelling method at a cement production plant can support the reduction of the total cost allocated to energy without altering production targets or maintenance schedules,
- No production downtime is necessary to implement the modelling system, and
- the payback period of the installation is instantaneous.
- The management and scheduling model is an ideal and recommended energy management tool.

1.4. RESEARCH QUESTION

In the light of these basic assumptions, the following research question was formulated to guide the study:

How can modelling for integrated energy optimisation at cement production plants reduce energy costs without altering maintenance schedules?

1.5. SCOPE OF THE STUDY

The development and implementation of a new modelling approach involves various steps. These steps include background and problem identification, component optimisation, implementation, measurement and verification. The problem identification and development will be further analysed, but the component optimisation, measurement, and verification will not be explored in depth.

This study is presented in the form of a research article that is included in Appendix B. The article is contextualised in the chapters that follow. The discussion included in these chapters will provide a more detailed description of the background and relevance of the study than described in the research article.

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- (1.8) Valderrama C., Granados R., Cortina J.L., Gasol C.M., Guillem M., Josa A., "Implementation of best available techniques in cement manufacturing: a life-cycle assessment study", *Journal of Cleaner Production*, 2012 (25), pp. 60-67.
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Two

Cement Production and Important Concepts

Chapter Two

In this chapter, the operation of the cement plant and its subcomponents, including their energy requirements are described.

2. CEMENT PRODUCTION AND IMPORTANT CONCEPTS

The cement production process consumes different forms of energy. During calcination fossil fuels are used to heat the kiln to temperatures capable of burning raw lime stone. These fossil fuels include fuel oil, coal, and natural gas. In South Africa, coal is of abundant supply and less costly than other fossil fuels. For this reason, coal forms the primary fuel for calcinations in the South African cement production process. Coal is also the primary expense when considering energy usage. The second form of energy consumption is electricity. Various electric motors use electricity to drive components and grinding equipment such as mills, crushers, large fans, compressors, and conveyor transport systems. Apart from these two primary forms of energy consumption, energy is also consumed in the form of fuel. Excavating equipment and post-production transport consumes fuel in the form of diesel or petrol.

To improve the analysis of energy consumption throughout the cement production process, the process can be subdivided into various independent operation units serving specific functions during the production of cement.

2.1. CEMENT PLANT LAYOUT AND COMPONENTS

Limestone is the primary raw material used for production of cement. A better understanding of the operation and interdependency of the various units can be obtained by following the route limestone follows during the production process [2.1].

The basic layout of a dry process cement plant is shown in Figure 5 to illustrate the limestone route.

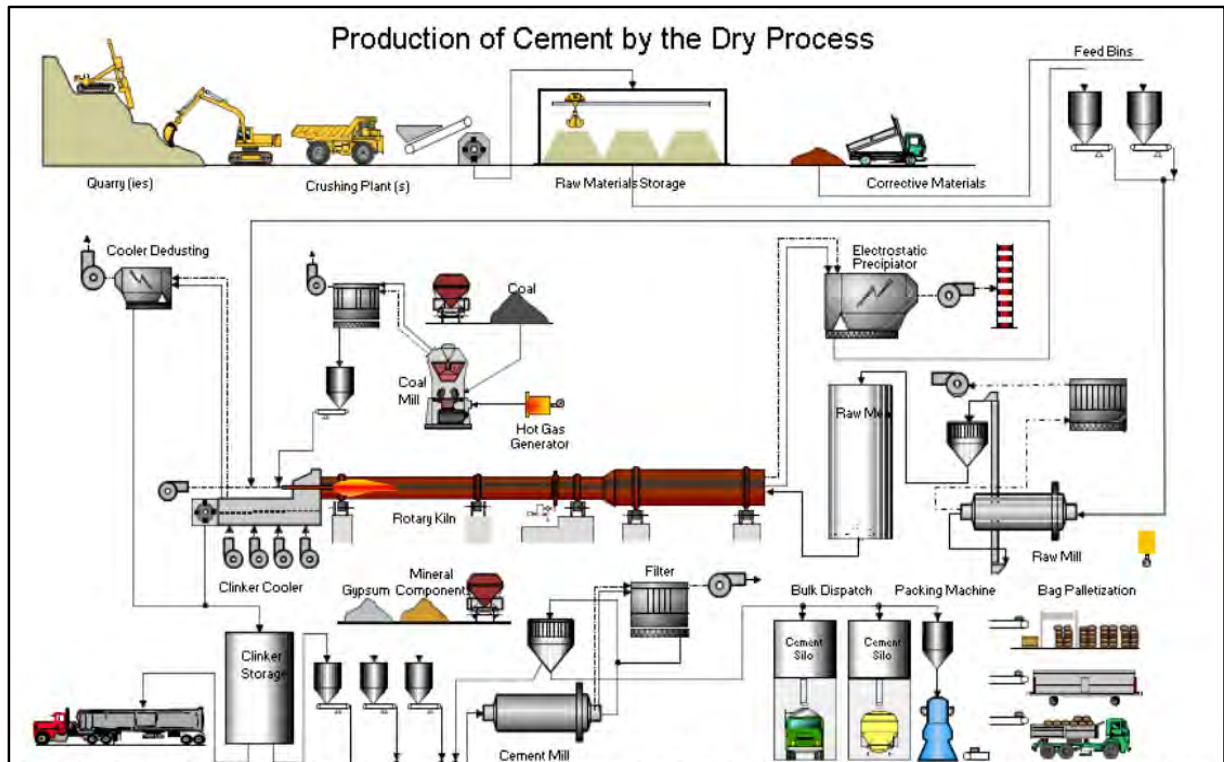


Figure 5: Dry process cement production flow diagram [2.2]

2.2. ENERGY CONSUMPTION IN A CEMENT PLANT

Various subsections form the basic building blocks of the layout of any cement plant. These subsections are functional units that perform specific functions during the production of cement. In most cement plants, duplicates of these units are placed parallel to each other to simplify maintenance schedules and decrease production losses during shut downs. Each of these units requires different forms of energy to operate. A discussion of the consumption of energy by each of these components follows.

2.2.1. MINING AND CRUSHING

Limestone is mined in large open pit mines, where blasting and excavation is used to extract raw limestone from the earth. At this stage, the limestone is still unprocessed, with a large variation in particle size. Therefore, it needs to be crushed.

The crushing process consists of a set of crushers of varying fineness to refine the particle size for further processing. In most of the cases, a crushing circuit consists of a primary,

secondary, and tertiary crusher. Such a circuit incrementally reduces the particle size of limestone through a process of crushing, screening and re-crushing. [2.1, 2.3 & ^a]

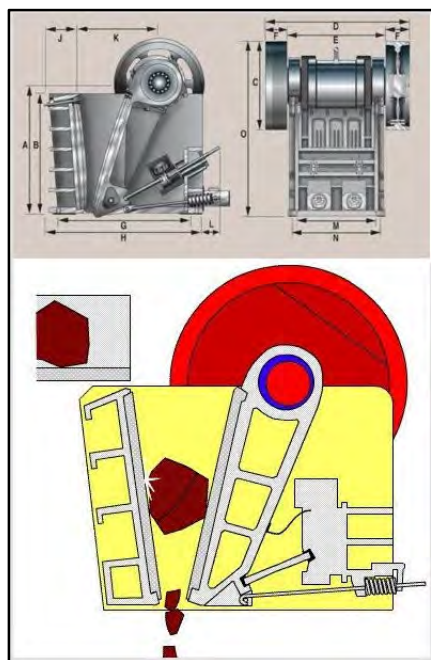


Figure 6: Jaw crusher operation ^b

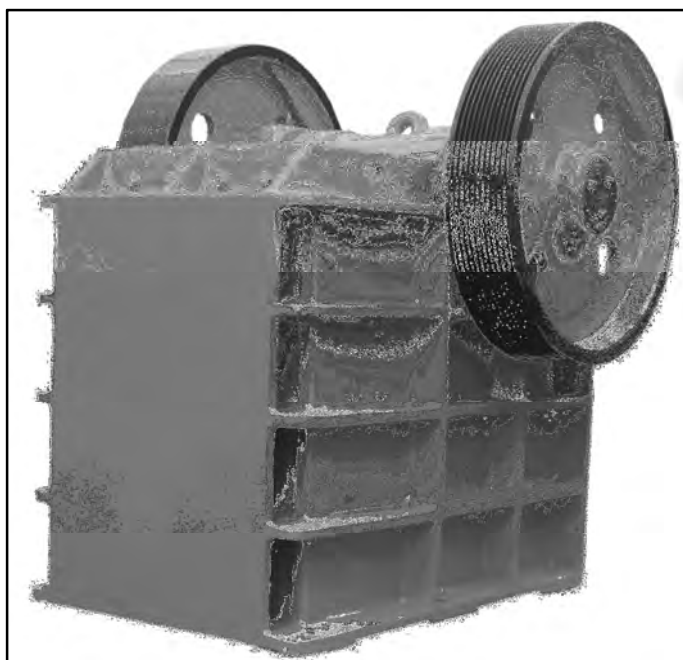


Figure 7: Jaw crusher ^c

The crushers, screens, and conveyor transport systems of the crushing circuit are driven by three phase electric motors. For this reason, the crushing circuits form one of the primary users of electric energy. The crushed limestone is transported from the crushing circuit via an overland conveyor transport system to a large stockpile. The limestone can be reclaimed and utilised from this stockpile for further production processes [2.1, 2.3].

2.2.2. RAW MILLING

The raw limestone is reclaimed and transported from the stock pile to a milling circuit, known as a raw mill, where the particle size is reduced to a finely monitored powder, known as *raw meal*. Various other raw materials are added to the limestone in the raw mill to adjust the chemical composition of the powder. The chemical composition is controlled by altering the proportion of additives added to the limestone. The fineness consistency and chemical composition of the raw meal is crucial to the quality of the final product [2.1, 2.3]

^a Henan Zhengzhou Mining Machinery Co., Ltd., Jaw Crusher, website: <http://www.kilninc.com/upload/2012/2/23235030486.jpg> [accessed on 15/08/2012], 2012.

^b Shanghai Liming Heavy Industry Co., Ltd., Jaw Crusher, website: <http://www.stonecrushermobile.org/uploadfile/201207/9/184922401.gif> [accessed on 15/08/2012], 2012.

^c Jaw crusher operation image, website: http://01.i.aliimg.com/img/pb/984/925/302/302925984_551.jpg [accessed on 15/08/2012]. 2012.

Various types of mills are used as raw mills, including ball mills and vertical roller mills. Similar to crushers, raw mills also operate in a milling circuit. This milling circuit however, consists of a single raw mill with various separators and precipitators or bag filters. The operation of these components is dependent on a controlled draught of air. This draught is induced by fans and blowers. All of the above mentioned components utilise electric motors. Large amounts of electricity are therefore allocated to raw mill circuits, making them one of the primary consumers of electric energy in a cement plant [2.1, 2.3].



Figure 8: Horizontal ball mill ^d

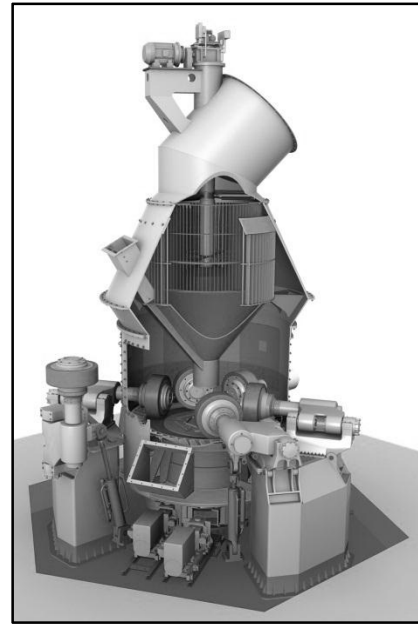


Figure 9: Vertical roller mill ^e

The raw meal is transported from the raw mill to a raw meal silo by means of either airlifts or *fluxo*-pumps, or air-slides and bucket elevators [2.1, 2.3].

2.2.3. PRE-HEATER, SEPERATOR AND PRECALCINATION

From the raw meal silo, the raw meal passes through a pre-heater, consisting of a series of cyclones, to transfer heat generated from the kiln to the raw meal. This pre-heater is also draught dependant. The needed draught is obtained from the kiln, in which large fans create airflow to assist the calcination and pre-heating processes. The main function of the pre-heater is to recapture the lost thermal energy from the kiln and to use this thermal energy to

^d Crushland, China Top Crusherland Co., Ltd., Horizontal ball mill, website: http://www.crusherland.com/cement_mill.html [accessed on 15/08/2012], 2012.

^e Gebr. Pfeiffer, Vertical roller mill, website: http://www.gpse.de/uploads/pics/Bild_1_01.jpg [accessed on 15/08/2012], 2012.

initially 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. The dust and emissions from the fossil fuel burnt in the kiln are then expelled through a smoke stack into the atmosphere [2.1, 2.3].



Figure 10: Preheater tower

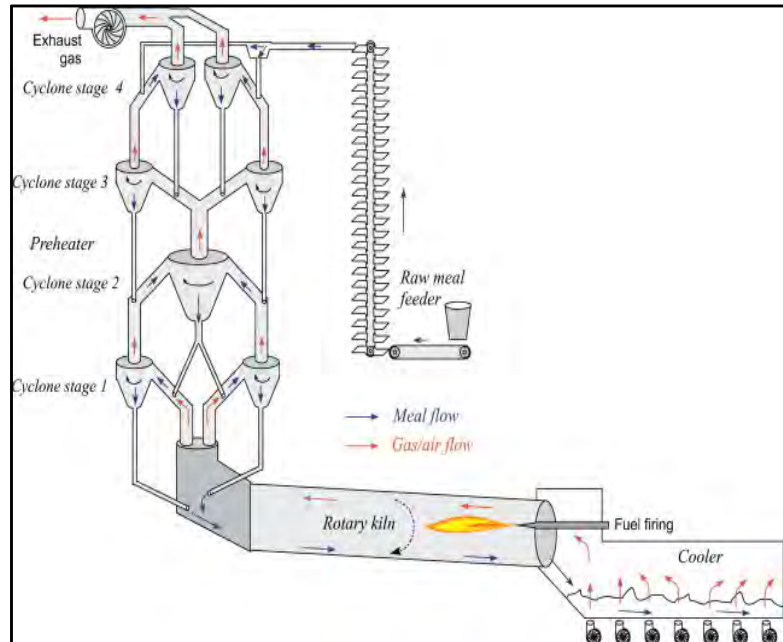


Figure 11: Preheater tower operational diagram ^f

A later design and addition to the pre-heater and separator is the so called pre-calciner. During this process, fossil fuels are burnt to heat the raw meal before it enters the kiln itself. By doing this, the total amount of coal used by the kiln is reduced. The pre-calciner heats the raw meal more effectively than the kiln, therefore it also offers a reduction in the total amount of fossil fuels needed to produce a ton of clinker [2.1, 2.3].

^f

Pre-heater schematic , website:
<http://ars.els-cdn.com/content/image/1-s2.0S0967066110001851-gr1.jpg> [accessed on 15/08/2012], 2012.

