Modelling techniques to minimise operational costs in energy intensive industries

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Thesis submitted for the degree Doctor *Philosophiae* of Mechanical Engineering at the Potchefstroom campus of the North-West University

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November 2014

ABSTRACT:

Title: Modelling techniques to minimise operational costs in energy intensive industries
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Degree: Doctor of Philosophy of Mechanical Engineering

Energy cost savings are key for South African industry to remain competitive in an international market. The South African gold-, platinum, and cement industries are three such examples. Recent electricity price increases have forced these industries to focus on reducing operational costs. Various methods of energy cost reduction are utilised in modern industry, usually with extended payback periods. Efficient operation planning and optimisation can however reduce energy costs with instant payback.

Operations modelling and computer-assisted optimisation allow plant personnel to schedule plant activities more effectively. Most literature steers research towards the modelling of specific applications, instead of widening the analysis for application on various systems. As a result, and due to the complexity of these modelling techniques, modelling and operations interventions are costly, as they are mostly implemented by expert personnel and consultants.

This thesis presents the compilation of integrated modelling techniques that simplifies modern methods. The simplification makes widespread implementation by less knowledgeable personnel possible. Unique component descriptions are developed that reduce the complexity of the mathematical representation of the real-world plants. New process- and link component descriptions are generated. These describe real-world components accurately which are flexible to characterise a multitude of plant designs.

As part of the study, a new continuous-time modelling approach was generated that reduces processing time. This time modelling approach is flexible to optimise any extent of time, using a continuous-time approach. This new optimisation and scheduling algorithm calculates lowest cost operations while considering continuously variable plant settings and interlinked component response, such as buffer levels. The modelling techniques are implemented using an automated energy management system.

The new techniques are compared to existing linear optimisers and show a reduction in processing time and complexity. The thesis describes the application of the modelling techniques on four cement production plants and generated energy cost savings of more than 10%, or R8.5 million *p.a.*. Further benefits include higher production outputs, improved product quality and the reduction of operational risks. The application on gold mining, platinum concentration and ore distribution logistics are also investigated.

Industrial processes are simulated to determine the savings potential of the new modelling techniques and the effectiveness of managing operations by integrated modelling of a system of components. The modelling technique is simple enough for plant personnel to compile. Conclusively, the new modelling techniques showed general energy savings of up to 6% and large potential for industry-wide cost savings, accounting for up R100-million *p.a.* in the considered South African businesses.

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, Prof M. Kleingeld and Dr J Vosloo for their 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 Waldt Hamer for his diligence and hard work, Raynard Maneschijn for his dedication and all other project engineers involved in the implementation of the considered case studies.

- I would like to thank my parents for motivation, support and love.

- I would like to thank Mariska Coetzee for her loving support and enthusiasm.

FOREWORD:

The work described in the thesis lead to a publication by the author entitled *Integrated energy optimisation for the cement industry: A case study perspective*:

Swanepoel J.A., Mathews E.H., Volsoo J.C., Liebenberg L., "Integrated energy optimisation for the cement industry: A case study perspective", Energy Conversion and Management, 2014 (78), pp. 765-775.

The article is included in Appendix B.

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NOMENCLATURE:

SYMBOLS

l_t	Volume capacity at time t
T_t	Time delay constant at time t
$C_{K,j,t}$	Inflow to outflow conversion factor for stream *j*
$C_{ad}(t)$	Adjusted maximum cost profile
C_j	Cost allocated to output *j*
C_{sj}	Specific cost of distribution at output at *j*
C_t	Total cost allocated to the distribution component
$D_{K,j,t}$	Distribution factor between outflow streams for stream *j*
E_{bl}	Base load energy consumption
E_c	Electricity cost profile
E_t	Energy consumption at time t
$G_{P,t}$	Feed quality from stream P at time t
$G_{S,t-T_t}$	Feed quality from stream S at time $t - T_t$
$K_{j,t}$	Inflow product flow rate at stream j at time t
$M_{K,j,t}$	Produced product mass of stream *j*
$M_{S,i,t}$	Supplied product mass of stream *i*
$M_{i,t}$	Supplied product mass
$M_{j,t}$	Produced product mass
O_o	Operational input
P_1	Summation component outflow
$P_{j,t}$	Outflow product flow rate j at time t
P_j	Produced process fluid output volume at *j*
P_t	Inflow rate at stream P at time t
S_1	Total supplied process fluid volume
$S_{i,t}$	Supplied product flow from stream i
S_i	Summation component inflow of supplied products at i
T_t	Delay or residence time at time t
$V_{P,t}$	Produced product variable of stream *j*
$V_{S,i,t}$	Supplied product variable of stream i
$V_{Silo,t-T_t}$	Silo content at time $t - T_t$
$V_c(t)$	Representative costs scaling profile for buffer volume

f_j	Output distribution factor
K	Transferred process flow
P	Produced process flow
S	Supplied process flow
$C(t)$	Maximum cost line
MC	Maximum cost value constant
$O(t)$	Operational profile
T	Time delay constant
e	End time of analysis period
i	Supplied product index
j	Output flow stream index
j	Produced product index
m	Number of outputs
m	Number of produced process flow streams
n	Number of inputs
n	Number of supplied products
o	Number of energy inputs
t	Analysis time indicator
t	Time
t	Time interval

ABBREVIATIONS

APC	Advanced Process Control
BMR	Base Metal Refinery
CP	Constraint Programming
EnMS	Energy Management System
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-linear Programming
MV	Manipulated Variables
NMD	Notified Maximum Demand
NPC	Natal Portland Cement
PGM	Platinum Group Metals
PLC	Programmable Logic Controller
PMR	Precious Metal Refinery
PPC	Pretoria Portland Cement
RD	Relative Density
RTN	Resource Task Network
SCADA	Supervisory Control and Data Acquisition
STN	State Task Network
TOU	Time of Use
UNFCCC	United Nations Framework Convention on Climate Change
VRM	Vertical Roller Mill
VSD	Variable Speed Drive / Variable Frequency Drive
VSR	Virtual System Representation
WDF	Water Droplet Formulation

GLOSSARY OF TERMS

Comminution	The reduction of a material’s particle size by means of mechanical grinding or milling
Grade/head grade	The average precious metal content of a specific ore measured in grams of precious metal per tonne of ore
Calcination	The heat treatment of a material in the presence of oxygen to achieve chemical transformation and removal of volatiles
Availability	The fraction of time during which a machine or component is available to process a fluid
Reliability	The fraction of time during which the mill is not shut down for breakdown maintenance
Utilisation	The fraction of time during which the mill is not shut down for all maintenance, including breakdown and preventative maintenance
Building blocks	Core fundamental concepts that are compiled to create a system
Model	A virtual representation of a physical system that is either existing, or that has not yet been constructed
Simulation	A virtual scenario created to mimic operational circumstances on a physical system, compiled using a model
Grit	The average particle size of solids in a process fluid
Batch process	The sequential processing of a production fluid
Continuous process	An uninterrupted continual processing of a production fluid
Discrete	A distinct and unique area or variable
Binary	A variable that can only be represented by two modes, either a zero or a one, on or off
Fuzzy logic	A multi-valued variable with a minimum of zero and a maximum of 1
MegaFlex	A tariff structure available from Eskom, dividing electricity costs into three tariff periods: Peak; Standard and Off-peak.
Real-time	Simulation that is aligned with real-world circumstances

CHAPTER 1

Introduction

Chapter one

Chapter one introduces the study and identifies a shortfall in present literature. The shortfall is described in a problem statement. A goal statement is developed that best solves the problem statement. The scope of the study is compiled and the layout of the thesis is summarised.

1 INTRODUCTION

1.1 PREAMBLE

Energy intensive industries operating in competitive global markets are under pressure to reduce the cost allocated to energy. The rapid growth of both electricity charges in South Africa and the international coal price has caused the cost of energy to increase disproportionally to inflation in this area (as shown in Figure 1-1) [1.1]. The cost factor allocated to energy during operation must be reduced for the South African industry to remain competitive.

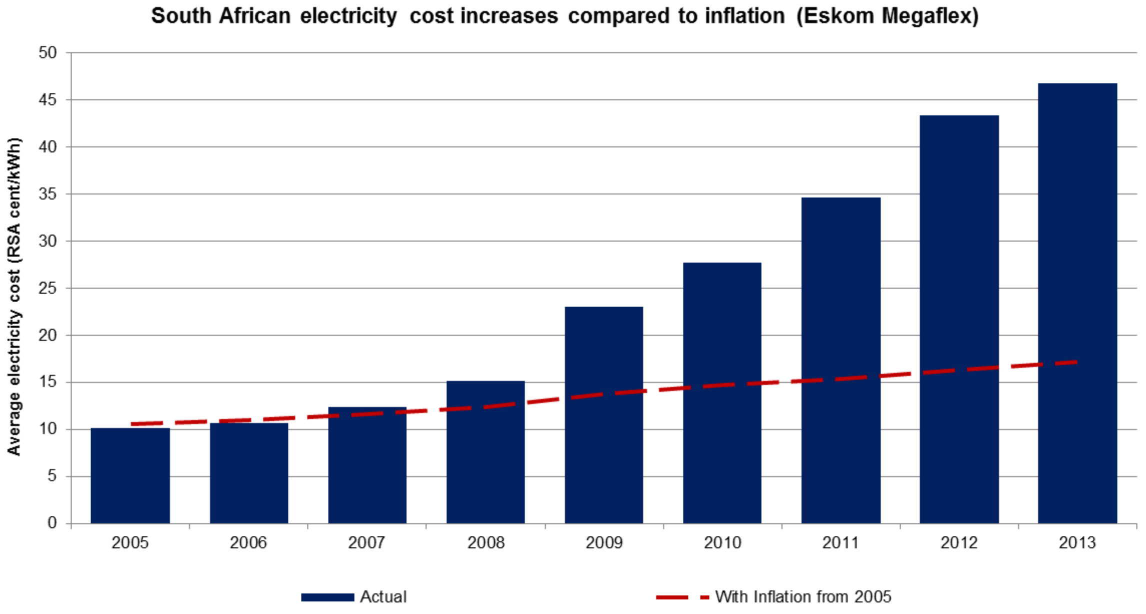

Figure 1-1: South African net energy charges for electricity[1] and inflation trend[2]

Three energy intensive industries in South Africa are good examples of where costs allocated to energy need to be reduced. These industries are gold mining, platinum mining and cement production. The ultra-deep mines in South Africa and the unique sales environment for cement and platinum force these industries to focus on production cost reduction. Most costs in these industries are fixed or limited to minimum constraints, such as sales prices or wages for employees. Cost allocated to energy, however, remains variable and can be reduced on a constant basis. New equipment technologies and varying electricity tariffs present the opportunity for large cost savings.

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

[2] Statistics South Africa, Consumer Price Index (CPI), website: http://www.statssa.gov.za/keyindicators/cpi.asp/ [accessed on 10 January 2013], 2013.

These industries consume energy in different forms and in different processes to produce the individual final products. Different large machinery and production components are used for these processes. The operation of the different industries presents unique challenges in energy cost reduction. The operation of the different industries and the unique sales environments are further described in the following sections.

1.1.1 GOLD MINING

South Africa is the fifth largest producer of gold in the world, producing 190 tonnes in 2011 ([1.2], [1.3]). Gold mining is also a large electricity consumer in South Africa, accounting for up to 5.5% of the national electricity demand in 2009 [1.4]. South Africa extracts gold from deep-level mines, up to 3.9km below surface. The components used to mine the ore and extract gold from the ore range in size and application. The components are divided into services- and production-related machines. Services include pumps, air compressors and cooling auxiliaries.

Gold production uses conveyors, winders, mills and various chemical processes to extract ore from the ground and gold from the mined ore. Of these installations, the largest interruptible energy consumers are the winders and grinding mills. Winders extract ore from underground and are either automated or manually operated. In ultra-deep mines, winders are separated into multiple legs where ore is extracted from the shaft bottom to an interim level, from where another winder extracts the ore to the surface. Trains and conveyor belts are used to transport ore underground. Different store capacities, such as ore-pass between levels and large silos are used as buffers between operations. [1.5]

Milling, or *comminution*, circuits reduce the particle size of the ore for further chemical processing. These mills use a wet process, where a mixture of ore and dilution water forms a slurry for further processing. Various pumps and separators are used to assist and improve the operation of these mills. This slurry’s relative density is then increased using thickeners, after which the ore passes through a sequence of leaching, activated carbon adsorption, elution, precipitation and smelting. Smelting also consumes large amounts of electricity, but is however, due to the high safety- and financial risk, not seen as interruptible equipment and is operated constantly. [1.6]

Due to the extreme depths encountered in South African gold mines, this equipment consumes large volumes of energy in the form of electricity. With the increasing electricity costs, operating costs show an increase that is disproportional to inflation. Figure 1-2 shows these increases since 2002. In addition to the operational cost increases, the total spent on wages have also increased since 2005. The combination of these two factors has forced the gold industry to alter its production strategies.

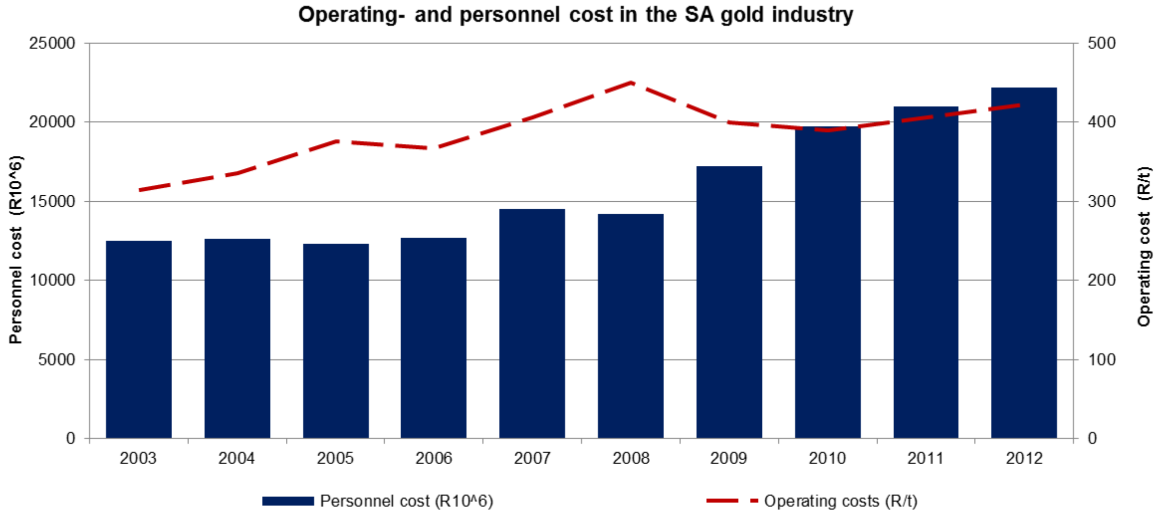

Figure 1-2: Operating- and personnel costs in the South African gold industry [1.7]

Figure 1-3 shows the average *grade* of ore processed with the total ore that is processed since 2003. The *head grade* of the ore processed has decreased dramatically in South Africa after 2005 [1.7]. In addition to the reduced head grade, the average volume of ore has also decreased between 2003 and 2006, where after lower grade ore was processed. Ore is extracted from old mine dumps and tailings dams, because mining costs have increased [1.8].

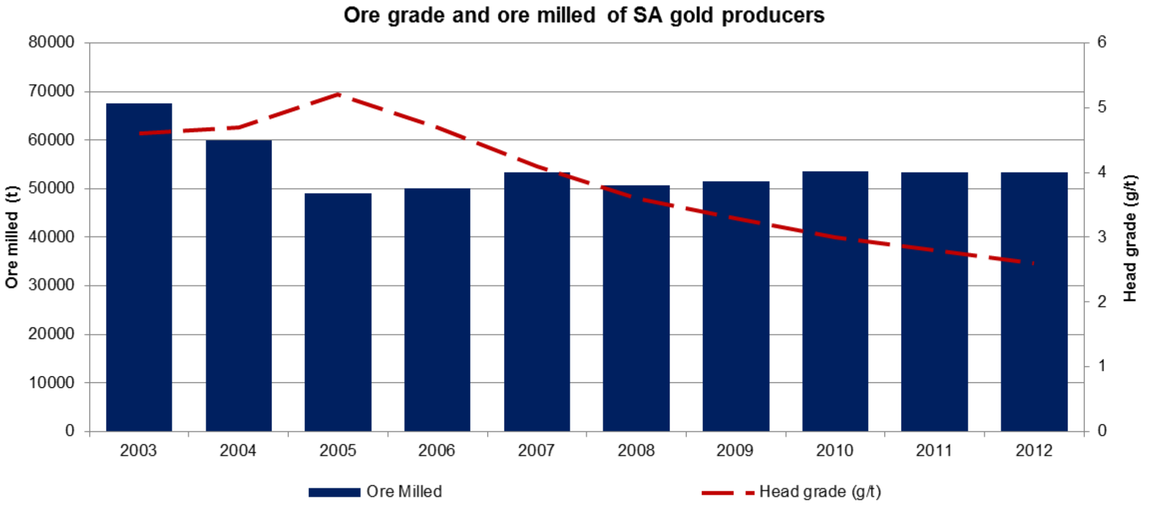

Figure 1-3: Ore grade and total ore milled in the South African gold industry [1.9]

With the reduced head grade, the South African gold production has decreased dramatically in recent years. Figure 1-4 shows what impact these increases have had on the industry. The decrease in gold production and increase in minimum wages have forced the industry to reduce the total amount of employees in the form of retrenchments.