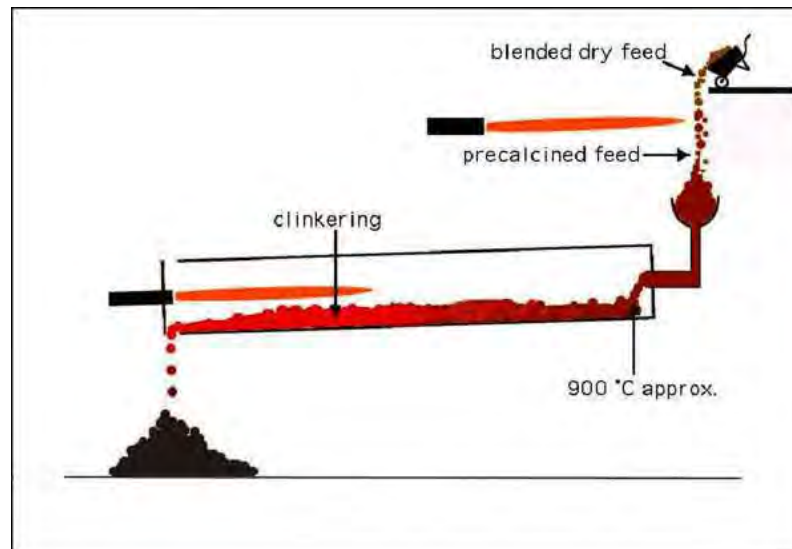


Figure 12: Schematic of a precalcining kiln⁹

2.2.4. CALCINATION

The calcination process takes place in a large rotating tube called a kiln. A kiln is a ceramic lined metal tube of constant diameter ranging from two to six meters. The length of these tubes can also range from forty to eighty meters. In the centre of the end of the tube is a fuel burner which forms the only heat source in the kiln. The raw meal is poured from the opposite end of the kiln to slowly make its way down the tube whilst being heated to a temperature of up to 1400 °C. This activates a chemical process in the raw meal - called calcination – to form clinker, the base material used for the making of cement. The pyro-process also removes volatile substances from the raw meal [2.1, 2.3].

⁹ Understanding Cement , pre-calciner, website: <http://www.understanding-cement.com/images/brecalciner.jpg> [accessed on 15/08/2012]

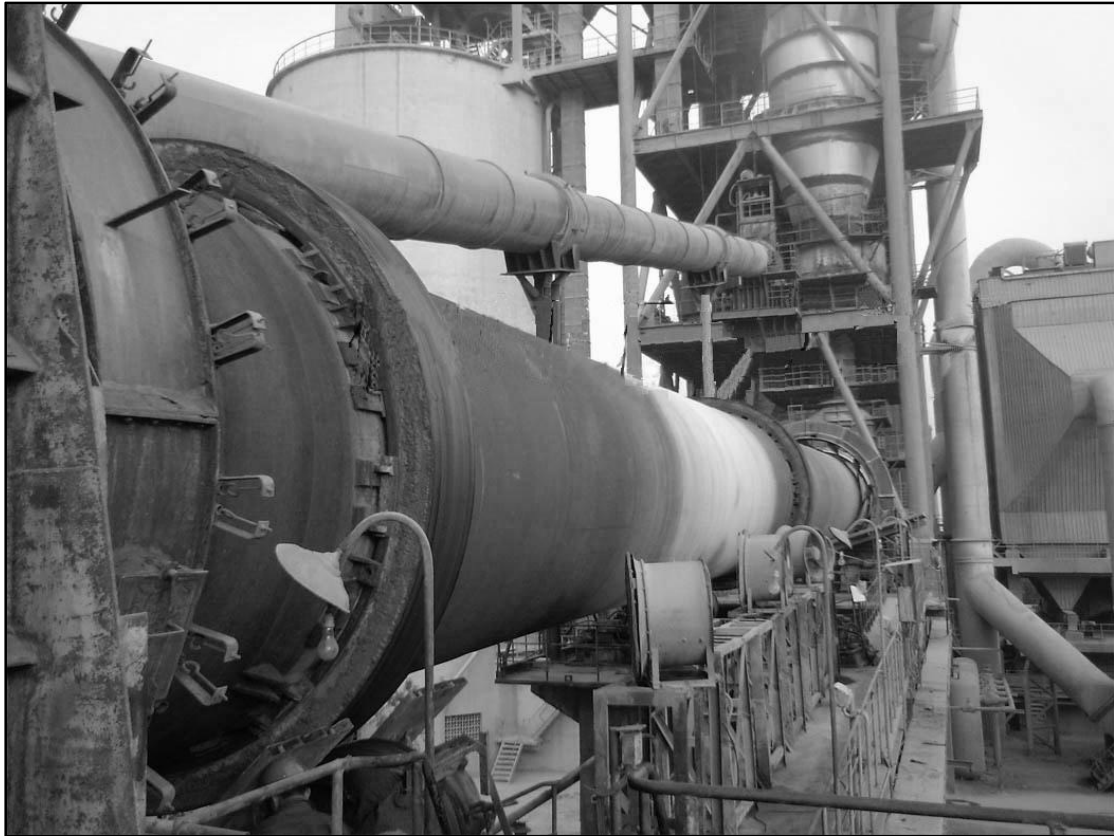


Figure 13: Rotary kiln for the cement industry ^h

The clinker is dropped from the kiln onto a cooler before it enters the clinker silo. These coolers cool the clinker down by passing a draught induced by electric fans over a moving grid [2.1, 2.3].

2.2.5. FINISHING MILLING

The final process is similar to raw milling and known as finishing milling. This milling process is used to grind clinker and other raw materials to an even more refined powder called cement. The active component of cement is clinker. However, other raw materials such as gypsum and fly-ash can be added to obtain different characteristics such as rapid hardening or high strength cement [2.1, 2.3].

This final milling is well controlled to ensure final product quality and consistency. It is also necessary to carefully control the temperature and fineness of the final product to ensure reliable and predictable cement quality. To ensure predictable and stable cement quality,

^h Kiln photograph, website:
<http://media.ebcu.com/product/imgage/Construction%26Decoration/2010102803/04e176f644c6a093895ed876b5131f6b.jpg> [accessed 15/08/2012], 2012.

the finishing milling process also consists of a milling circuit which includes accurate separators and classifiers. Similar to raw milling, it is also dependent on a draught induced by large electrical fans. The temperature of this draught is regulated to ensure that chemical processes do not initialise [2.1, 2.3].

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Three

Motivation and Relevance

Chapter Three

This chapter summarises the methods used for reducing energy cost in the cement industry. It shows that energy modelling and operations planning are the most cost effective intervention. It concludes by highlighting standards set for the generation and implementation of an energy management system.

3. MOTIVATION AND RELEVANCE

3.1. ENERGY CONSUMPTION IN THE CEMENT INDUSTRY

The cost of energy has become a notable problem which needs implementable solutions to generate actual results. For this reason, a study (summarised in this thesis) was undertaken to focus specifically on developing a method to decrease the cost of energy during the production of cement. The study was undertaken during a time period (2011-2012) when the supply of electricity was limited in South Africa.

The South African electricity utility, Eskom, launched various initiatives to control and manage the limited electricity supply effectively. One of these initiatives, known as DSM (Demand Side Management) involved the manipulation of demand trends. This study utilises this initiative to focus on electricity usage to reduce energy cost in the South African cement industry. The major energy consuming components can be subdivided into four categories as shown in Figure 14.

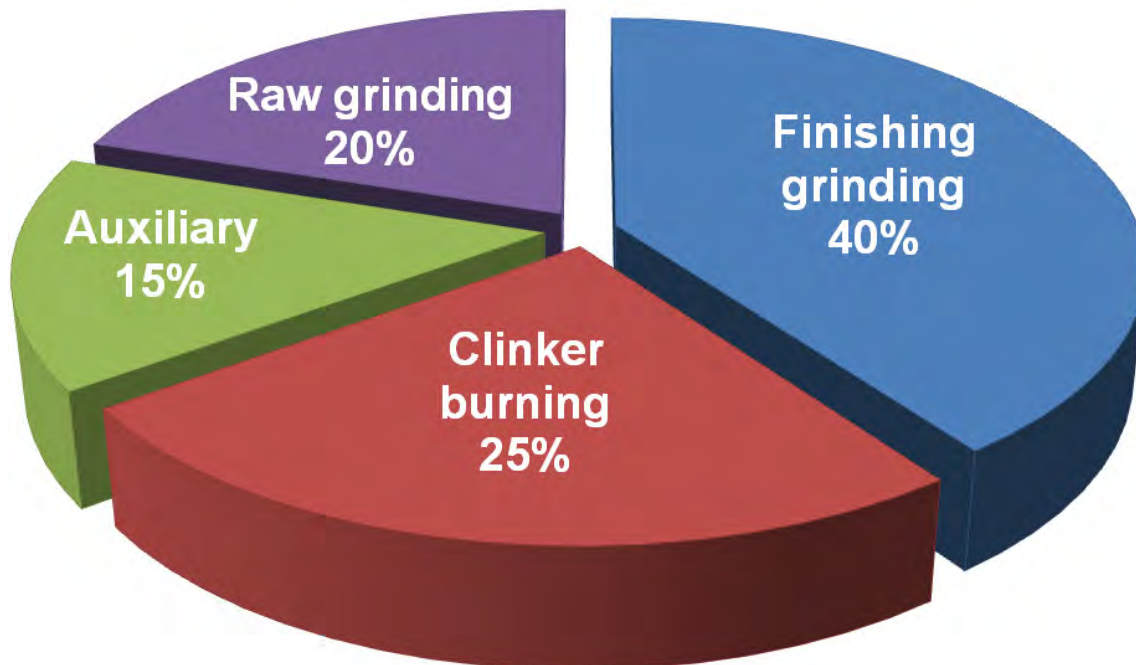


Figure 14: Energy distribution of cement manufacturing equipment [3.1]

Figure 14 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 [3.1, 3.2]. The electrical auxiliary systems of the grinding circuits include air compressors, conveyor transport systems, water- and oil pumps, and various large fans. The combined electrical energy consumption of grinding circuits can constitute up to 75% of all energy used in the cement industry [3.1, 3.3].

The energy consumption in a cement plant corresponds to a total production cost of 50% - 60% of which 18% - 43% is allocated to electricity alone [3.3]. The large variation is attributed to different pricing structures and electricity costs in different areas in the world.

3.2. EMISSIONS IN THE CEMENT INDUSTRY

In addition to energy costs, reducing carbon dioxide (CO₂) and nitrogen oxides (NO_x) emissions is a global concern regarding environmental conservation [3.4]. Thirty-three per cent of global emissions are directly linked to energy usage [3.5, 3.6]. The cement industry contributes up to 7% of global CO₂ emissions [3.5, 3.6].

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 by coal-fired power plants and the remaining 7% is generated by hydro -, nuclear -, gas turbine - and pumped storage plants^a. Reducing the electricity demand of cement plants in South Africa will therefore also contribute to reducing CO₂ emissions. Managing the demand of the cement industry will assist in creating a more uniform daily demand distribution by eliminating peaks and valleys in the demand profile. Detrimental gas emissions from coal fired power plants have been quantified by Mann and Spath [3.7] (see Table 1).

^a Eskom, Eskom Enterprises (Pty) Limited, website: <http://www.eskom.co.za> [accessed on 23 June 2012], 2012.

Table 1: Typical emissions for coal-fired electricity supply [3.7]

| 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 CO₂ emissions, indirectly emitted by using electricity are estimated to be between 101.8 kg and 122.2 kg CO₂ per ton cement produced. This is a large amount of CO₂ compared to the 137 kg CO₂ directly emitted by a production plant during the production of 1 ton of cement as reported by Velderrama [3.8].

3.3. PRESENT ENERGY SAVINGS MEASURES FOR THE CEMENT INDUSTRY

Various new technologies are available to allow the cement manufacturing industry to operate more efficiently [3.3]. These technologies are available for various components including mills, kilns, and conveyor transport systems [3.3, 3.9]. The available technologies are summarised below.

3.3.1. ENERGY RECOVERY

An important method for improving energy efficiency in the cement industry is the recovery of waste heat. Two simple forms of recovering waste heat are:

- Cooler waste heat recovery [3.9],
- Waste heat recovery from the kiln surface [3.11, 3.12].

3.3.2. REPLACEMENT COMPONENTS

Another method that can be used to reduce the electricity demand of a cement plant is to replace outdated systems or components with modern, more efficient alternatives. The physical installation of these systems is expensive when compared to the amount of savings that can be achieved. Possible replacement components include:

- Bucket elevators to replace airlift systems [3.2],
- Vertical roller mills (VRM) [3.2],
- Pre-calciner installation [3.2],
- Variable speed drive (VSD) [3.9, 3.10].

Most of the mentioned technologies and components require the installation of new equipment and offer an average electrical energy saving of between 1 kWh and 5 kWh per ton [3.11-3.12]. In a life-cycle assessment, Valderrama [3.7] reported that the implementation of best available technologies (BAT) reduced the electricity consumption of clinker production from 76 kWh to 69 kWh per ton.

One example of cost effective technologies that can reduce energy consumption, are variable speed drives (VSD). The flow of air in the draught dependent components of a typical cement production plant is controlled and regulated by damper systems. Dampers increase the resistance in the duct which increases the differential pressure a fan needs to supply a draught. This influences and controls the flow of air through the duct. This added resistance dissipates energy and is therefore not energy efficient. The installation of a variable speed drive on the drive motor of these fans offers a reliable way to reduce electrical demand when the flow required is less than the installed capacity of the fan [3.9]. *Saidur et al.* quantified this saving and found that the electrical demand of a ducted fan can be reduced by 30 %-60 % [3.9].

These installations are however costly and require extended production down time [3.1, 3.2]. The payback period for these installations is often longer than 10 years [3.12].

3.3.3. IMPROVED ENERGY EFFICIENCY

Optimising equipment to operate at their maximum capacity offers another technique to reduce energy consumption. It provides simpler implementation than the replacement of components. An example of this technique is vibration monitoring to control mill feed ^b.

3.3.4. IMPROVED OPERATIONS THROUGH CONTROL SYSTEMS

Specific energy consumption improvement can be achieved by monitoring system characteristics such as production feed rates. An example of this is Advanced Process Control (APC) [3.13].

The improvement of control systems provides a simple, cost effective technique to reduce energy consumption. These systems optimise specific component operation, thus ensuring stable, optimal operation [3.14]. Savings of between 1.4 kWh and 6 kWh per ton can be realised [3.11, 3.12, 3.14 & 3.15]. Valderrama [3.8] reported a 4% reduction in CO₂ emissions by implementing BAT. Reduction in NO_x, SO₂ and dust emissions of 20.5%, 54% and 84% respectively are also possible. However, larger savings can be achieved when components are viewed as a single system.

3.4. INTEGRATED MODELING OF PLANT OPERATIONS FOR ENERGY CONSTRAINTS

Casto *et al.* [3.16] stated that the optimisation of the operation of multiple components in unison will generate energy savings. Such a perspective on reducing energy consumption provides a simple solution for reducing energy costs. By simply rescheduling plant component operations to time sensitive electricity tariff structures, the total cost of electricity and energy can be reduced [3.16]. The literature did not provide any evidence of the application of management and computerised modelling systems to simultaneously integrate numerous production components.

Therefore, a new modelling system is proposed to provide a solution for reducing emissions and energy consumption by integrating various production components of a cement plant.