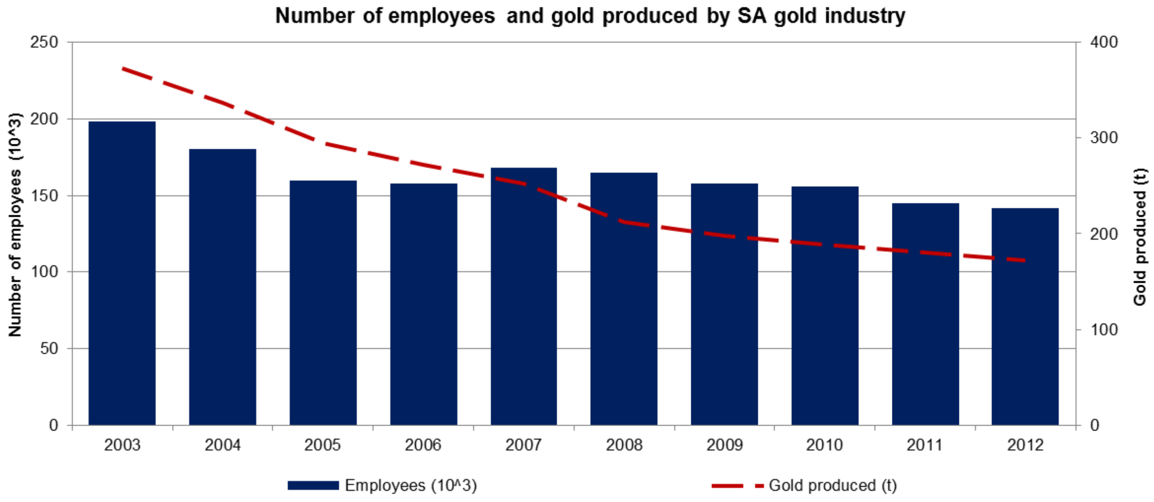

Figure 1-4: Number of employees in- and total gold produced by the South African gold industry

It is clear that this industry is under pressure. South Africa was the largest producer of gold in the world in 2002. As a result of the above-mentioned factors, South Africa has dropped to the fifth largest producer globally [1.2]. To avoid further retrenchments and loss of economic market share, costs allocated to energy need to be reduced for this industry to stay competitive in an international market.

1.1.2 PLATINUM MINING

South Africa is the largest producer of platinum in the world, producing 145 tonnes in 2011 [1.10]. Platinum mining consumes energy in the form of electricity and fuel for transportation in South Africa. Platinum is mined using similar techniques to that of gold mining. The mine shafts are however, not as deep as that of gold mining, which reduces the winding and cooling energy requirements. Platinum ore contains a multitude of different precious metals know as Platinum Group Metals (PGMs). [1.11]

The extraction process for these PGMs differs from that of gold refining. The ore is sent to concentration plants where the particle size of the ore is reduced and a PGM concentrate is extracted in slurry form by means of froth floatation. The concentrate is then transported and dried of which it enters a smelting and converting process, producing a PGM-rich matte. The matte then passes through a series of hydrometallurgical processes, including Base Metal Refining (BMR) and in the end Precious Metal Refining (PMR)[1.11]. Smelters and other refining facilities are susceptible to critical failure when energy-saving measures are applied; however, large energy savings can be achieved in the transport of the ore and concentrate, as well as in the milling during the concentration phase of the PGMs refining process. [1.11]

In recent years, the South African platinum industry has suffered personnel difficulties. Legal and illegal strikes forced personnel payment raises. Figure 1-5 depicts the personnel costs and the number of employees in the platinum industry in South Africa. The personnel costs have shown a sharp increase between 2006 and 2008 and between 2010 and 2012.

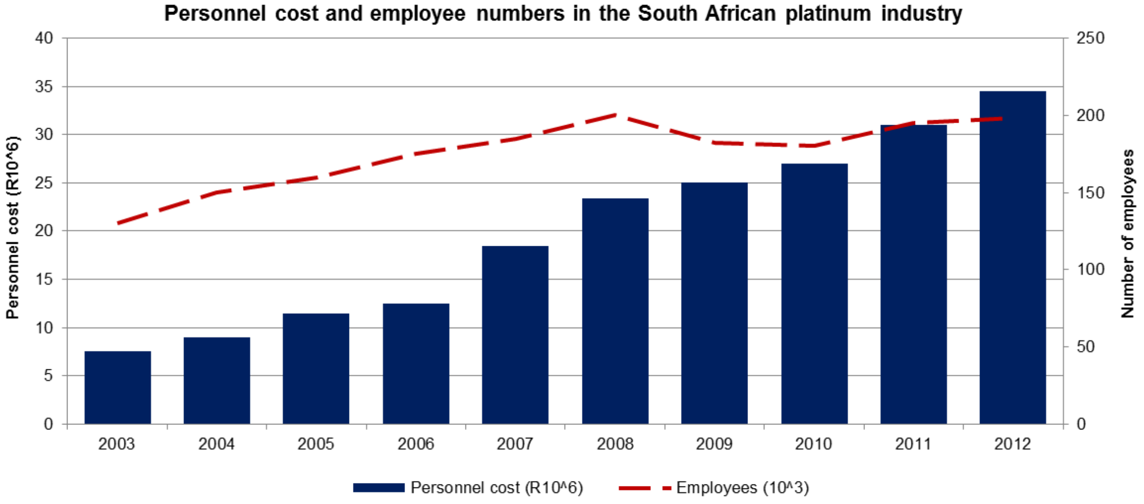

Figure 1-5: Personnel cost and employee numbers in the South African platinum industry[1.12]

After 2008 the total employee numbers dropped, representing job losses by means of retrenchments. A similar, yet larger impact is expected with the personnel cost increase between 2010 and 2012. Large platinum mine groups have undergone downscaling. The downscaling will also have a detrimental effect on international market share for the South African platinum industry. Figure 1-6 shows the total PGM and platinum production from South Africa and the international market share enjoyed by the platinum industry in this area since 2008. [1.12]

The downscaling seen in Figure 1-5 had a large impact on the total PGMs produced in South Africa. The platinum production also dropped between 2006 and 2008. The personnel cost increases between 2010 and 2012 also show an impact on the South African share of the international platinum market. South Africa remains the largest producer of platinum in the world; however, the volume has dropped from 77% in 2009 to 72% in 2012. With rising personnel costs and the decreasing market share for the South African platinum industry, further cost savings have to be investigated and implemented. [1.12]

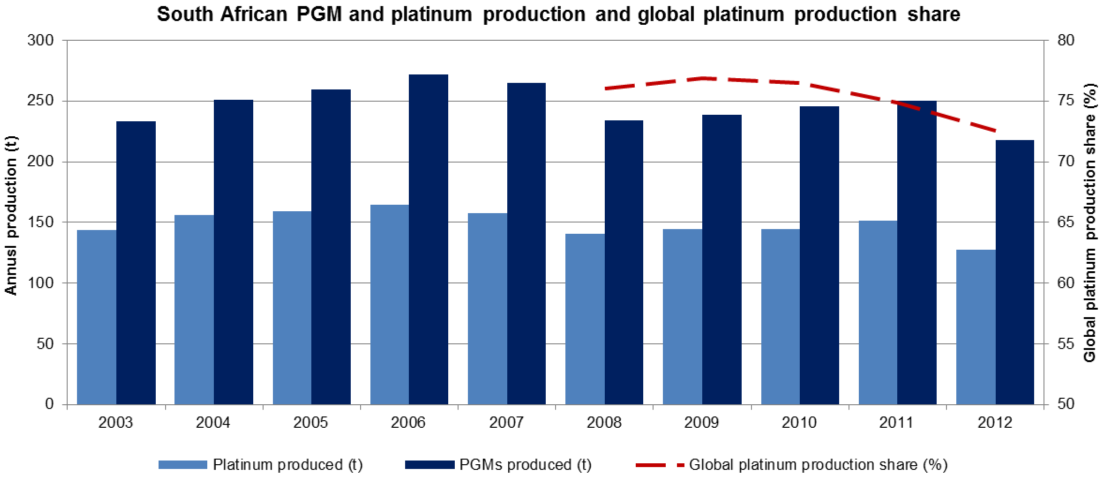

Figure 1-6: South African PGM and platinum production and global platinum production share [1.12]

Energy costs in the platinum industry shows large potential for cost saving. Possible energy-saving projects should be implemented to limit the ongoing loss of international market share and downscaling of South African platinum mine personnel numbers.

1.1.3 CEMENT PRODUCTION

In 2012, South Africa had a cement production capacity of 18.8 million tonnes per annum, although only 70% of this capacity was utilised in 2009 and 2010 [1.13]. The country produces cement from 19 plants, with a further three facilities scheduled to start production by 2015 [1.14]. Modern cement plants consume approximately 100 kWh electricity per tonne of cement produced [1.15], and the reduction of this figure is one of the key areas of research in cement production [1.16].

Cement is produced in a simple, energy intensive process. The process uses large milling machinery, varying in size and efficiency, to grind media to very fine powders in both raw material milling and cement finishing milling. These mills consume large amounts of electrical energy. Kilns are also used for *calcination*. These kilns consume energy obtained by the burning of fossil fuels, of which coal is the primary fuel used in South Africa. In addition to these components, various fans are used to induce draft in separators and coolers. Auxiliary compressors, pumps, transport conveyors, bucket elevators, blenders and packing equipment also consume electricity.

Figure 1-7 shows the sales figures for cement in South Africa. The cement sales showed a substantial spike in 2007, after which the sales decreased. 2011 showed a small rise in sales, which stayed stable in 2012. The South African cement industry consists of four major cement producers. These cement producers are Pretoria Portland Cement (PPC), Lafarge, AfriSam and Natal Portland Cement (NPC).

A fifth cement producer, Sephaku, has also entered the market, increasing market pressure further. With the increasing energy costs of both electricity and coal prices, and the reduced market size for cement in South Africa, operational costs also need to be reduced.

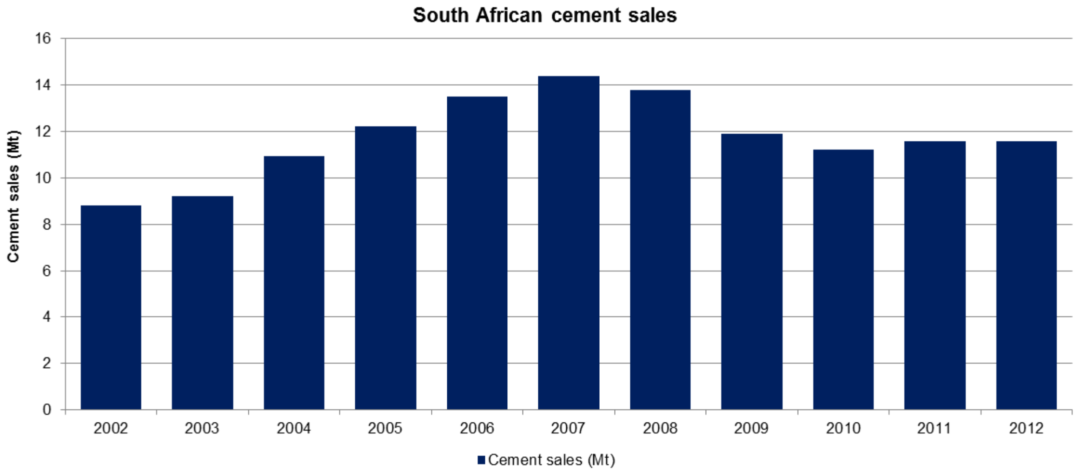

Figure 1-7: South African cement sales

1.2 ENERGY COST SAVINGS

Various methods of energy cost reduction are utilised in modern industry. Costs can be reduced by replacing or improving old or outdated components. These components include pumps, air compressors, cooling auxiliaries, heating installations and various other components - apart from well-known energy saving infrastructure that have been used for many years, such as horizontal kilns, compressor guide vanes and other new technologies. Literature discussing these energy consumption improvements are summarised in Table 1-1. Table 1-1 gives the energy improvement of the listed interventions or installations.

Table 1-1: Summary of literature regarding energy cost reduction by implementing component upgrades

Industry	Equipment	Authors	Description	Improvement (kWh/t)	Ref.
Cement	Renewables	Marimuthu et al.	Renewables - Wind		[1.17]
		Marimuthu et al.	Renewables - Solar		[1.17]
	Raw materials	Worrell et al., Madlool et al.	Efficient transport	2–3.4	[1.18],[1.19]
		Hasanbeigi et al.			[1.17],[1.20]
		Saidur et al.	Raw meal blending	1-4.3	[1.21]
		Hendriks et al.	Raw meal blending	1.4-4	[1.22]

Table 1-1 (continued): Summary of literature regarding energy cost reduction by implementing component upgrades

Industry	**Equipment**	**Authors**	**Description**	**Improvement (kWh/t)**	**Ref.**
Cement	Raw materials	Holderbank C.	VRM	6–11.9	[1.23]
	All mills	Salzborn et al.	Classifiers and separators	3.18–6.3	[1.24]
		Cembureau	Slurry blending and homogenizing	0.3–0.5	[1.25]
	Fuel preparation	Cembureau	VRM	7–10	[1.25]
	Clinkering	Lowes et al.	Improved refractories	*0.12–0.63 GJ/t	[1.26]
		Price et al.	VSD for kiln fan	4.95–6.1	[1.27]
Cement	Clinkering	Price et al.	Improved pre-heater	*0.08–0.111 GJ/t	[1.27]
		Bump J.A.	Grate cooler conversion	6.6	[1.28]
		Worrell et al.	Indirect kiln firing	*0.015–0.22 GJ/t	[1.18]
		Birch E.	Improved clinker cooler	*0.05–0.16 GJ/t	[1.29]
		Ahamed J.U.	Improved clinker cooler	*0.03 GJ/t	[1.30]
		UNFCCC	Low temperature heat recovery	*3.4 GJ/t, 35 kWh/t	[1.31]
		Price et al.	Efficient kiln drive motor	0.45–3.9	[1.27]
		Worrel et al.	Kiln precalciner conversion	*2.77-2.89 GJ/t	[1.32]
	Finish milling	Schneider U.	VRM for cement grinding	10–25.93	[1.33]
		Aydogan A.	Roller press for cement grinding	8–28	[1.34]
		Worrell et al.	HRM for cement grinding	*0.3 GJ/t	[1.18]
		Parkes F.F.	Classifiers and separators	1.9–7	[1.35]
		Worrell et al.	Improved grinding media	1.8–6.1	[1.18]
	General	Vleuten F.	High efficiency motors	0–25	[1.36]
		Nadel S.	VSD on fans and coolers	0.08-9.15	[1.37]
		UNFCCC	High efficiency fans	0.11-0.7	[1.31]
Mining	General	Vleuten F.	High efficiency motors	0–25	[1.36]
	Air supply	Dindorf R.	PRV	8%	[22]
		Dindorf R.	Replace compressors	7%	[1.38]
	Cooling	Du Plessis et al.	VSD on pump	19.40%	[1.39]
	Comunition	Worrell et al.	Improved grinding media	1.8–6.1	[1.18]

Energy improvement shown in J/t

The payback period of the considered physical component improvements for energy cost savings are extended [1.40]. Apart from the payback periods, component upgrades require production downtime for installation [1.41]. A further solution that reduces energy costs is operational optimisation.

V.K. Batra *et al.* [1.42] states that implementing the most advanced technologies does not alone ensure optimal cost of operations, but needs to be combined with sound operational practices to achieve minimal production cost. Operations planning and optimisation can reduce energy costs, but complex production systems make this a difficult task. A possible solution is to automate the planning of operations by using operations modelling. This can be achieved by implementing an Energy Management System (EnMS) with integrated operations modelling as core.

Operations modelling provide an instantaneous solution to reducing energy costs [1.43]. Although operations modelling do not ensure that the industry constantly remains competitive, it still provides the opportunity for further physical upgrades by achieving cost savings. Altering control strategies have been shown to improve costs allocated to energy [1.44]. These energy consumption interventions require no production downtime and have also been shown to reduce the payback period of the cost improvement initiative. In the considered cases, this proves to be a better solution to a certain extent (excluding extensive facility capacity increases).

1.3 ENERGY COST REDUCTION BY ALTERING OPERATIONAL PRACTICES

The South African utility bills clients according to a TOU tariff structure. The MegaFlex tariff structure is a good example of how TOU is implemented in practice. The energy costs of the MegaFlex structure is charged as different rates for different periods of the working week. These rates are categorised as Off-peak, Standard and Peak. The time allocation of these different tariff periods is shown in Figure 1-8.

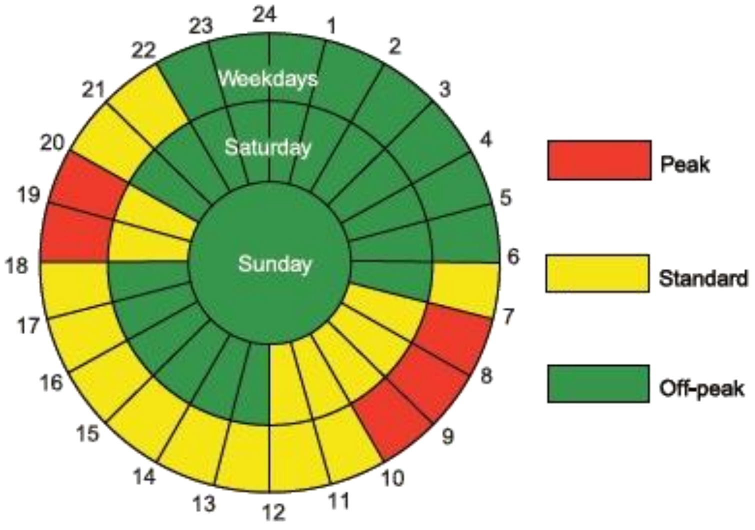

Figure 1-8: Eskom MegaFlex TOU tariff periods

The tariffs are also adjusted for seasonal fluctuations in national electricity demand. The tariff periods are divided into high demand season and low demand season. June, July and August is categorised as high demand season, during which the tariffs for Off-peak, Standard and peak periods are increased from the rest of the year which is categorised as low demand season. The 2013/2014 MegaFlex costs are shown in Appendix A to better define the influence of time-of-day on the cost of electricity.