^b Gugel K.S., Moon R.M., "Automated Mill Control using Vibration Signal Processing", Digital Control Lab, website: http://www.digitalcontrollab.com/documents/ieee_charleston_paper_v04_19_07.pdf [accessed on 6 June 2012], 2010.

An integrated model was developed and implemented as an energy management system (ENMS).

3.5. ENERGY MANAGEMENT STANDARDS ISO 50 001, DIN EN 16 0001 AND PAS 55

Woodhouse [3.17] provides three definitions of asset management as used by the financial sector, equipment maintainers and infrastructure or plant owners and operators. The definition of asset management for infrastructure or plant owners, states that asset management is maintaining and operating physical infrastructure to the maximum capabilities [3.17]. This definition is applicable when considering operations scheduling.

A standard for asset management in this context is set out in PAS-55. The objective of active and improved asset management is to reduce operational or production cost. PAS-55 also describes asset management during the different stages of the life-cycle of a plant or installation. These different life-cycle stages are displayed in Figure 15.

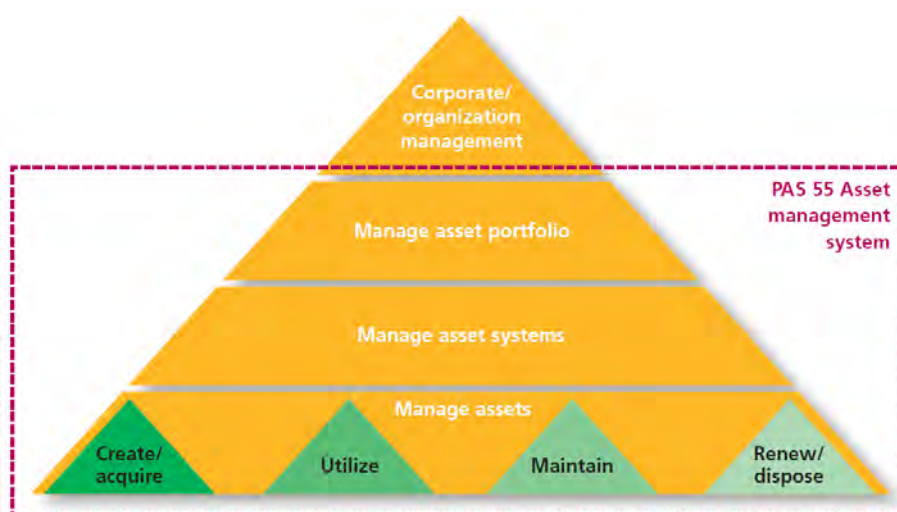


Figure 15: Structure of integrated asset management as described by PAS-55 [3.17, 3.18]

Figure 15 shows that asset management applies to the different stages of a component life-cycle. These stages include creating or acquiring assets, utilising or operating these assets, maintaining assets and at the end of the life-cycle, either disposing or replacing the asset. Profit is acquired during utilisation of the physical assets or components. During the acquisition, maintenance and disposal phases, cost is incurred with the intention to create or to maintain possible income. Installation of the best available technologies at a cement production plant means that all the above mentioned stages are completed. This includes

the disposal of the old infrastructure, installing the best available technologies and maintaining it to incur an income through utilisation. The reduction in cost relies on the new installed component to be efficient enough to both cover the costs of all the different life-cycle stages and reduce net production costs.

By extending the life-cycle of a component and managing the operation thereof, both the installation and disposal costs are eliminated. The total value of operational savings is less than the BAT, but with the eliminated life-cycle stages, a comparable improvement in cost can be extracted. Efficient operations management can be achieved by implementing an energy management system (ENMS).

Due to increased public awareness of energy consumption and emissions, benchmarks and regulations have been set to create a structure in which energy consumption and emissions are monitored [3.19, 3.20]. Standards for the structure and implementation of such an ENMS are set out in the DIN EN 16001 [3.19] and ISO 50001 [3.20].

Certain basic functions, that have to be included in an ENMS, are summarised in DIN EN 16001 as shown in Figure 16.

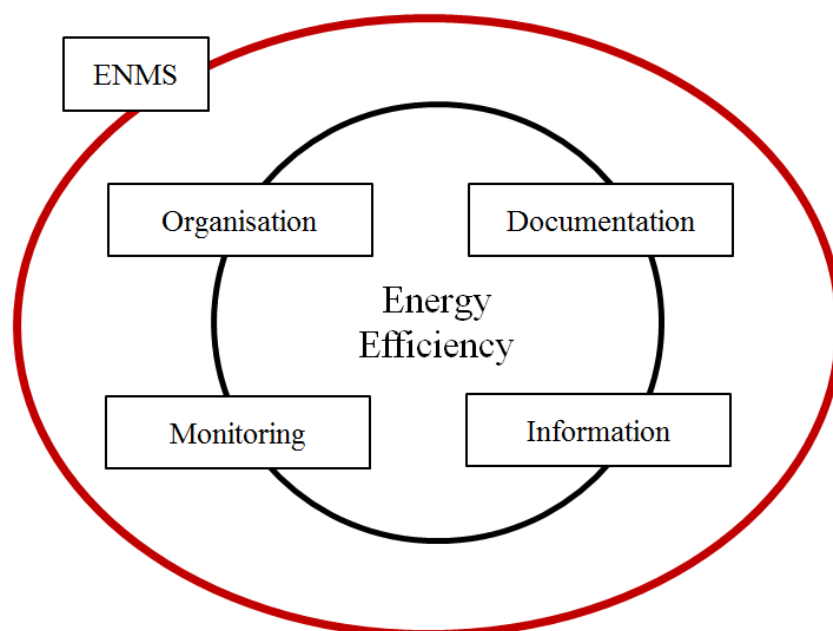


Figure 16: Energy management system characteristics [3.19]

When creating an effective ENMS, the components as highlighted in Figure 16 must be included. The energy management system must record, organise, document and finally monitor the operations of the considered machinery. To achieve these savings, the

ISO 50 001 standard provides guidelines for the “planning”, “doing”, “checking” and “acting”, known as the PDCA structure [3.20]:

I. Planning

Planning includes establishing energy-saving targets, determining the strategy of obtaining these targets, identifying measures and responsibilities, providing the necessary resources to achieve these targets and preparing an action plan [3.20].

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 [3.20].

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 evaluating the effectiveness of the ENMS. Finally, a re-evaluation of the original savings strategies and targets, as described in step I, is done [3.20].

IV. 4. Acting

Using an iterative process, these new saving strategies and targets are implemented. These savings strategies are constantly monitored to continuously maintain and improve the implemented energy-savings measures [3.20].

Using these standards as base, the modelling and optimisation of operations schedules can be implemented on a modern cement plant. Conforming to these standards will assist the success and sustainability of possible energy savings that can be achieved by this modelling method.

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Four

Method and Analysis

Chapter Four

This chapter describes the development of a flexible energy management system that will conform to the relevant standards associated with the implementation of an energy management system. It describes the configuration of the energy management system and how it will be applied to the four South African cement plants as case studies.

4. METHOD AND ANALYSIS

4.1. MODELLING

Castro. *et al.* [4.1] and Mitra I. *et al.* [4.2] present sound modelling techniques that can be used in the operations optimisation of various industries. They indicate that monitoring and managing operations and storage can reduce operations cost. Castro [4.1] describes methods of using discrete and aggregate scheduling during modelling to optimise operations of multiple components for energy constraints. An example of the layout of the multiple components he considered is shown in Figure 17.

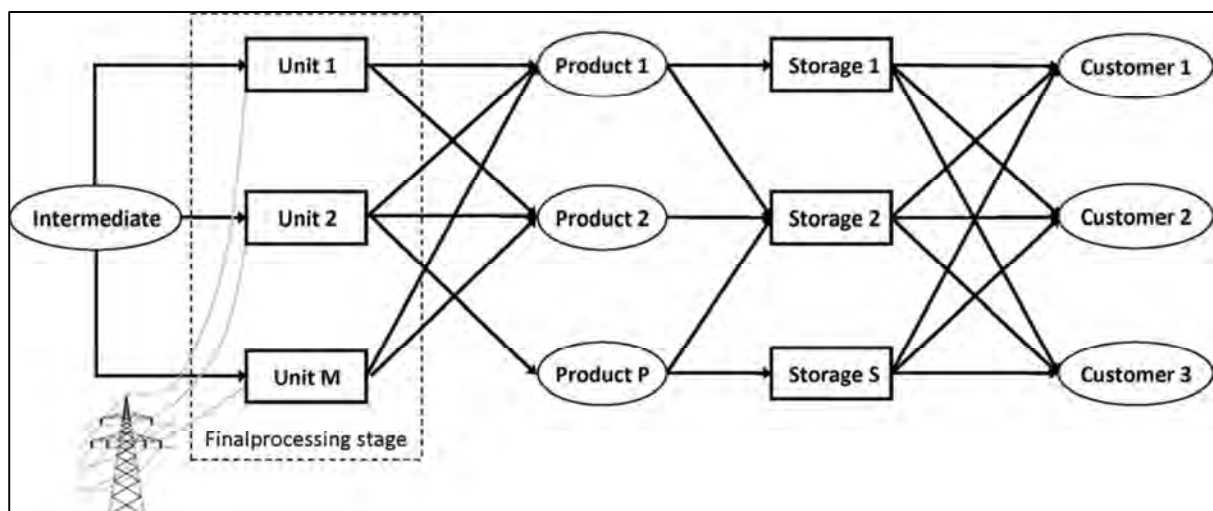


Figure 17: Case study of a processing stage with multiple components [4.1]

From this layout it can be seen that these modelling methods can be used in plants with similar layouts as the cement industry. The difference between the discrete and aggregate approaches is shown in Figure 18.

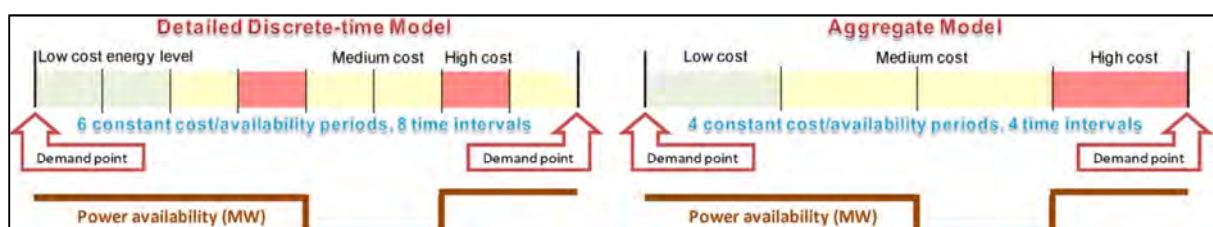


Figure 18: Discrete modelling compared to aggregate modelling [4.1]

A discrete time model simulates the system of components with time, assuming that each event is discrete with the time interval. An example is a product extraction event from a silo or a production event. The model simulates this event at the considered time interval, accurately simulating silo levels and system response throughout the analysis period. The aggregate model rearranges the time interval and merges similar cost intervals to create extend interval lengths. By doing this, the amount of considered time intervals are decreased, reducing the model complexity.

The aggregate approach assumes that the end result of the analysed time period is accurate enough to simulated variables (including silo levels and plant production). The specific time interval values are however not accurate to real world events. During real world application, the silo capacities are in some instances smaller than the production capacity during the considered time intervals when they are merged. To accurately predict the silo response to a production or a product extraction event, the discrete modelling approach was used.

For the application of scheduling management, it was decided to utilise the discrete modelling method due to the continuous nature of cement plant operations [4.2]. In the application of this modelling method, Mitra [4.2] used the discrete modelling method to simulate the cement production process. In Figure 19 Mitra [4.2] shows the utilisation of storage capacity to shift production load with time to reduce the electricity cost of a cement plant.

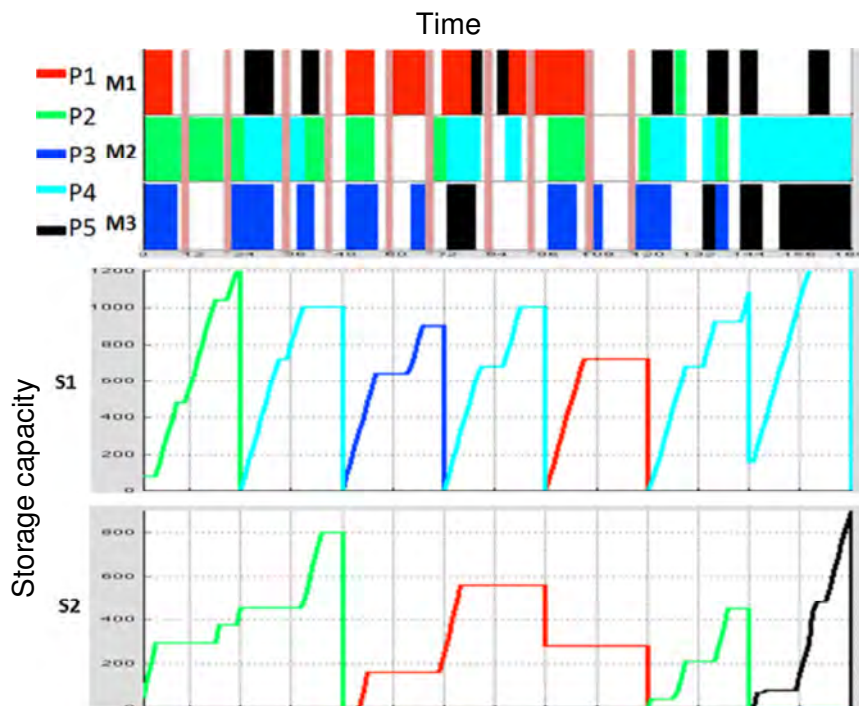


Figure 19: Optimal storage and production profiles during application in the cement industry [4.2] (P_i = Product i , M_i = Machine i , S_i = Storage i)

Though these studies showed that the discrete modelling method can be used to reduce energy costs, no indication of the application of these methods at an operational plant could be found. Therefore, the method of discrete time modelling was restructured and incorporated into an ENMS for application at four different cement production facilities.

4.2. SYSTEM DEVELOPMENT AND IMPLEMENTATION

Swanepoel et al. [4.3] describe the development of this ENMS:

“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. 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. The energy management system (ENMS), referred to as the Process Tool Box (PTB), includes an integrated modelling system.” [4.3]

“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.” [4.3] (Figure 20 represents Figure 3, Swanepoel *et al.* [4.3]).

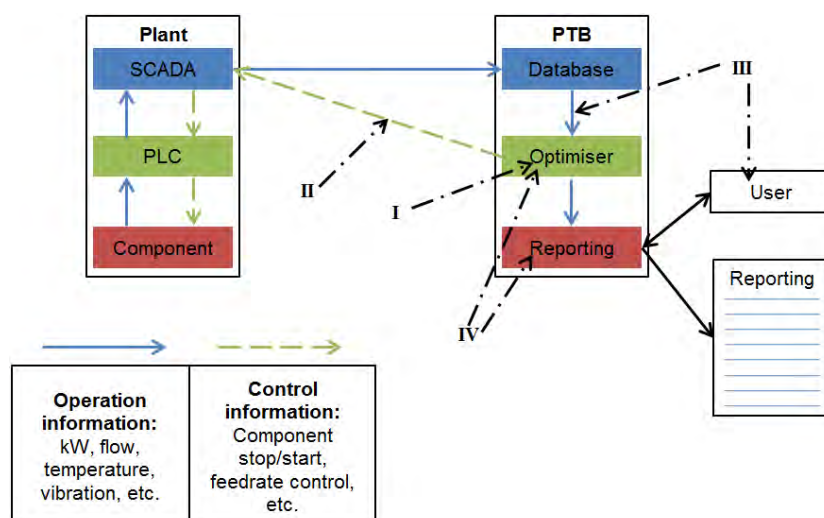


Figure 20: Schematic of PTB system integration and functionality [4.3]

“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” [4.3].