Altering operational practices, when effectively applied, improve the cost allocated to energy. The impact of these interventions is subdivided into three basic strategies. These strategies are energy efficiency improvement, load reallocation/shift, and in combination, peak load reduction or peak clipping. Energy efficiency improvement reduces energy consumption without preference to time period. An example of the results recorded during an energy efficiency improvement intervention is shown in Figure 1-9 a. [1.45]

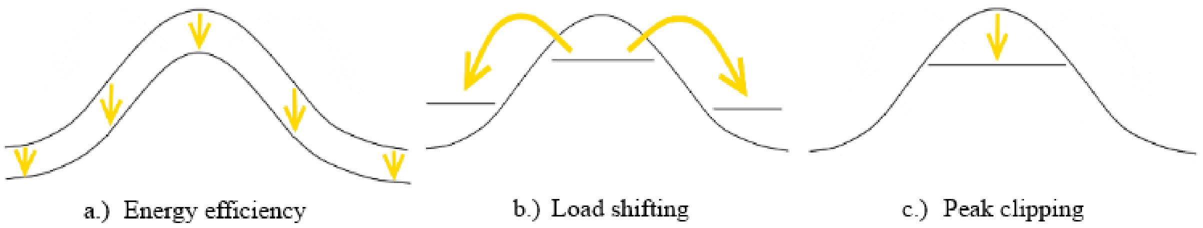

Figure 1-9: Results of an energy efficiency intervention [1.45]

Time-of-use (TOU) electricity tariffs present the opportunity to reduce costs by reallocating production times. Operating during less expensive time periods instead of expensive peak electricity demand periods will reduce electricity costs. There are two factors that determine the feasibility of a load-shift operations intervention. These factors are operational or production redundancy and excess buffer capacity. An example of the results of a load-shift intervention is shown in Figure 1-9 b. [1.45]

Combining energy efficiency improvements with load-shift interventions produce a peak clip intervention. This can be as a result of energy efficiency improvement during a specific time period of a TOU tariff structure, or an improvement of facility capacity (specific energy consumption improvement) and using created reserve capacity to reduce peak period operation. The results of a peak clip intervention are shown in Figure 1-9 c. [1.45]

The discussed operational intervention strategies present cost reduction opportunities. Implementing these interventions takes place in different forms. Manual intervention by dedicated personnel shows improvement, but however, poses optimising and sustainability restrictions. Miscommunication between planning and operational personnel has been shown to reduce savings achieved. Additionally, this requires expert personnel, who are not freely available, for implementation. Manual interventions have also been shown to creep with time, deviating from optimal savings.

The three mentioned industries, gold mining, platinum mining and cement production, will be used as case studies in this thesis. A new operations modelling approach will be implemented on specific installations in these three industries.

1.4 PROBLEM STATEMENT

Most literature steers research towards the modelling of specific applications, instead of widening the analysis for generic or global application on various systems. Modelling specific scenarios generates accurate results; however compiling a generic modelling method simplifies application and makes large-scale implementation possible. The challenge is combining the two approaches: generating a generic model that accurately describes the system being modelled *and* supplying the information necessary to make sound operational planning decisions.

Literature investigates different building blocks for effective operations modelling. These building blocks are, however, developed for specific applications. Additionally, these building blocks are not applied in real time to automate operations planning. Combining multiple components is also a topic requiring further investigation. Combining multiple components in series and in parallel, including buffer capacities, may improve variability in the calculated solution, in turn increasing possible savings that can be achieved. Literature also describes discrete and aggregated scheduling approaches; however the suited applications and combined solution are not investigated.

Multiple plants and varying component characteristics make the compilation of application specific operations models a time-consuming task. A limited number of skilled personnel also restrict the number of modelling projects that can be initiated. This thesis aims at developing a generic operations model that can simulate various types of applications and different industrial installations. The model must be duplicable for new project implementations by less knowledgeable personnel. The model must be capable of simulating and forecasting operations for different horizon spans. It should incorporate various cost components, whilst taking mechanical operation constraints into account (including *availability*, *reliability* and *utilisation*).

1.5 GOALS AND CONTRIBUTIONS

Automating the scheduling of components has various advantages. Operations models can however be refined to focus on specific interests, such as maximising availability, minimising cost or improving personnel planning. This thesis will discuss the implementation of a modelling method that will achieve selected advantages to best resolve the problem statement. A goal statement will identify the specific areas that will form the main focus of this thesis. The goal statement will form the starting point for solution development in the research and also accurately validate the results. The goal statement is as follows:

Goal statement:

Develop a generic model (1) that accurately describes the system being modelled, supplying the information necessary to make sound operational planning and system settings decisions (2) on a frequent to constant basis and in real time, (3) focussing on real-world application (4).

1. *Develop a generic model*;

   Production systems and different industries use a multitude of different processes. As a result it is difficult to generate a generic modelling system. The goal of the global solution to modelling is to enable less knowledgeable personnel to implement an operations optimisation intervention to generate a feasible and effective solution. A generic model is thus not investigated, but a simplified global approach to generating a system model is compiled. This approach provides so-called *building blocks* in generic form, with which a system operations model can be generated.

2. *Accurate and comprehensive*

   Another research goal is to make modelling applicable. The gap between scientific analyses of systems and operating personnel discourages the implementation of operations modelling in day-to-day operations planning. It is thus imperative that the simplified system provides accurate results. Accurate results in simplified form will motivate personnel to apply these techniques and will ensure that modelling and forecasting become a valuable tool in managing operations and reducing operational costs.

3. *Frequently and in real time*;

   Present modelling techniques are used in consultation. Though effective, these sporadic and singular optimisation events do not provide an optimal for a constantly fluctuating environment. Most implementation examples present an environment of fluctuating demand, costs and market values. It is necessary to provide an optimal solution each moment one of these factors varies, i.e. constantly. In addition, this solution needs to be provided in time in order for personnel to make sound decisions when they are applicable – in real time.

4. *Focussing on real-world application*;

   All of the mentioned factors and considerations focus on one key element: real-world feasibility. The goal of operations management interventions is cost savings, which can only be achieved with successful, real-world implementation. The modelling techniques are generated by analysing real-world systems; management theory is developed; and real-world systems operation is altered to generate cost savings. Deductively, instead of a theory-to-application approach, an application-to-theory-to-application approach is followed.

Should an operations model effectively attain the four aims as set out by the goal statement, the compilation of a site-specific model will be simplified and larger operational costs will be achieved by integrating more than one component in the operations model and by updating the optimal solution in real time.

Original contributions:

The study goal focusses on four areas where literature seems to be incomplete. These areas form the primary focus of the solution development and the implementation as described in this thesis. The original contributions are as follows:

Different production constraints, multiple components and plants are combined in one model:

- Current modelling techniques focus on specific design or operational challenges (i.e. fluctuating electricity costs, production demand fluctuations, raw materials costs, facility production bottle necks and buffer constraints).
- Multiple components with different operational constraints, such as kilns and grinding mills, or parallel lines with different cost characteristics are common in real world systems.
- Real-world systems present more than one contradicting operational challenge. These challenges need to be compared to derive a global optimal point of operation.
- Considering more than one component or facility is required to optimise production and to generate an all-inclusive minimum production cost.

A new model is developed that combines all of the mentioned production challenges to generate a simultaneous, global optimal production schedule for a multiple component system.

A flexible simulation technique that can accommodate long periods of time, frequent production demand fluctuations and new applications:

- Long periods of time are not considered in scheduling of operations.
- Extended simulation horizons are necessary to account for weekly- or seasonal TOU tariffs and varying raw material costs to minimise annual expenses.
- Due to a more competitive and rapid market changes, adaptable simulation techniques are becoming more important.
- Present simulations are generated for specific applications to analyse a specific problem, i.e. a transport shortfall, a bottleneck in production or a specific storage silo volume management.
- Production personnel plan stock levels and production in response to market fluctuations. Thus rapid demand changes are not considered.
- Simulation methods are not dynamically flexible to account for demand fluctuations, time analysis variations and multiple applications.

A new simulation technique is compiled that is flexible to account for dynamic variables and constraints, multiple timelines for different industries and multiple layouts of industrial plants.

Simple optimisation algorithm that can be applied to real-world problems:

- Presently, the optimisation of schedules or set-points on industrial machines are done using basic mixed integer linear program, mixed integer non-linear programming or constraint programming.
- The current solutions and optimisation methods remain complex and as a result are not implemented in day-to-day planning in industry.
- Most day-to-day operations schedules are compiled with little regard given to a global optimum cost.
- Production planning personnel use their experience to schedule operations, which does not necessarily account for most optimal operations.

A new optimisation algorithm is presented that includes all cost factors. It produces a production schedule that is simple to implement on real-world industrial systems.

Combination and application of operational best practices:

- Operations at different production- or processing facilities are planned by on-site personnel.
- Each sub-section related to the planning of operations is managed by a separate person or department (i.e. production, maintenance, raw materials acquisition and sales).
- Very little communication and development of best practices are done between production planning personnel.
- As a result, most plants plan operations according to set constraints and do not apply industry best practices.

The new planning approach compiles plant production schedules that include the best practices and planning techniques to minimise operational costs.

1.6 SCOPE OF THE STUDY

This thesis will generate a modelling method that can be used to analyse the operations of different industries. The modelling method will be implemented on these industrial installations by using automated software and networked systems. These systems will be described, but not investigated in detail in the thesis. The modelling method will be developed; however, the programming thereof will not be discussed in detail. Formulae and algorithms for the effective analysis will be developed that can be incorporated into different software packages to simplify the application in different industries.

The model will not incorporate possible stops for product change-overs. The change-over stops are in most cases conducted by plant personnel and are well implemented. Larger savings can be achieved by longer-term operations planning, buffer- and production planning. The start-up costs of major equipment will however, be included in the analysis, as this will have a large influence on the feasibility of the generated schedules and settings feedback. The simulation feedback will be simplified to make the implementation of the solution easy for less knowledgeable personnel.

Though the model is targeted at reducing energy costs, different costs associated with operational planning will be included. These additional costs are raw-material costs, transport costs and inventory costs. Risk is also considered and included in the schedules and storage volumes. Base loads and overhead costs will also be included when comparing components in parallel. A statistical approach is followed to incorporate reliability and other maintenance considerations in the longer term analysis. The maintenance schedules will also be incorporated in the discrete analysis of the operating schedules.

Systems associated with the production line and the production stream in the different industries will be analysed. The services and supporting systems will be included with relevance. Auxiliary systems in mines have been assessed with effective results, and have little influence on the production stream, apart from critical failure. An example of these components is dewatering pumps and compressors in mining. These systems are analysed separately, as they do not have a direct influence on production volumes, however critical failure of these components will cause mining to halt.

The different components present in the different industries that are considered will be used to generate the modelling methods. The model is developed with practical implementation as aim, and thus the model is not derived from design principles, but operational (practical day-to-day) analysis. The thesis is subdivided to report on a literature review, solution development and results obtained when implementing the solution. The layout of the thesis is further described in the following section.

1.7 LAYOUT OF THE THESIS

Chapter 1: Introduction

Chapter 1 introduces the study and identifies a shortfall in present literature. The shortfall is described in a problem statement. A goal statement is developed that best solves the problem statement. The scope of the study is compiled and the layout of the thesis is summarised.

Chapter 2: Literature review

In Chapter 2 the relevant literature on operations modelling will be summarised. A summary table, including published work regarding the modelling and scheduling of different processes will be compiled. From this table the state-of-the-art will be identified and used to improve the solution that will be developed in chapter three.

Chapter 3: Solution development – modelling components

The solution development will be subdivided into two categories. The first of these categories will describe how the industrial components will be defined in modelling form. It will describe a unique approach to analysing process and buffer components for batch- and continuous processes.

Chapter 4: Solution development – time analysis

Chapter 4 will continue the solution development by describing how the new modelling components will be analysed over time. Different time periods, analysed in aggregate and discrete time intervals, will be used to reduce the processing requirements of the system.

Chapter 5: Implementation and results

The implementation of this method for three different applications will be described in Chapter 5. This description will include the results of the implementation in the form of savings achieved over extended periods of time.

Chapter 6: Conclusions and recommendations

Chapter 6 will test the results of the implementation to the original hypothesis and draw a conclusion as to the success of the new approach. Advantages and shortfalls will be described, from which recommendations for further study will be made.

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CHAPTER 2

Literature Review

Chapter Two

In chapter two the relevant literature on operations modelling will be summarised. A summary table, including published work regarding the modelling and scheduling of different processes, will be compiled. From this table the state-of-the-art will be identified and used to improve the solution that will be developed in chapter three.

2 LITERATURE REVIEW

2.1 PREAMBLE

Energy costs are increasing at a rapid rate. The reduction of cost is imperative for competitive trades and forms a large research area in global industries. A lot of research has been done to improve the cost allocated to energy. Automating the scheduling of operational practices is an effective way of reducing energy- and operational costs.

2.2 AUTOMATING OPERATIONAL PRACTICES TO IMPROVE ENERGY COST REDUCTION

A proven solution to prevent less-than-optimal achieved savings is operational intervention automation. Different levels of intervention automation have been implemented, varying in implementation complexity and success. The simplest form of intervention automation is to use electrical relays to switch off key components during more expensive peak periods in the case of load shifting. Altering settings on major components, such as compressors or supply valves, have also shown energy cost improvements.

These automation methods are simple; however they limit the flexibility of the solution. Most industries are subject to varying constraints and operational parameters. These varying factors include production demand and natural fluctuations, such as rainfall or temperature. In this case, altering the intervention set points will improve achieved savings. This can be done by applying a control system that uses these fluctuating parameters, such as buffer levels, as control variables.

Control systems extracting data from the existing programmable logic controller (PLC), or supervisory control and data acquisition systems (SCADA), will improve the flexibility of the intervention. However, setting up a control strategy, even when these control parameters are available requires an accurate modelling method. Simple modelling methods, such as the use of control ranges with TOU prioritising, are effective but also limit the total achievable savings. The savings limitation is accredited to basic logic restrictions. Only a set number of components can be considered and controlled in accordance with singular control variables. In compiling an integrated solution, considering more than a single parameter can be done by compiling a more versatile modelling method.

2.3 OPERATIONS MODELLING

Many forms of operations modelling are available in literature. The different techniques are developed for different applications and can be used with varying accuracy. Firstly, the improvement of a control setting can be done by considering various control variables. A good example of this implementation is an *advanced process control* (APC) system that is implemented on milling components in the cement industry. APC systems focus on single components and ensure that these components operate at optimal settings that improve the efficiency. This efficiency improvement may occur in the form of an energy efficiency improvement – reducing the electrical load required for milling, or a federate improvement which increases idle time and can be used to implement a peak clip intervention [2.1].

An APC uses multiple variables to alter a specific control set point. In the case of cement grinding circuits, the control set points, or *Manipulated Variables* (MV), are fresh feed rate controlled by a belt feeder VSD, separator speed and the separator airflow controlled by a fan with an altering damper. To control these set points, the APC monitors multiple variables, including the grinding efficiency, the total mill through-put, the final product quality and the grits, or over-size particle return to the mill input. The different variables are shown in simple form in Figure 2-1 [2.1].

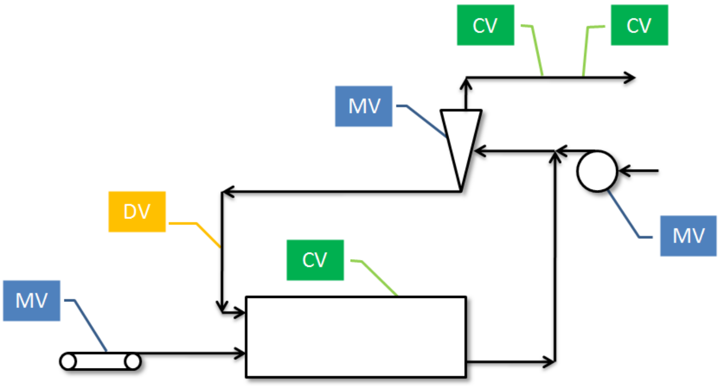

Figure 2-1: Advanced process control description for APC at cement milling circuits [2.1]

Different APC systems use personalised algorithms to calculate the control variables. The control variables are implemented with PLCs and PID control. Due to the implementation complexity, the set-up of these controls is executed by specialised personnel. Apart from the specialised personnel that are required, the APC also only focusses on a single component and does not consider more than one component. In a system of interdependent production components, the influence that these components have on each other needs to be considered to optimise savings when controlling the equipment.

The contractors who install these systems also charge extensively for this form of operations optimisation. Though these interventions are effective, the sporadic nature of the optimisation (a single initial consulting event) also reduces the sustainability of the savings that are initially reported. Varying characteristics, such as grinding media wear, input product hardness and abrasiveness and multiple other influences, reduce the accuracy of the control with time. This forces industries to undertake maintenance contracts with the contractors who supply these solutions, in turn costing the clients more, also reducing net savings.

Further examples of this control variable optimisation are summarised in Table 2-2.

Table 2-1: Summary of literature regarding modelling methods for operational cost reduction

Industry	Equipment	Authors	Description	Improvement (kWh/t)	Ref.
Cement	Raw materials	Martin G. et al	VRM process Control	0.8–1.0 kWh/t	[2.2]
	Clinker production	ETSU	Kiln process control	2.35–5 kWh/t	[2.3]
		Jarvensivu M. et al.	Kiln process control	7%	[2.4]
		Stadler K.S. et al.			[2.5]
		Ahamed J.U.	Kiln process control	*0.03 GJ/t	[1.30]
		Lauer D.	Finishing mill process control	1 – 4.2 kWh/t	[2.7]
Mining	Cooling auxiliaries	Du Plessis et al.	Cooling systems flow regulation	31.50%	[2.8]
		Du Plessis et al.			[2.9]

***** *energy consumption improvement not directly related to electricity consumption*

Production or auxiliary components operate in a system of interdependent sub-components. Though these components can be optimised in singular form, as discussed in Table 2-1, considering the system of interdependent components in unison will generate a larger intervention impact. Examples of modelling methods in which more than one component are integrated in a global solution are shown in Table 2-2.

Table 2-2: Summary of literature regarding modelling methods for integrated component optimisation

Industry	Equipment	Authors	Description	Shortcoming	Ref.
Mining	Pump network	Vosloo et al.	Integrating water network control	Focussed on mining water network, not applicable to other industry	[2.10]
	Cooling auxiliaries	Du Plessis et al.	Integrating cooling auxiliary control	Focussed on mine cooling systems	[2.9]

Vosloo *et al.* describes an operations optimisation strategy on the water reticulation network of an ultra-deep South African gold mine. The objective of this optimisation was to minimise electricity costs for the entire network. Though this optimisation proved that larger energy savings can be achieved by considering an interdependent system instead of single components, the system that Vosloo et al. proposed showed limitations due to lack of solution variability.