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. 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” [4.3].

“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.” [4.3]

“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." [4.3] (Figure 21 represents Figure 4, Swanepoel et al. [4.3].

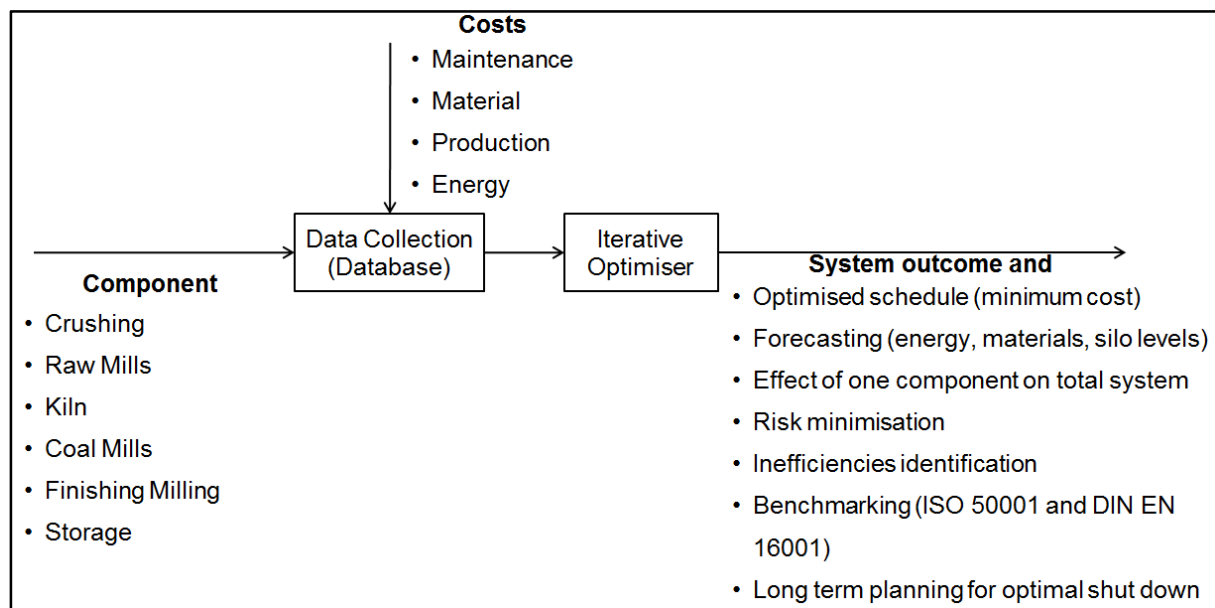


Figure 21: Variables considered in the integrated system, and the resultant system outcomes and capabilities. [4.3]

The developed system is dependent on accurate plant characteristics, which include component production rates, silo capacities, sales targets, etc. During the development of the operations model, these plant characteristics (production flow rates) were assumed to remain constant. However, some of these characteristics may vary with time.

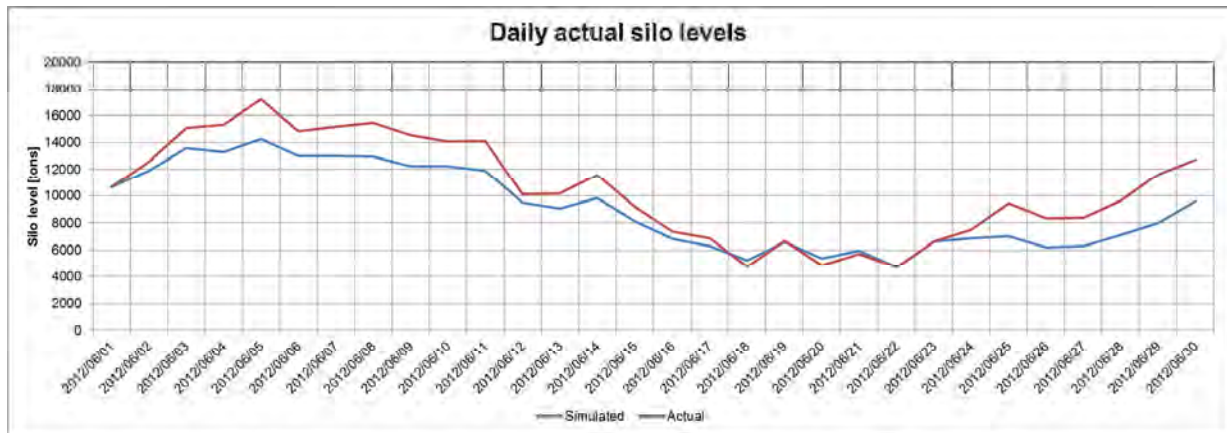


Figure 22: Model accuracy without calibration

As can be seen from the profile (Figure 22) the system, as expected, does not accurately predict the actual operation of the plant. When considering a raw meal silo (as shown in Figure 22), an average deviation of 13% from actual recorded data was obtained. This is attributed to the fluctuating nature of the modelling constants. The rate of raw meal production varies according to the abrasiveness of the raw limestone, amount of additives added and raw material moisture. These influences are difficult to simulate in most cases.

The system was connected to the Supervisory Control and Data Acquisition (SCADA) system used at the plant. This system is able to automatically revise the plant characteristics for more accurate simulation as shown in Figure 23. The average deviation from actual data recorded (raw meal production rate), using continuously revised parameters, was only 1.2%.

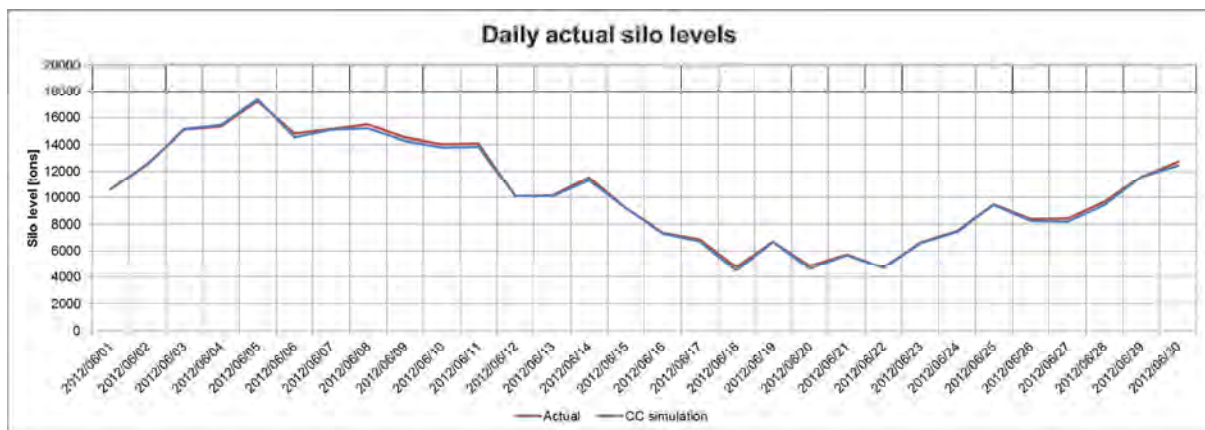


Figure 23: Model accuracy with continuous calibration (daily)

With the improved accuracy of the operations model, forecasting and prediction of plant characteristics such as silo levels, stock levels, sales, acquisition volumes and electricity requirements are always available.

“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.” [4.3]

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. 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)” [4.3]. (Figure 24 represents Figure 5, Swanepoel [4.3]).

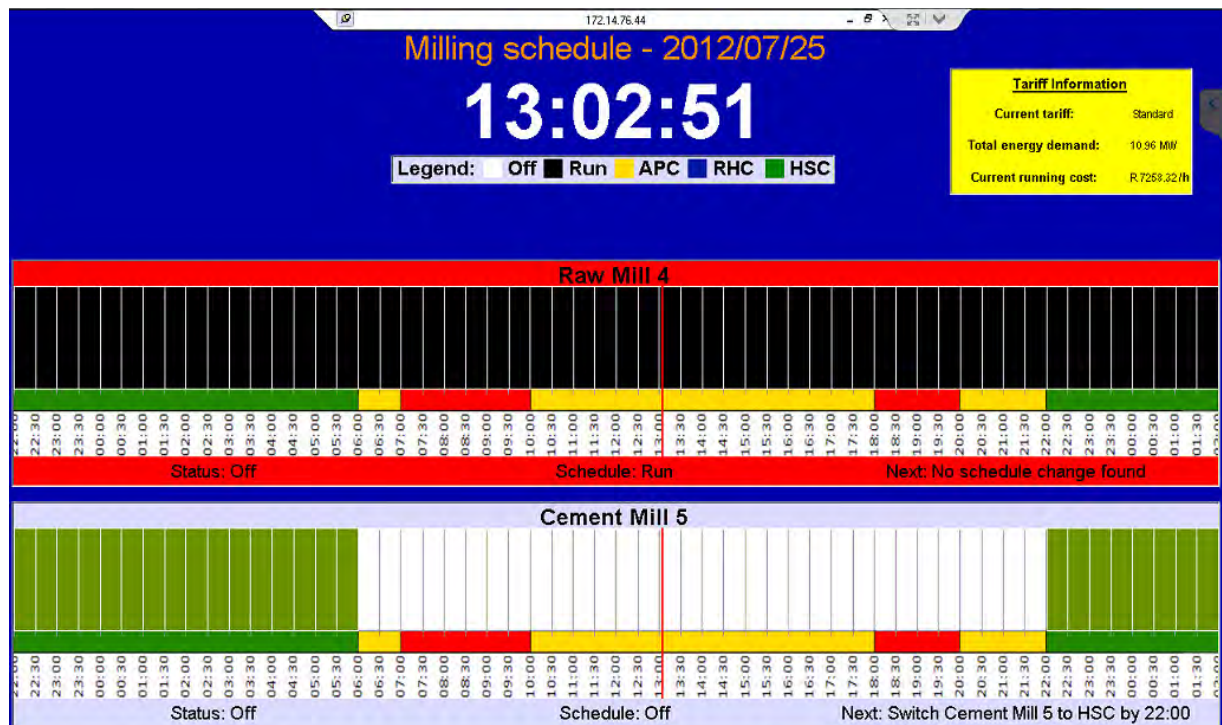


Figure 24: Daily operations schedule plan (APC = All-Purpose Cement, RHC = Rapid Hardening Cement, HSC = High-Strength Cement) [4.5]

“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.” [4.3]

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. 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.” [4.3]

“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.” [4.3]

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. 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.” [4.3]

“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.” [4.3]

“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.” [4.3]

4.3. REFERENCES

- (4.1) Castro P.M., Harjunkoski I., Ignacio E., Grossmann I.E , 2011 “Optimal scheduling of continuous plants with energy constraints”, *Computers and Chemical Engineering*, 2011 (35), pp. 372-387.
- (4.2) Mitra S., Grossmann I.E., Pinto J.M., Arora N, 2012, “Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes”, *Computers and Chemical Engineering*, 2012 (38), pp. 171-184.
- (4.3) Swanepoel R., Mathews E., Vosloo J., Liebenberg L., 2013, “Integrated energy optimisation models for the cement industry”, *Applied Energy*, in review.

Five

Application and Results

Chapter Five

This chapter describes the application of the energy management system on four cement plants in South Africa. It indicates the challenges posed by each application and shows how the flexible nature of the energy management system adapts to these unique challenges.

5. APPLICATION AND RESULTS

The results of the implementation of this ENMS are summarised by Swanepoel et al. [5.1]:

5.1. 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.” [5.1]. (Figure 25 represents Figure 6, Swanepoel et al. [5.1]).

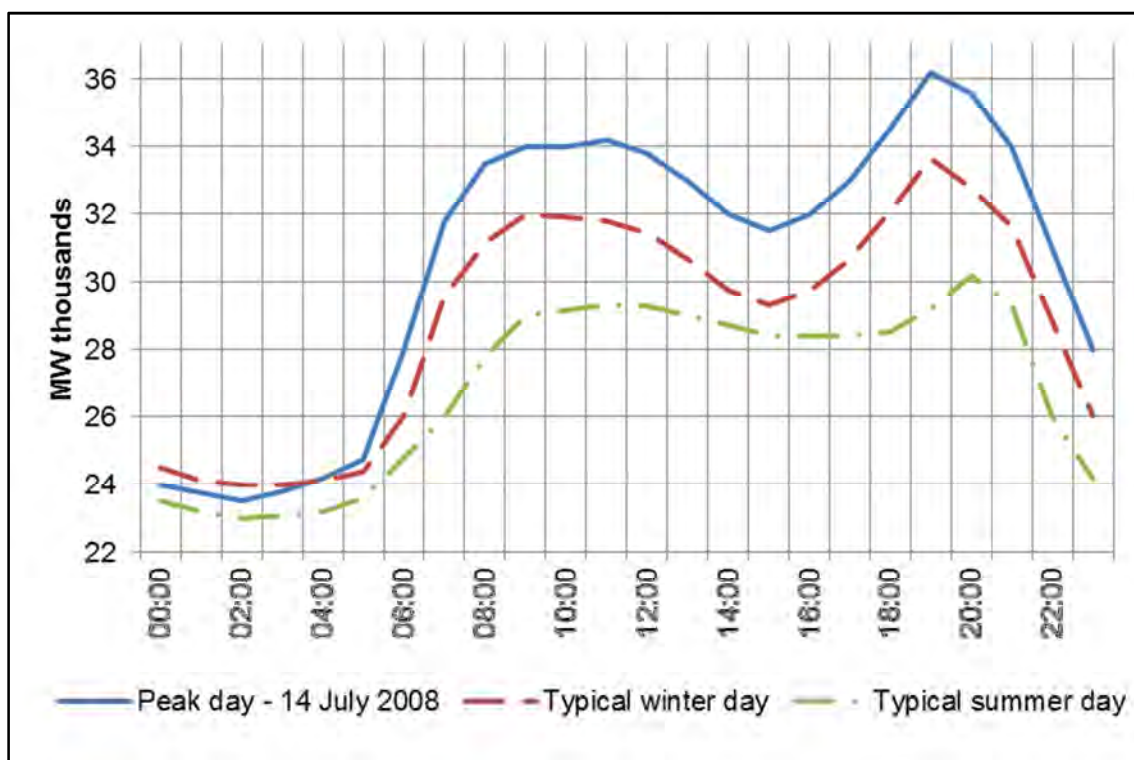


Figure 25: South African average daily electricity demand profile in 2008 [5.1]

“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, as shown in Figure 7.” [5.1]. (Figure 26 represents Figure 7, Swanepoel et al [4.3]).