Vosloo *et al.* states that, by simulating the flow circumstances throughout the mine, including cooling systems, turbine pumps and dam levels, the mine water-reticulation network can be optimised for energy cost. However, only electricity cost was considered. Additionally, the system was developed specifically with a water reticulation network as case study. Using this control strategy on other systems will not be possible. The variability of the control strategy is also limited, as the system only implements a set of predetermined flow parameters. When these parameters fluctuate, the solution will deviate from optimal cost optimisation [2.10].

As seen with Vosloo *et al.,* the interventions described in Table 2-2 are effective. However, they are application-specific. Compiling one of the mentioned interventions require extensive research and system analysis also executed by expert energy management personnel. Simplifying the methodology used during these analyses, and widening the application to different industries will satisfy the goal statement generated in Chapter 1. Automating the *modelling and simulation* of an integrated system of components, and not limiting the automation to control an implementation of a pre-calculated set of control variables, will increase savings.

Modelling approaches have been published in literature. These modelling approaches describe implementation on plants. These approaches are however not suited to mass implementation and form short case studies to validate the research. Examples of different modelling approaches are described in Table 2-3.

Table 2-3: Modelling approaches that combine multiple components

Authors	Description	Shortcoming	Ref.
Castro P.M.	Aggregate modelling of multiproduct continuous parallel milling components	Limited flexibility, aggregate approach	[2.11]
Mendez C.A.	Review of batch modelling techniques	Limited to batch process modelling and design	[2.12]
Mitra S.	Discrete modelling using MILP for TOU tariffs and DR	Short production periods, limited system boundaries	[2.13]
Rodriguez M.A.	Supply chain planning under uncertain demand constraints	Focusses only on supply chain	[2.14]

Harjunkoski *et al.* (2014) [2.15] reviews all modelling methods used in modern production scheduling. This publication summarises the different approaches and methods of solving and scheduling various processes. Harjunkoski *et al.* proposes methods of identifying the modelling method by analysing a specific system of components and generating the algorithms required to implement this solution [2.15]. The implementation of these systems required skilled personnel and time-consuming system analysis. This limits the mass implementation on various systems of components.

Harjunkoski *et al.* (2014) [2.15] proposes a strategy to address operations planning problems. Firstly the system is analysed and operational information is gathered. Most problems are assumed to be linear, unless time-dependent or constantly varying influences are present in the system, in which case the problem is assumed to be non-linear. The production systems are subdivided into two different analysis approaches. These approaches are allocated to sequential and network production environments [2.15].

Sequential production environments are typically facilities that process a single batch of product fluid or unit through multiple sequential production stages. An example of this production environment is vehicle production, or other manufacturers, like bottling industries and brewing. Production stages are executed by a single machine or piece of equipment with multiple functions, or a series of consecutive machines/stages with respective production tasks. The sequential environments are investigated by representing the environment as a standard network from where a continuous-time representation of either precedence-based or multiple time grids are used [2.15].

A network production environment represents processes where continuous product flow is present. This product can be a continuous fluid stream, or a batch that is mixed, homogenised, processed or split into multiple streams. Examples of network production environments are cement production, iron production, metals refining and mining. A network production environment is represented by either a *Resource Task Network* (RTN) or a *State Task Network* (STN), from where the problem is analysed in one of the following: discrete-time with a single uniform grid; discrete time with multiple non-uniform grids; continuous time with unit-specific grids; or continuous time with a single time grid [2.15].

Once the problem has been identified and quantified by using the best-suited analysis, the indices, variables and parameters of the system are specified. Indices represent all resources, time slots, tasks and demand points. Variables include allocated assignment to the equipment, timing and various production settings. Parameters describe production rates, time horizons, due date and required delivery volumes [2.15].

The most common solution methods to scheduling or operations problems are *mixed integer linear programming* (MILP) and *mixed integer non-linear programming* (MINLP). To reduce computing complexity, most MINLP solutions are reformulated to MILP solutions by approximating linearity or considering piecewise linear regions. An example of this is an environment with TOU electricity tariffs, where each tariff period is considered to be linear. Other solution methods include *constraint programming* (CP), heuristic and meta-heuristic methods. In many specific applications, hybrids of solution methods are used to accuracy and processing capacity [2.15].

2.4 OPERATIONS MODELLING SOLUTION METHODS

Solutions to operations modelling techniques present simple MILP analyses. Various authors have published research focussing on solving scheduling problems in both batch and continuous processes. The results obtained from the research show promising results; however, each application focuses on a single outcome. The different outcomes and solutions methods are summarised in Table 2-4. Most of the analyses also present theoretical solutions, where the application to real-world systems forms a small part of solution verification.

Table 2-4: Modelling approaches for schedule using MILP and MINLP approaches

Authors	Description	Shortcoming	Ref.
Méndez C.A. *et al.*	MILP for short term schedule of single stage batch plants	Limited to batch problems, limited to short term scheduling	[2.16]
Méndez C.A. *et al.*	MILP for continuous-time for short term scheduling for batch plants	Limited to batch problems, limited to short term scheduling	[2.17]
*Méndez C.A. *et al.*	MILP for continuous-time for short term scheduling for continuous plants	Limited to continuous problems, limited to short term scheduling	[2.18]
Aguirre A.M. *et al.*	MILP for AWS scheduling	Aimed specifically at AWS scheduling	[2.19]
Westerlund J. *et al.*	MILP for multidimensional allocation	Theoretical approach, not focussed on practical application	[2.20]
Roe B. *et al.*	Hybrid MILP/CLP for multipurpose batch scheduling	Theoretical approach, not focussed on practical application, focussed on batch scheduling	[2.21]
Scott F. *et al.*	MILP for process alternative selection in lignocellulose bioethanol production	Specific application, not suited for other implementations	[2.22]
Jianyu W. *et al.*	General MILP for batch process with sequence dependent change-overs	Specific application, limited to batch problems	[2.23]
Mao K. *et al.*	Langrangian relaxation approach for hybrid flow shop scheduling	Specific application to the steelmaking-continuous casting process, not applicable to other industries	[2.24]
*Behdani B. *et al.*	Scheduling of integrated batch and continuous process systems	Specific application, not applied to various industries	[2.25]
Sun L. *et al.*	Mixed schedule optimisation for steelmaking-continuous casting process	Specific industry application	[2.26]
Hadera H. *et al.*	MILP with energy price-related optimisation and demand side management	Specific model for steel making applied during consultation	[2.27]

Table 2-5 (continued)**:** Modelling approaches for schedule using MILP and MINLP approaches

Authors	**Description**	**Shortcoming**	**Ref.**
Shrouf F. *et al.*	Optimisation of single machine for day-ahead energy costs	Single machine, not integrated system, short term scheduling	[2.28]
Yuan-yuan T. *et al.*	Mathematical scheduling approach for steel making with varying electricity cost	Focussed specifically on steel making industry	[2.29]
*Engell S. *et al.*	Integrating operational scheduling and advanced control	Focusses on review of technologies, no practical results	[2.30]
Chen C. *et al.*	Resource task approach to short term scheduling of thermal batch plants	Focussed on thermal batch process	[2.31]
*Neumann K. *et al.*	Scheduling of batch and continuous processing in an integrated system with storage	Theoretical, not applied to physical systems	[2.32]
Castro P.M. *et al.*	Scheduling in strip packing problems	Focussed only on strip packing	[2.33]
Yuceer M. *et al.*	Semi-heuristic to convert MINLP to MILP	No large scale industrial application, no energy constraints	[2.34]
Rejowski R. Jr. *et al.*	MINLP for multiproduct pipeline system	Single component (pipeline) optimisation for target supply volumes	[2.35]
Klanšek U. *et al.*	MINLP optimisation for a time-cost trade off	Not applied to operations planning	[2.36]
*Sahinidis N.V. *et al.*	MINLP for multiproduct parallel continuous lines	Not applied to cost optimisation, only parallel lines were considered	[2.37]

***** *Discussed in text according to problem relevance*

Méndez C.A. *et al.* [2.18] moved away from the traditional batch process modelling to model a continuous system, as encountered in the consumer goods industry. He considers a plant with multiple continuous components in parallel with limited storage volumes, with minimum demand for the final product and with a pre-determined scheduling horizon. The aim of the published research was to optimally schedule processes of the different products to optimise the total production. Using product balances and storage constraints an effective MILP was set up to solve the scheduling problem [2.18].

Méndez C.A. *et al.* [2.18] started by identifying system constraints and parameters. A STN description of the process was used to describe the different tasks that were implemented and the link characteristics of the production system. A total of 15 different products were produced, using three parallel mixers producing seven intermediate products. The mixed products were then sent to either three storage containers, or directly to five continuous packing machines. This process provides similar constraints to the three considered industries.

Méndez C.A. *et al.* [2.18] reported an improvement in schedule effectiveness and also showed a reduction in processing requirements. The presented model did not, however, optimise the result for operational costs. Additionally, the solution was aimed specifically at solving the considered problem, and will not be duplicable to other processes. The result was also not automated and does not consider natural fluctuations in production demand on a constant basis. The generated solution may therefore deviate from optimal operation with time, indicating a loss in sustainability of the proposed solution. Logistic tasks and transport costs between processes were also not considered.