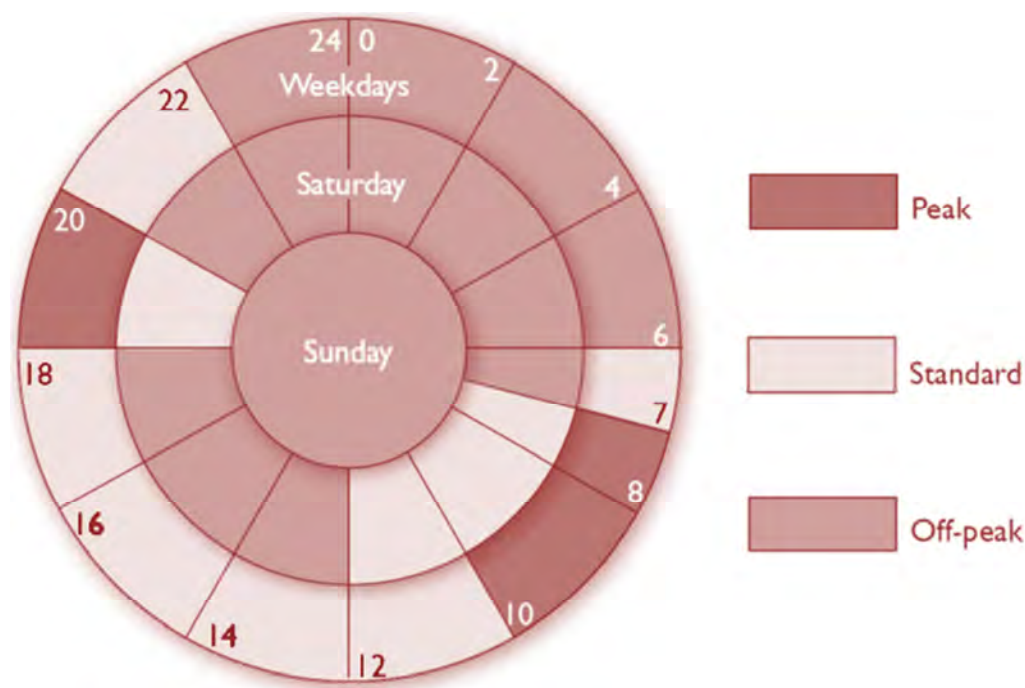


Figure 26: Time of use tariff structure implemented by electrical utility, Eskom [5.1]

“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.” [5.1]

“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).” [5.1] (Figure 27 represents Figure 8, Swanepoel et al [5.1]).

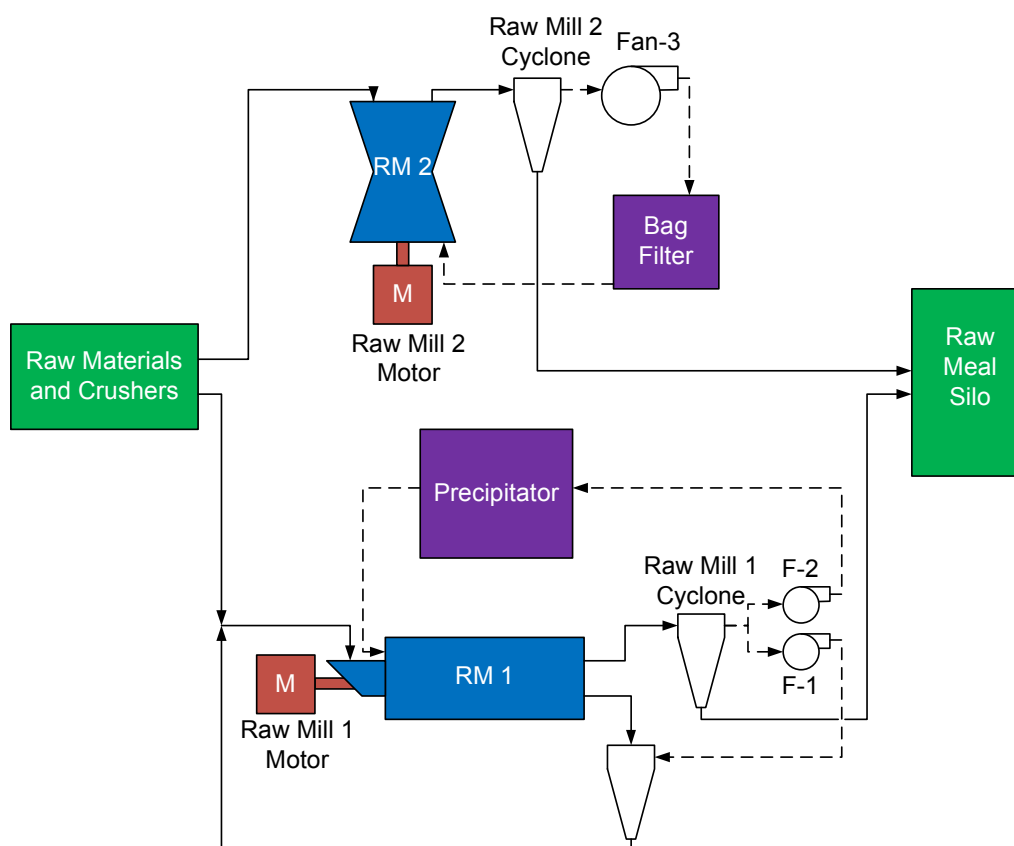


Figure 27: Schematic representation of Case Study 1 with two different raw mills operating in parallel. (“RM” = raw mill; “F” = fan) [5.1]

“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.” [5.1] (Figure 28 represents Figure 9, Swanepoel et al [5.1]).

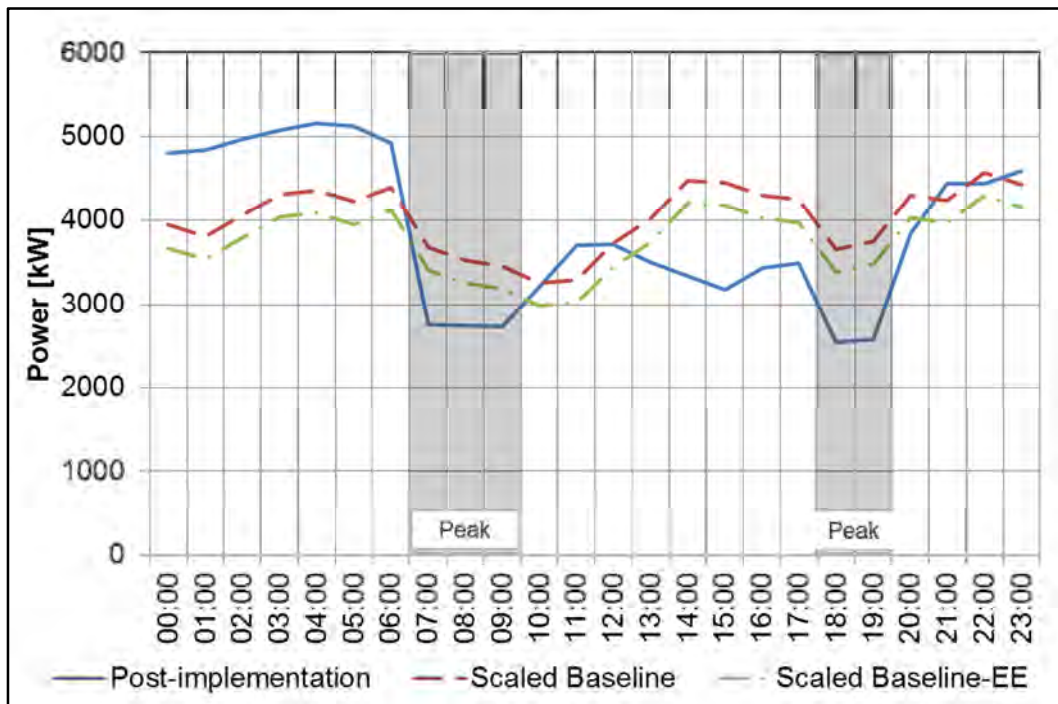


Figure 28: Power consumption with load-shift and energy efficiency trend during the implementation of PTB in Case 1 [5.1]

“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.” [5.1]

5.2. 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.” [5.1]

“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.” [5.1] (Figure 29 represents Figure 10, Swanepoel et al [5.1]).

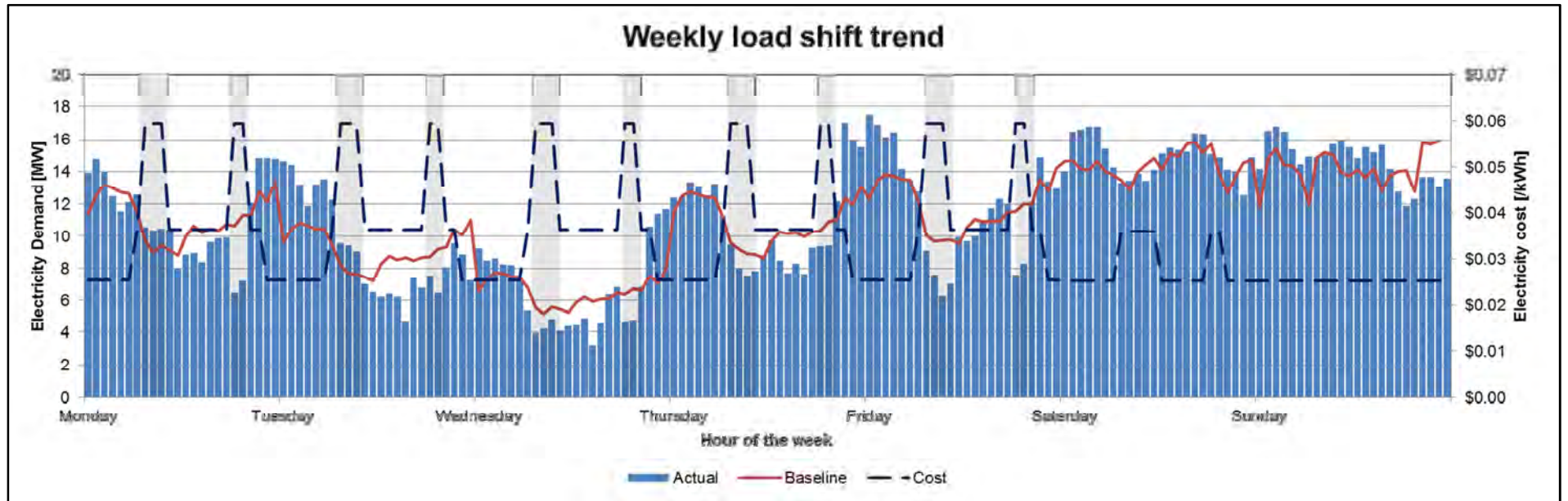


Figure 29: Power consumption trend for weekly load shift of Case 2 [5.1]

“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.” [5.1] (Figure30 represents Figure 11, Swanepoel et al [5.1]).

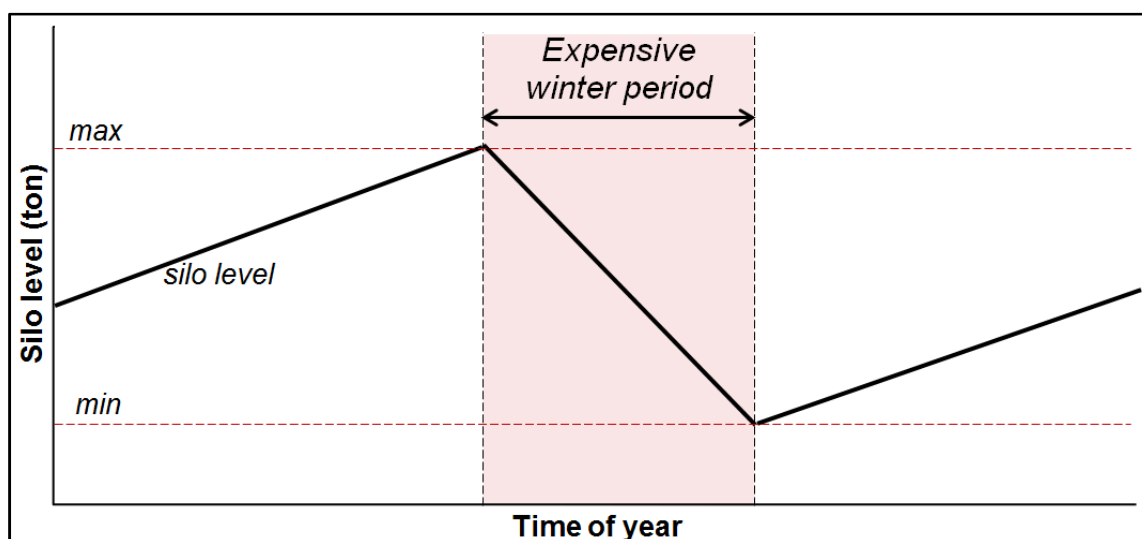


Figure 30: Storage utilisation (i.e., silo usage) to reduce annual electricity cost [5.1]

“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.” [5.1]

5.3. 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.” [5.1]

“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.” [5.1]

“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.” [5.1] (Figure 31 represents Figure 12, Swanepoel et al [5.1]).

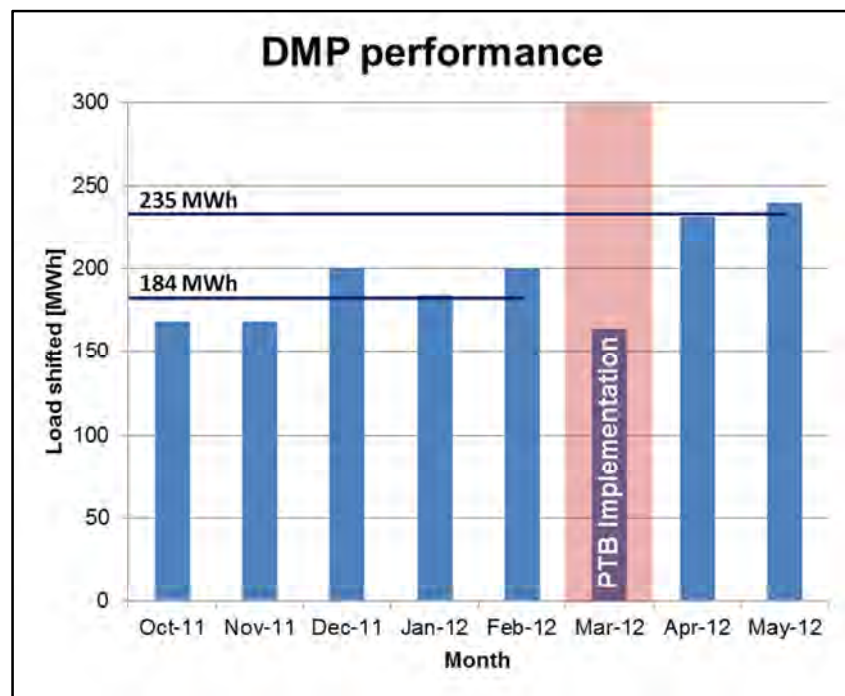


Figure 31: DMP performance before and after implementation of the PTB System (Case 3) [5.1]

5.4. 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.” [5.1] (Figure 32 represents Figure 13, Swanepoel et al [5.1]).

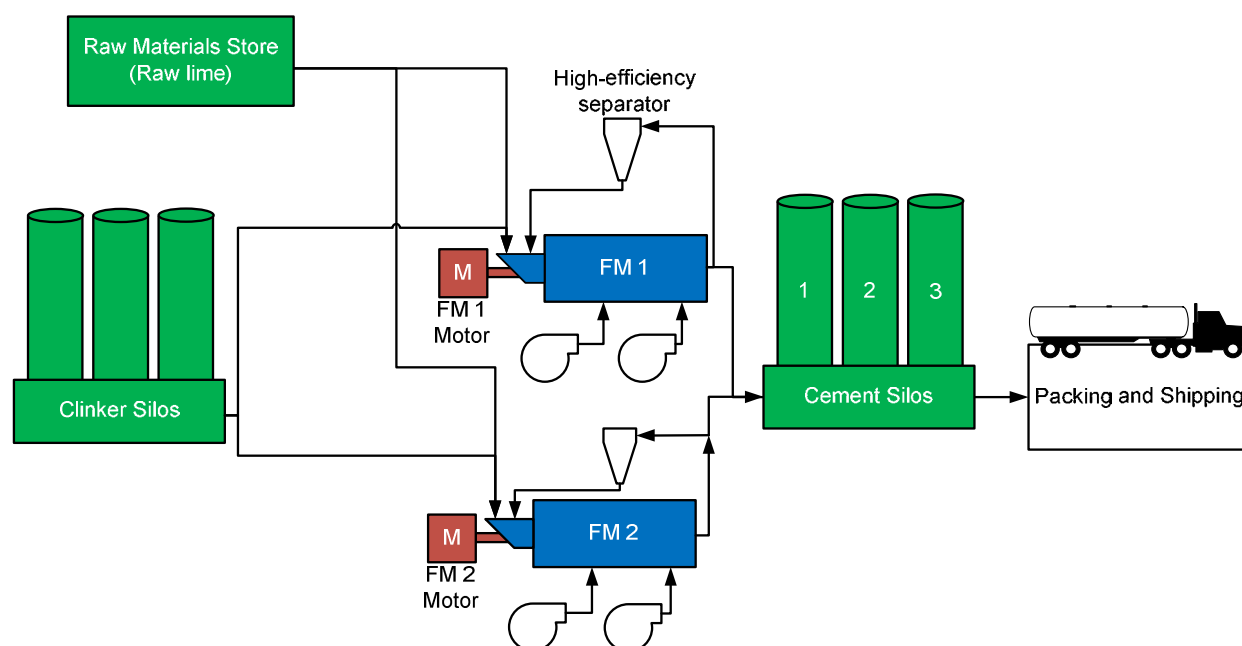


Figure 32: Production component schematic indicating two finishing mills in parallel, with different separators. [5.1]

“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.” [5.1]

“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.” [5.1] (Figure 33 represents Figure 14, Swanepoel et al [5.1]).

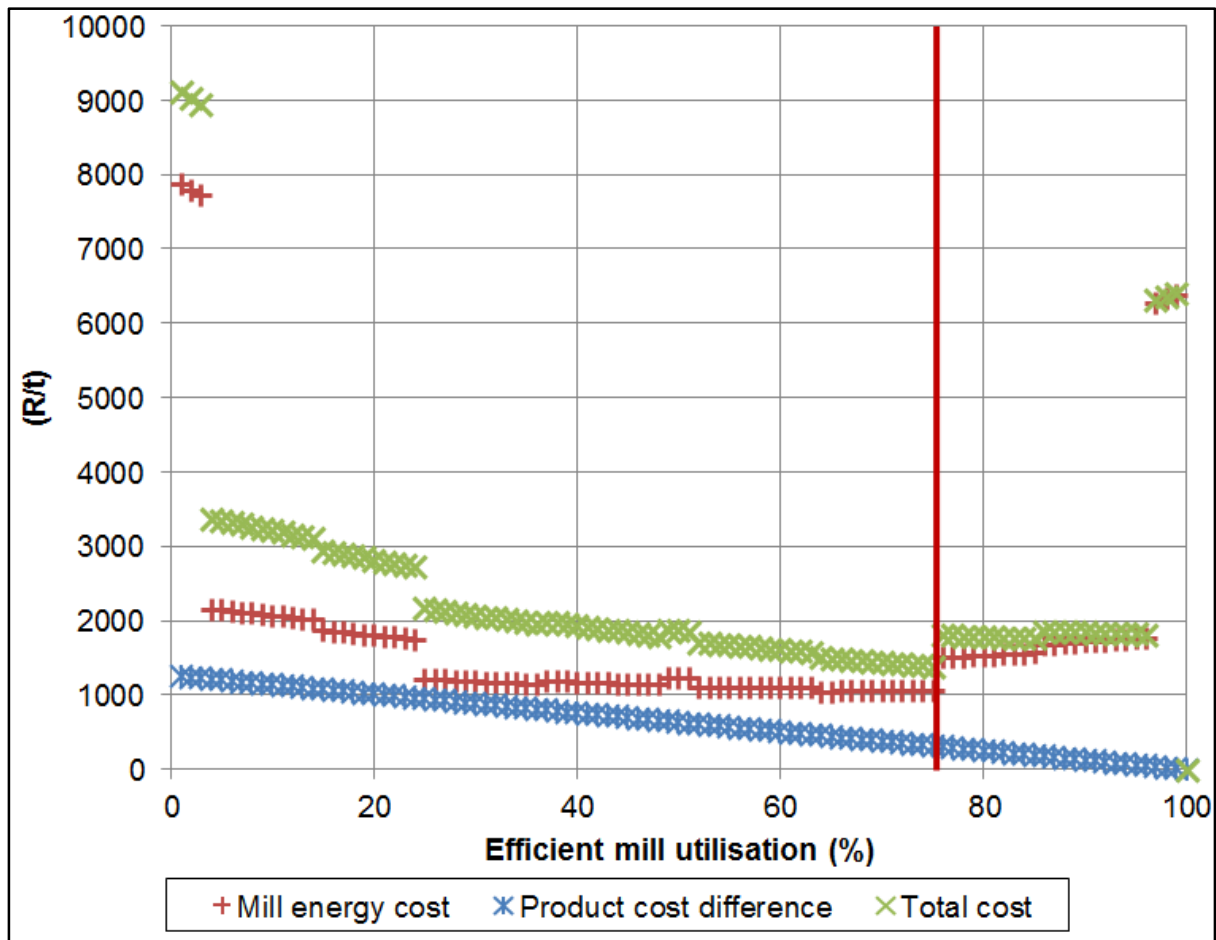


Figure 33: Cost comparison of raw materials cost to electricity cost of operation [5.1]

“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%”. [5.1]

The implementation of the ENMS generated savings on all four cement plants. The total average savings achieved amounted to 10.6% reduction in electricity costs on the milling circuits. The savings achieved on the four sites are summarised in table 2.

Table 2: Summary of savings achieved during the implementation of the ENMS [5.1]

| | Actual operations | Baseline cost | Savings | |
|---------------|--------------------------|----------------------|----------------|----------|
| | Per annum | Per annum | 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 |

The flexibility of this modelling method and the application thereof made the ENMS ideal to be implemented in real-world systems. Updating the modelling constants and targets in real time, made it possible for the ENMS to operate effectively and generate electricity savings.

5.5. References

- (5.1) Swanepoel R., Mathews E., Vosloo J., Liebenberg L., 2013, "Integrated energy optimisation models for the cement industry", Applied Energy, in review.

Six

Summary and Conclusion

Chapter Six

This chapter summarises the results obtained during the application of the energy management system and draws a conclusion of the success of this intervention. The chapter concludes by proposing further research topics and further study of the application of this energy management system.

6. SUMMARY AND CONCLUSION

6.1. 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.” [6.1]

Table 3: Summary of savings achieved during the implementation of the ENMS [6.1]

| | 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 |

Swanepoel [6.1] used these results to show that the total electricity consumption of a cement plant can be reduced by implementing discrete modelling into the daily operations planning of a cement plant. The results show that an average electricity cost reduction of 10.6% was obtained. This shows that the implementation of the ENMS was not only successful, but it can also compete with other methods of reducing energy cost during the production of cement.

The implementation of the ENMS showed that modelling operation with variable electricity tariffs can generate savings. In addition to this, 10.6% compares well to present technologies, with a simpler implementation. The payback period of the implementation is also instantaneous, since no large infrastructure upgrades were necessary.

6.2. 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.” [6.1]

“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.” [6.1]

“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.” [6.1]

“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.” [6.1]

6.3. RECOMMENDATIONS

It is recommended that similar ENMS's should be applied by other industries and production facilities to minimise production cost. Industries such as the mining sector could benefit from these savings. The concentration and extraction facilities of gold and platinum mines have similar layouts to the cement production process, with large mills and smelters. The basic layout of a gold extraction plant is shown in Figure 34.

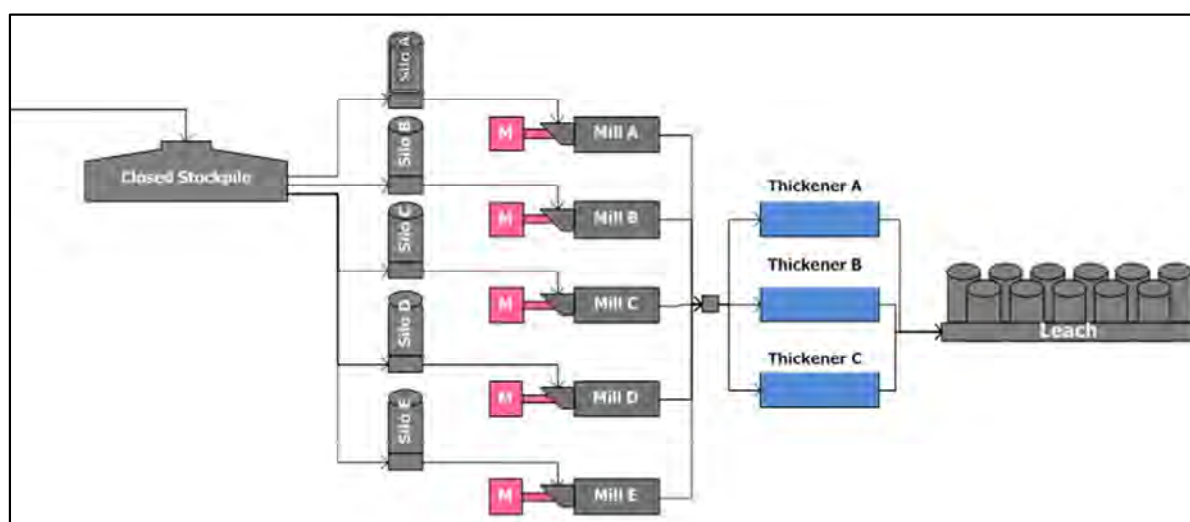


Figure 34: Example layout of a typical gold plant

The basic layout of a platinum concentrator plant is shown in Figure 35.

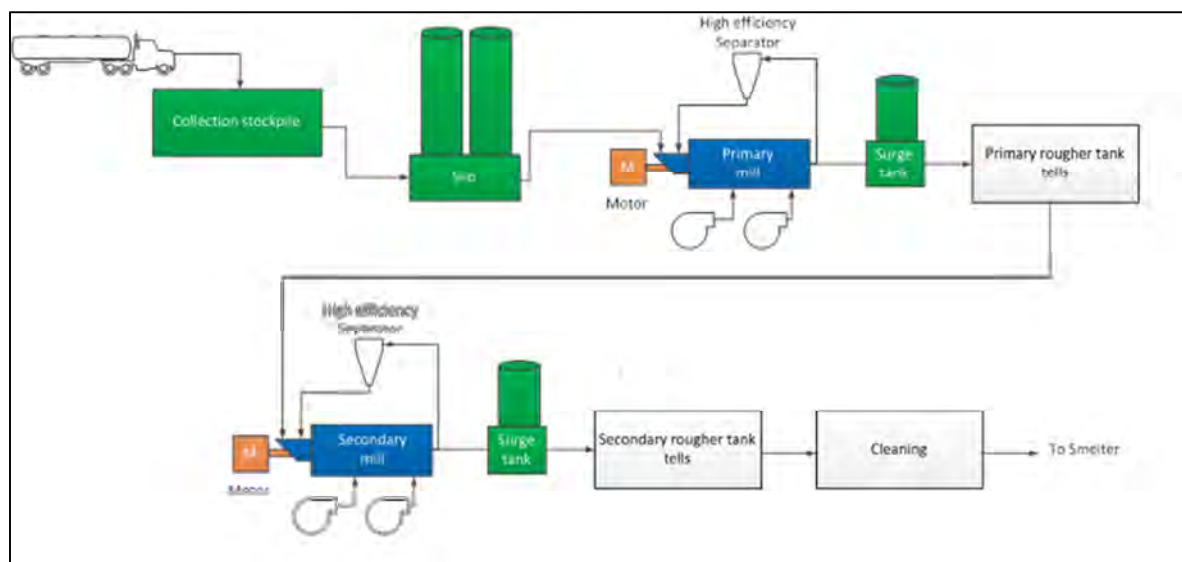


Figure 35: Example layout of a typical platinum concentrator plant

Other industries such as chrome and iron pelletizing plants can also consider using ENMS. The continuous nature of these plants makes the application of this modelling ENMS ideal for reducing electricity costs.

Further study can also be done to optimise larger systems, for example, the distribution systems between cement plants and other industrial facilities. In this case, modelling the production rates and accounting for the cost of raw materials and the transport between the individual production facilities can provide opportunities for saving energy. The ENMS presented in this thesis can be used to generate the energy consumption rate of the individual plants, which will form a base for larger scale modelling.

6.4. References

- (6.1) Swanepoel R., Mathews E., Vosloo J., Liebenberg L., 2013, "Integrated energy optimisation models for the cement industry", Applied Energy, in review.

Seven

Appendices

APENDICES

ANNEXURE A

WRITER REQUIREMENTS FOR ARTICLES SUBMITTED TO APPLIED ENERGY

The article given in Annexure B was submitted to the international scientific journal Applied Energy and is presently under review. The specific writer requirements of the journal are given in this annexure (Applied Energy 2012).

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ANNEXURE B

SWANEPOEL R., MATHEWS E., VOSLOO J., LIEBENBERG L., 2013,
“INTEGRATED ENERGY OPTIMISATION MODELS FOR THE
CEMENT INDUSTRY”, APPLIED ENERGY, IN REVIEW.

**INTEGRATED ENERGY OPTIMISATION MODELS
FOR THE CEMENT INDUSTRY**

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1 **ABSTRACT:**

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

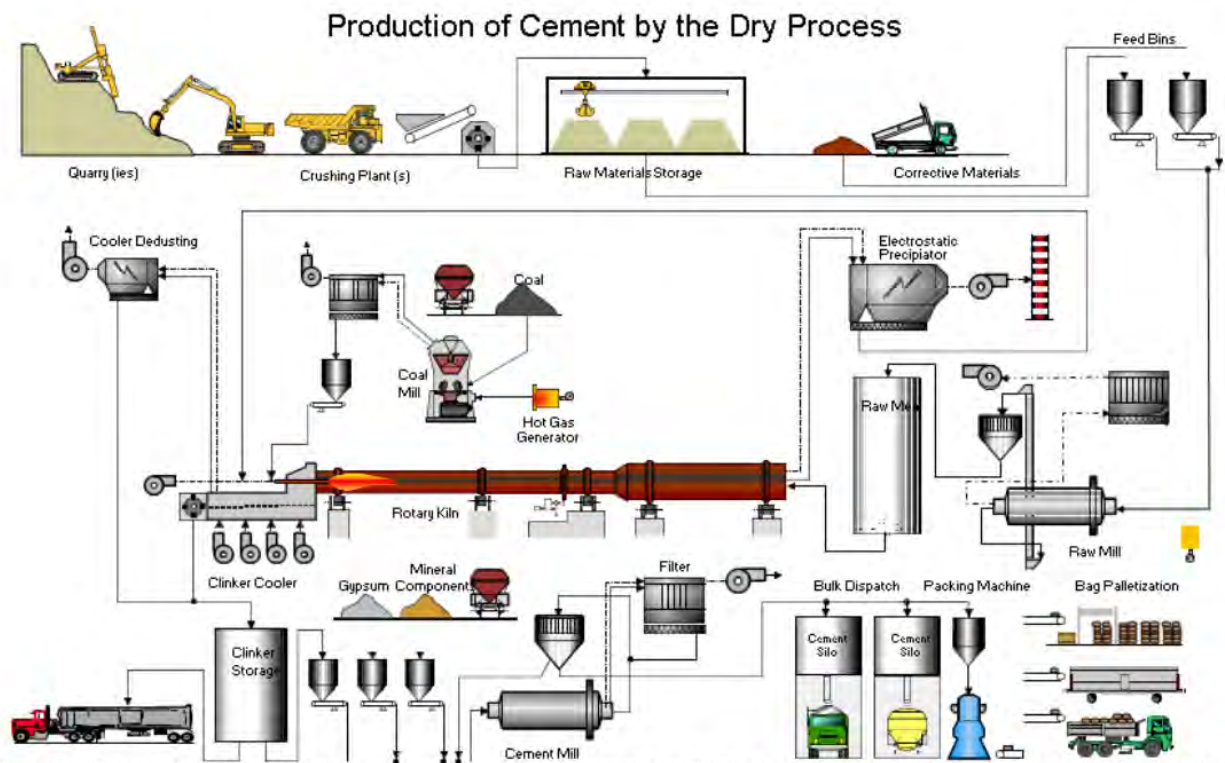
14 **Keywords:** integrated energy model, cement plant, energy management system

15 **1. INTRODUCTION**

16

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

22



23

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

25

26 Limestone is the primary raw material that is used in the production of cement. It is mined in large
27 open cast mines, through blasting. The unprocessed limestone has large variations in particle size
28 and therefore passes through a crushing process. This process incrementally reduces the particle
29 size of the limestone by systematically crushing, screening and re-crushing the limestone. From the

30 crushing plant, the crushed limestone is transported via an overland conveyor transport to a large
31 stockpile [11]. The crushers, screens and conveyor transport are all driven by electric motors.

32

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

43

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

54

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

59

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

68

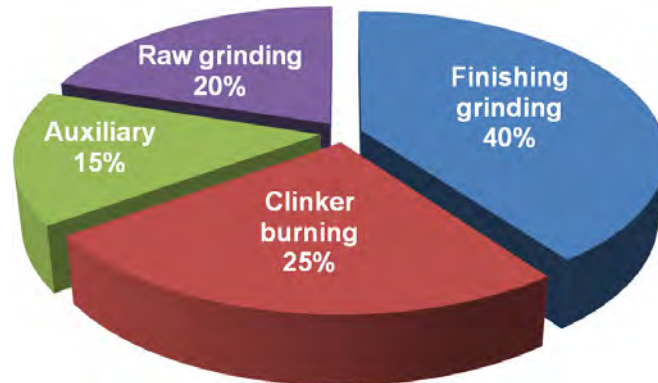
69 The final process in the production line is known as finishing milling. Similar to raw milling, this
70 milling process is used to grind clinker and other raw materials to a very fine powder called cement.
71 The active component of cement is clinker. To obtain different final characteristics of the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

78

79

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

82



83

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

85

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

90

91 Electrical auxiliary systems of the grinding circuits include air compressors, conveyor transport,
92 water- and oil pumps, and various large fans. The combined electrical energy consumption of
93 grinding systems can constitute up to 75% of all energy used in the cement industry [2, 11]. This
94 corresponds to a total production cost component of 50% - 60% for energy of which 17.75% -
95 42.6% is allocated to electricity alone [2]. The fairly large variation is attributed to different pricing
96 structures and electricity costs in different areas in the world.

97

98 In addition to energy costs, environmental conservation in terms of reducing carbon dioxide (CO₂)
99 and nitrogen oxides (NO_x) emissions is a global concern [13]. Thirty-three per cent of global

100 emissions are directly linked to the use of energy [14, 15] of which the cement industry contributes
101 up to 7% of global CO₂ emissions [14, 15].

102
103 South Africa's primary electricity utility, Eskom, produces 95% of the electricity consumed in
104 South Africa. Ninety-three per cent of this electricity is generated in coal-fired power plants and
105 the remaining 7% produced by hydro-, nuclear-, gas turbine- and pumped storage generation [16].
106 Reducing electricity demand of cement plants in South Africa will therefore serve to reduce CO₂
107 emissions. Managing the demand of the cement industry will also assist in creating a more uniform
108 daily demand distribution and eliminating peaks and valleys in the demand profile. Detrimental gas
109 emissions from coal fired power plants have been quantified by Mann and Spath [17] as indicated in
110 Table 1.

111

112 **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 |

113

114 The additional CO₂ emissions indirectly emitted as a result of the use of electricity is estimated to
115 be between 101.8 kg and 122.2 kg CO₂ per ton cement produced. This is fairly large when
116 compared to the 137 kg CO₂ per ton cement produced that is directly emitted by the production
117 plant and reported by Valderrama [18].

118

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

127

128 Another technique for achieving energy savings is improved control systems. These systems
129 optimise specific component operation, thus ensuring stable, optimal operation [23]. Savings of
130 between 1.4 kWh and 6 kWh per ton can be realised [20-23]. Valderrama [18] reported a 4%
131 reduction in CO₂ emissions by implementing BAT. Reduction in NO_x, SO₂ and dust emissions of
132 20.5%, 54% and 84% respectively are also possible.

133

134 No literature publications on the application of management and computerised modelling systems
135 that simultaneously integrate the numerous production components could be found in literature. A
136 new modelling system is proposed that provides a solution for reducing emissions and energy
137 consumption by integrating various production components. An integrated model was developed
138 and implemented for this energy management system. Four existing South African cement plants

139 were investigated. Reports on the financial savings achieved during the implementation are also
140 given.

141

142 **2. INTEGRATED MODELLING**

143

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

153

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

156

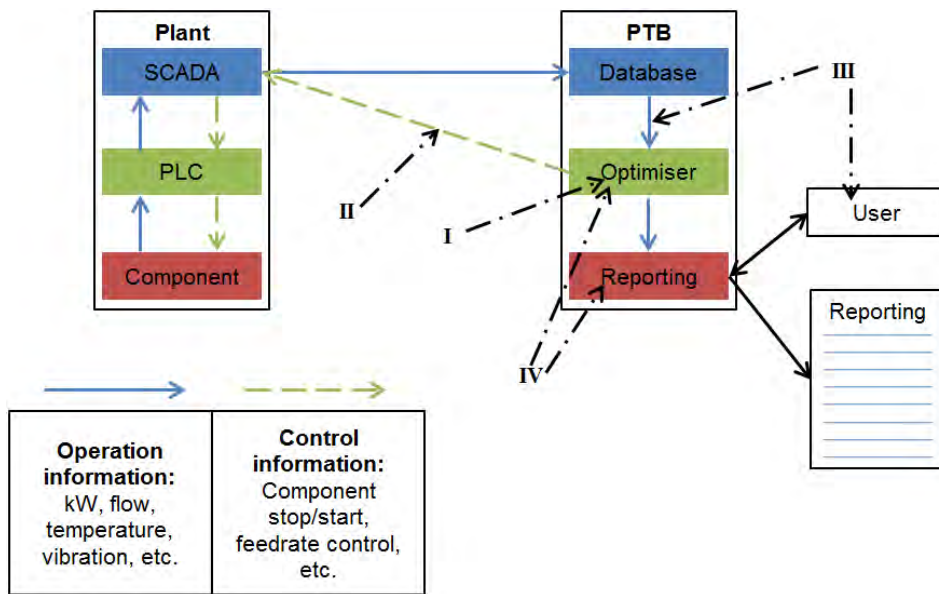


Figure 3 – Schematic of PTB system integration and functionality

157

158

159

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

170

171 I. Planning:

172 Planning is set out as establishing energy-saving targets, determining the strategy for obtaining
 173 these targets, identifying measures and responsibilities, providing the necessary resources to

174 achieve these targets and preparing an action plan [25]. The core of the ENMS is the PTB
175 modelling system that operates within the larger system (refer to section IV for “Acting”). Various
176 production components have an influence on the cost of the final product and on electricity
177 consumption. In most cases these are either directly or indirectly linked to the operation of the
178 plant. The modelling system therefore considers various constraints that were not previously
179 integrated in similar operations models.

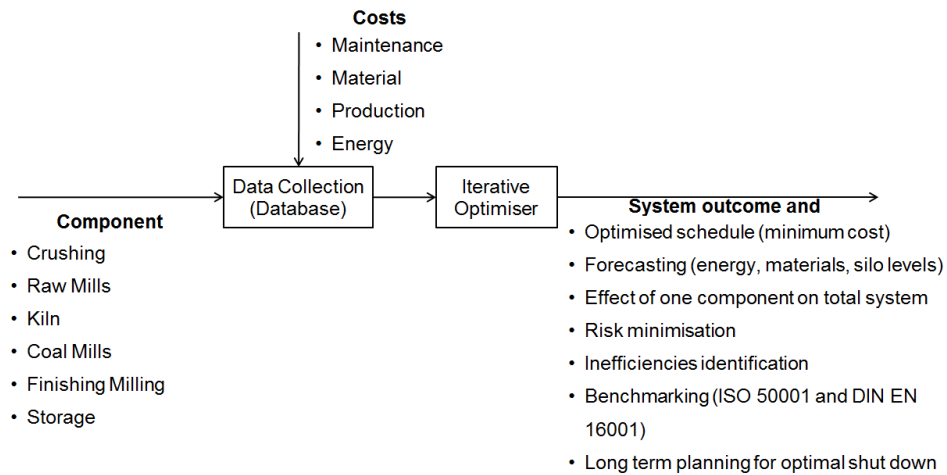
180

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

188

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

198



199

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

202

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

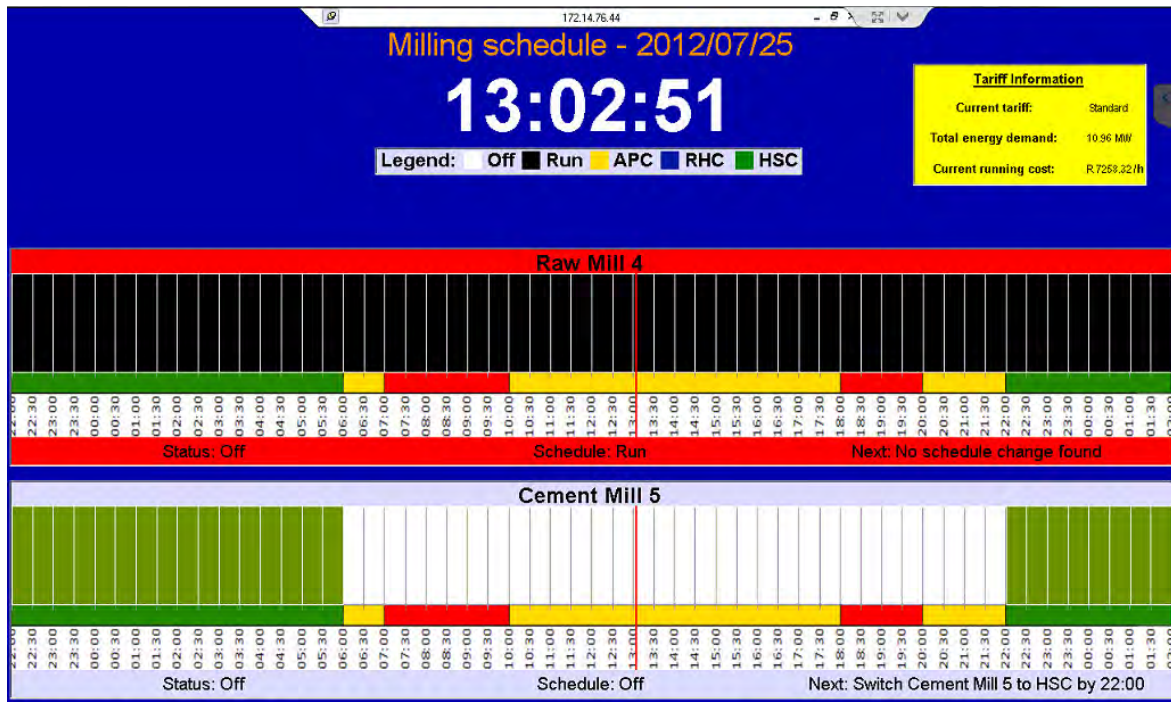
207

208 II. Doing:

209

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

217



218

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

221

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

228

229

230 III. Checking

231

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

238

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

246

247 IV. Acting

248

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

253

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

261

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

265

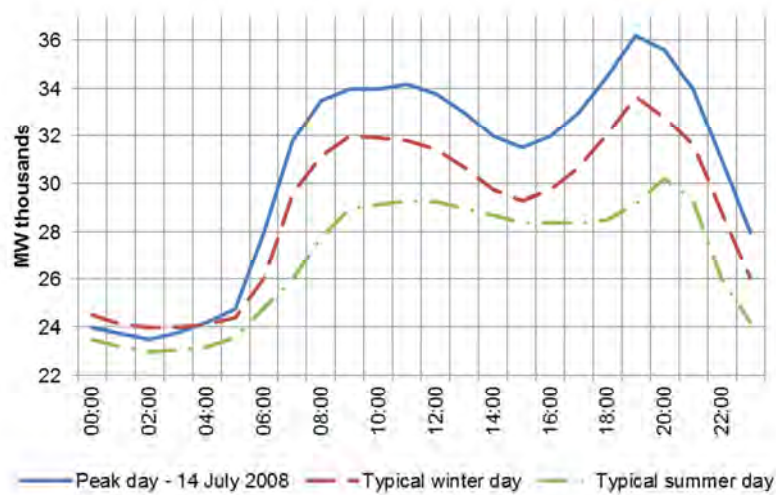
266 **3. CASE 1: TIME-OF-USE TARIFFS WITH PARALLEL COMPONENTS**

267

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

271

272



273

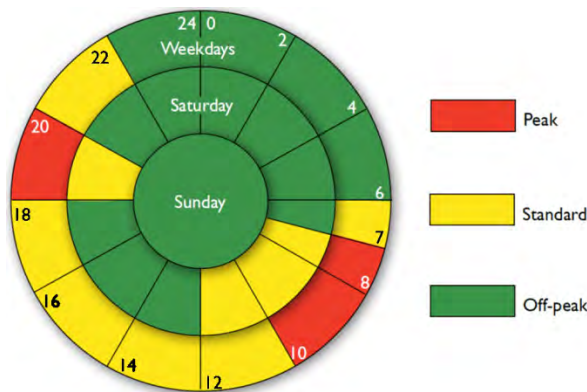
274

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

275

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

280



281

282

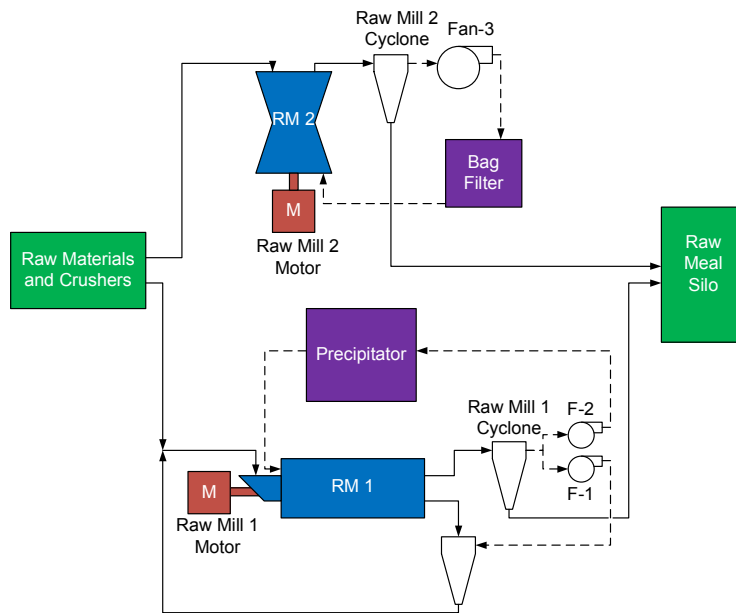
Figure 7 – Time of use tariff structure implemented by electrical utility, Eskom [8]

283

284 Optimising costs will ensure that the operation during the most expensive periods is restricted to a
 285 minimum. This will not only reduce operating costs for the cement plant but also reduce the power

286 requirement during peak electricity demand periods. Two different cost savings strategies are
287 possible for a cement plant. First the plant operation and cost can be optimised by considering the
288 TOU tariff structure. This can be done by simply restricting operations during the expensive peak
289 periods and, depending on production targets, rescheduling operations to the less expensive periods.
290
291 Second, if two components operate in parallel but with different specific electricity consumptions
292 (kWh per ton), as indicated by Figure 8, optimising electricity cost without considering TOU tariffs
293 can also be done. In this case, a horizontal ball mill and a vertical roller mill (VRM) operate in
294 parallel, feeding from the same stockpile and filling the same raw meal silo. It will be more cost-
295 effective to operate the more efficient VRM mill at its maximum availability, and the less efficient
296 ball mill only to essential production requirements. This will be possible when production is lower
297 than the maximum plant capacity. However, in general, the solution in most cases requires a more
298 detailed analysis of components in parallel and taking TOU tariffs into consideration. Analysing
299 the problem now becomes more complex. For instance, it might be more cost-effective to operate
300 the less effective mill during off-peak periods than it is to operate the more effective mill during
301 peak periods (i.e., not operating the more effective mill at its maximum availability as suggested by
302 the second strategy).

303



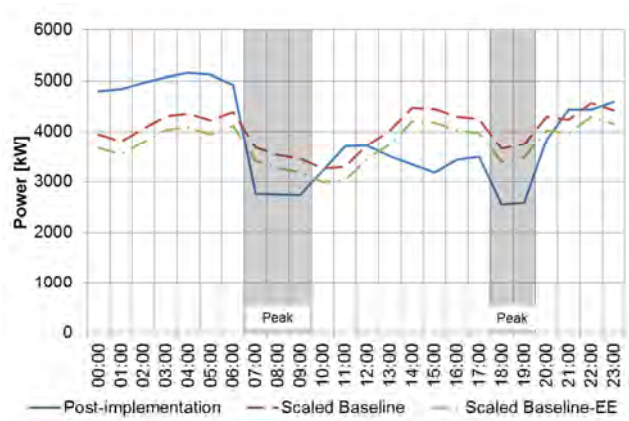
304

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

307

308 Complexity is increased by the continuously changing production volumes and maintenance
 309 requirements, particularly when the number of production components increases. However, by
 310 integrating these components in the simulation model, and regularly updating the model, an
 311 optimised operations solution is possible. Implementing this ENMS on the circuits as indicated in
 312 Figure 8 realised an average 0.97 kWh per ton improvement on the combined electricity
 313 consumption of the two mills. Furthermore, 19% of peak electricity usage was also shifted to daily
 314 off-peak periods. The combination of these two components of savings resulted in a total saving of
 315 14.8% in electricity costs on the raw milling circuits. Two essential characteristics must however
 316 be available to ensure that this operation optimisation is possible. These are reserve production
 317 capacity (where production targets are lower than the maximum plant production capacity) and
 318 storage capacity. The daily power consumption trend for Case 1 is shown in Figure 9.

319



320

321

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

322

323

324

The trends in Figure 9 are based on three months average production data after implementing PTB.

325

A daily baseline is then compiled using three months average operations data before implementing

326

PTB and scaled with total production volume. This baseline is then further scaled to be energy

327

neutral to the post-implementation power consumption trend. The difference between the

328

production scaled baseline and the energy neutral scaled baseline is considered as the average

329

energy efficiency.

330

331

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

333

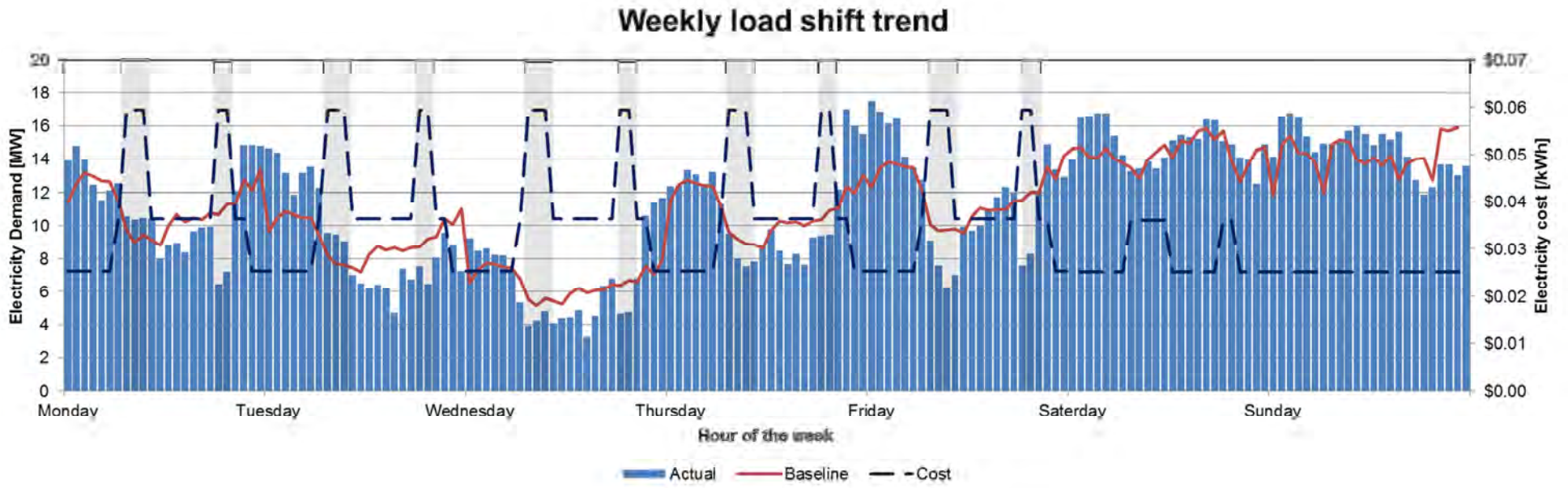
334 Production load-shifting is largely dependent on available storage capacity. Consider for example,
335 a raw meal silo that stores a constant supply of material. If the production rate of the raw mill
336 preceding the silo is greater than the production rate of the kiln, electrical load can be shifted.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

343

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

353

354



355

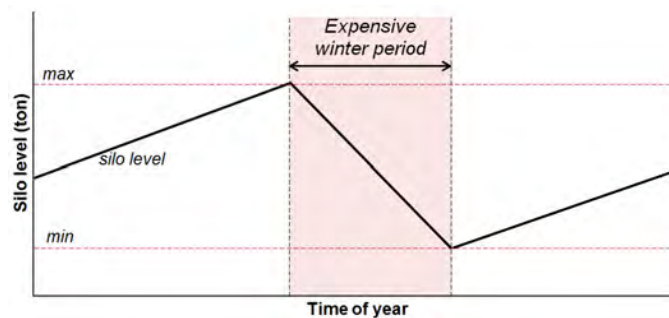
356

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

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

366

367



368

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

370

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

373

374 **5. CASE 3: DYNAMICALLY FLUCTUATING ELECTRICITY COST**

375

376 Real-time data updates allow PTB to adapt and iterate the operations solution to dynamic variations
377 in energy costs. Reduced reserve supply margins compelled Eskom to introduce an initiative called

378 Demand Market Participation (DMP). This initiative rewards clients for reducing electricity
379 demand on request by the utility. Requests are conveyed on a short-term basis, typically only a few
380 hours before a reduction in demand is required. This short-term notification further complicates
381 optimal operations planning which incorporates DMP.

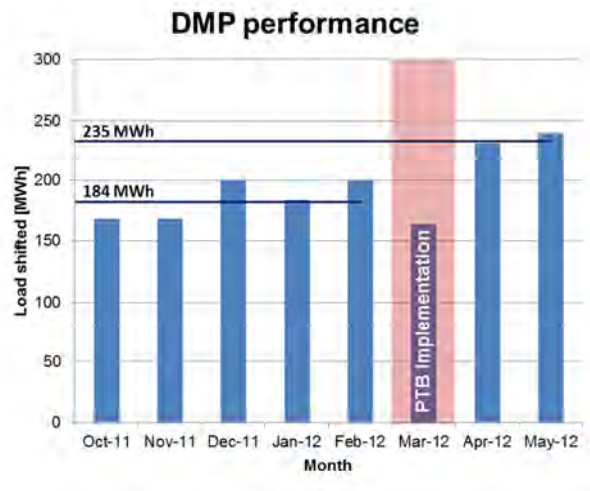
382

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

391

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

396



397

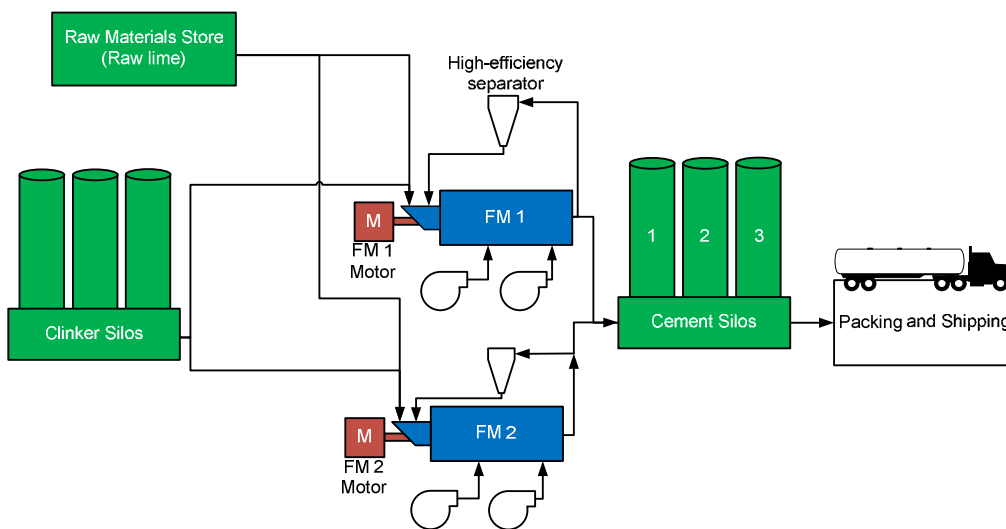
398 **Figure 12** – DMP performance before and after implementation of the PTB System (Case 3)

399 **6. CASE 4: RAW MATERIALS COST**

400

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

406



407

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

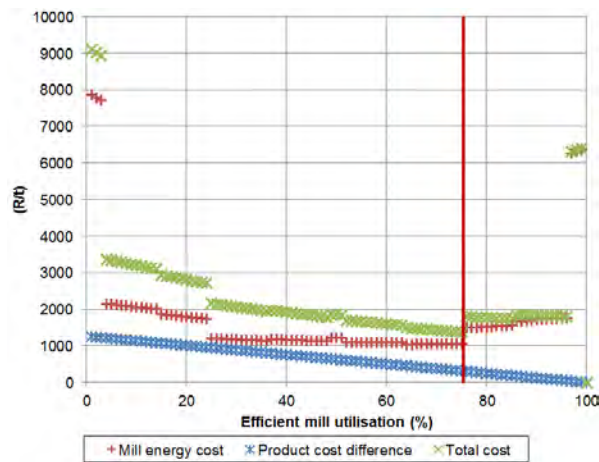
410

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

415

416 Once again, as with parallel mills of differing efficiency, it is clear that the production of the more
417 efficient mill (with regards to raw materials cost) should be maximised during normal operation.
418 However, combining TOU tariffs, raw material cost and dynamic electricity cost influences, this
419 problem also becomes too complex to analyse manually. Figure 14 shows an example of
420 combining the costs of both electricity usage and raw materials cost.

421



422

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

424

425 Figure 14 is compiled for a specific cement product and for a specific production target. It indicates
426 the cost spread with increasing utilisation of the more efficient mill and subsequently decreasing

427 utilisation on the less efficient mill. It can be seen that the minimum cost is reached at a 75%
 428 utilisation of the more efficient mill and a 25% utilisation of the less efficient mill, instead of the
 429 initially assumed full utilisation of the more effective mill. When production targets fluctuate and
 430 different constituents are produced, the production costs vary considerably. By integrating each of
 431 these influences and rapidly re-evaluating the most cost effective solution, the plant can be operated
 432 at the lowest possible cost. In a similar way, the cost of raw materials can be optimised when a pre-
 433 determined quantity of coal is added to a raw milling circuit. Implementation of PTB in Case 4
 434 produced a combined saving in electricity cost on the milling circuits and raw materials cost of
 435 8.1%.

436

437 7. SUMMARY OF CASE STUDIES

438

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

442

443 **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 |

444

445 8. CONCLUSION

446

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

455

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

466

467 Optimising cost and integrating different component characteristics meant that raw material costs
468 could also be incorporated in the model. This not only reduces energy costs and emissions, due to
469 lower electricity demand, but total cement production cost is reduced as well. The advantages of an
470 integrated modelling approach allow the cement plants to obtain larger total savings than when the
471 modelling and planning of operations of large components is done individually. Implemented

472 studies clearly revealed the individual benefits of the system. The ENMS combines these benefits
473 to form an integrated solution and showed a 7.1% improvement in operations costs on each milling
474 system on which it was implemented.

475

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

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