Behdani B. *et al.* [2.25] presented a novel approach to developing an operations model. The research proposed combining different forms of modelling to generate a more effective and widely-applicable modelling approach. The solution is also ideal for developing schedules for industries that include sales and energy constraints in the considered systems. The modelling approach does not consider the optimal cost of operation, which forms the primary focus of this thesis. Simply limiting the energy consumption to a *Notified Maximum Demand* (NMD) will not optimise component scheduling for energy or operations *cost*.

Engell S. *et al.* [2.30] published literature that describes the modelling of a system and combines this with system control to develop an effective intervention solution (similar to Du Plessis et al. [2.9]). Though this is where this thesis aims as a solution, Engell S. *et al.* [2.30] does not describe in detail how this method was applied to real-world systems. Implementation is imperative to obtaining results, which Engell S. *et al.* [2.30] identified. However, the research did not develop a modelling technique that is focussed on simplifying the scheduling and integrated control.

Neumann K. *et al.* [2.32] also presents a sound modelling technique that incorporates buffer volumes into the scheduling of different components. This makes it possible to more accurately simulate system response to operations planning. It also combines all the different processes in the considered system, either batch or continuous and integrates the total approach. This method does however not consider operational cost reduction and optimisation and unlike Engell S. *et al.* [2.30] does not integrate the modelling technique with a real-world system for real-time continuous application.

Focussing on real-world applications will present large-scale implementation to reduce operational cost. The theoretical approaches, though sound, remains complex for less knowledgeable personnel to implement. The mentioned personnel have a detailed understanding of the physical plants or systems that they manage; however, considering complex mathematical approaches to solving scheduling tasks are tedious. Modelling complexity of the theoretical approaches forces personnel to resort to tried and tested methods, either using Excel or simple manual calculations. Commercial planning and scheduling software packages have been developed to simplify interventions for plant personnel.

2.5 COMMERCIAL OPERATIONS MODELLING SYSTEMS

Commercial packages have been developed that use MILP and MINLP to solve scheduling or operations management tasks. These systems, however, also require expert personnel for operation. These systems also present limited capabilities and flexibility. Similar to reviewed literature, the software systems also move towards specific applications, focussing on specific industries or problem sets. A widely-applicable simulation approach is required that simultaneously simplifies the model compilation and is widely applicable to multiple problem sets or industries.

Table 2-6: Commercial modelling packages that are used for scheduling problems

Authors	Description	Shortcoming	Ref.
ARC Advisory Group	Schneider process control and planning	Specialist consultation for industry specific solutions, process control as focus	[2.38]
Advanced Process Combinatorics	Advanced Process Combinatorics automated scheduling	Limited optimisation capabilities, not focussed on operations cost, unless specifically programmed	[2.39], [2.40]
Aspen Technology	Aspentech process scheduling	Limited optimisation capabilities, focusses on steady state conditions	[2.41]
Asprova Corporation	Asprova APS customised production scheduling	Limited optimisation for production cost integration	[2.42]
Infor	Infor planning for intime performance improvement	Limited to performance improvement and not focussed on global cost reduction, intricate implementation	[2.43]
Intellegen INC.	Intellegen finite batch process schedule planning software	Does not consider continuous systems	[2.44]
OM Logistics Ltd.	OMPartners logistics planning	Focussed on logistics planning, consultation focussed	[2.45]
Optisol	Optisol scheduling software for high-variety custom production	Highly customised and consultation based, intricate implementation	[2.46]
ORSOFT	ORSoft, integrated SAP for production scheduling	Consultation based and high capital expenditure	[2.47]
ORTEMS	Ortems scheduling solution with flexible production targets	Optimisation limitations, intricate implementation	[2.48]
Preactor International	Preactor process planning software	Optimisation limitations, steady state analysis	[2.49]
Quintiq Inc.	Quintiq flexible scheduling software	Large capital expenditure, extended implementation times	[2.50]
Taylor Scheduling Software Inc.	Taylor real time scheduler	Focussed on timing, effective operations but not cost optimisation focussed	[2.51]

The commercial modelling and simulation packages each have unique strengths and focus areas. The modelling packages are ideally suited to specific industries and application to specific processes. A good example is the Aspen Technology process scheduling.

Aspen process scheduling is a widely used software package with extensive capabilities; however, the software focusses on steady-state analysis that limits the application to fluctuating or dynamic systems. Additionally, the software is developed for the analysis of a system, and presents limited real-time analysis capabilities. Aspen HYSYS Dynamics™ provides the analysis of a dynamic environment; however, it remains focussed on system analysis and not real-time control. [2.41]

Taylor scheduling software, in contrast with Aspen, is available for real-time application. Real-time application is however, cumbersome and is applied by contracting companies, which increases the cost expenditure. The Taylor scheduling system focusses on effective operations scheduling, which is ideal for identifying possible bottlenecks in a process system and reduces unforced shut-downs. The scheduling system, however, presents limited cost optimisation capabilities, which are essential to keep marginal industries competitive. [2.51]

The listed modelling packages also move towards specific applications to specific industries. The modelling suppliers also set up and customise the modelling suites specifically for client needs. This reduces flexibility in applications and is also costly to implement. Fixed software packages also limit the customisable flexibility for application in different industries [2.15].

2.6 APPLICATION TO REAL-WORLD SYSTEMS

Swanepoel J.A. *et al.* [2.52] developed a modelling system to simulate the operations of a cement plant. The operations optimisation package was implemented with great success on various cement plants; however, the modelling package was not described by the author. The automated system for acquiring operations data and continually updating modelling parameters show a lot of promise and provide the foundation for implementing an operations scheduling model.

Multiple tests have also been done in industry, as summarised by Harjunkoski *et al.*, however these also form case studies to test the theoretical approach to schedule- and operations planning [2.15]. Operations planning or scheduling literature steers research towards the modelling of specific applications. The implemented projects are also sporadic and do not account for continuously fluctuating market variables, such as sales demand and availability of raw materials. Modelling research also follow a theoretical approach. A theoretical approach remains essential; however, focussing on real-world practical implementation will ensure that these methods see the light of day.

Combining the automated intervention techniques used in Table 2-2 with the modelling techniques summarised in Table 2-3 and by Harjunkoski *et al.* [2.15] will enable mass implementation on multiple industries and multiple plants. Each of the modelling approaches poses strong building blocks. However, these building blocks need to be combined to create a flexible and widely-applicable solution. Implementing it with real time and instantaneous data communication will also keep these interventions sustainable and approach the close-to-optimal operations cost with existing components.

Regarding modelling, Harjunkoski *et al.* presented a summary of the state-of-the-art modelling methods for industrial production scheduling in 2014 [2.15]. The article concluded that many recent developments have proven successful; however, computational complexity and cost of implementation remain constricting challenges during implementation of these methods. Harjunkoski *et al.* also added that many different types of modelling are suited to different scheduling problems, but have to be developed specifically for the application. The adaption of a model without altering the core algorithms is required. Harjunkoski *et al.* states: "*Ideally, we would like to be able to build models such that they can be simply configured to new problems without touching the algorithmic core*" [2.15].

2.7 CONCLUSION

Chapter 1 showed that component upgrades and replacements are expensive. Operations scheduling is a solution with a lower initial capital expenditure. Integrating an entire system of components, instead of optimising a single component, will improve possible savings. Extending the platform from control automation to complete automation during modelling, simulation and implementation will increase the project sustainability and ensure constant optimal operation. The modelling method must be duplicable for different industries and applications without altering or recompiling the algorithmic core.

The problem statement will be resolved by re-evaluating the approach to modelling. Generating a model with the focus on mass implementation and industrial applicability instead of a theoretical-to-practical approach will generate larger operational savings. Secondly, when this modelling method is automated and implemented in real time, a flexible solution will be created that adapts to fluctuating system- and market constraints. The generated solution will thus also keep the implemented solution continuously optimal and sustainable.

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CHAPTER 3

Solution development – modelling components

Chapter Three

The solution development will be subdivided into two categories. The first of these categories will describe how the industrial components will be defined in modelling form. It will describe a unique approach to analysing process and buffer components for batch- and continuous processes.

3 SOLUTION DEVELOPMENT – MODELLING COMPONENTS

3.1. PREAMBLE

The solution development is subdivided into two categories. The first category considers modelling: how the physical installation is represented in a virtual environment on a computer. The second category considers simulation and optimisation: using the virtual representation of the plant to test operational scenarios over time and change these operational strategies to obtain the most cost-effective solution. Chapter 3 discusses the new modelling components that are generated, and Chapter 4 discusses the new simulation and optimised technique used for these new models.

A new modelling method is proposed that focusses on real-world mass implementation to systems. Though thorough and effective modelling techniques have been developed, as listed in Chapter 2, a new approach is investigated that develops a modelling method from the analysis of real-world systems. The solution is described in existing modelling terminology; however, these techniques are applied by using new methodology. The analysis boundaries and the considered components for the three considered industries are as follows:

Cement production

The components that are considered in the cement production process are the raw material stockpiles, the raw mills, raw meal/homogenisation silo, the kiln (including coal milling), the clinker storage, the finishing mills and the cement storage. The analysis is limited to these components and no components preceding the raw material stockpiles (i.e. quarrying and crushers) and nothing following the cement storage silos (i.e. secondary blending and packing) will be considered. All raw material sources and coal sources are considered to be infinite, with forecasted production targets extracted from the cement silos as boundary values.

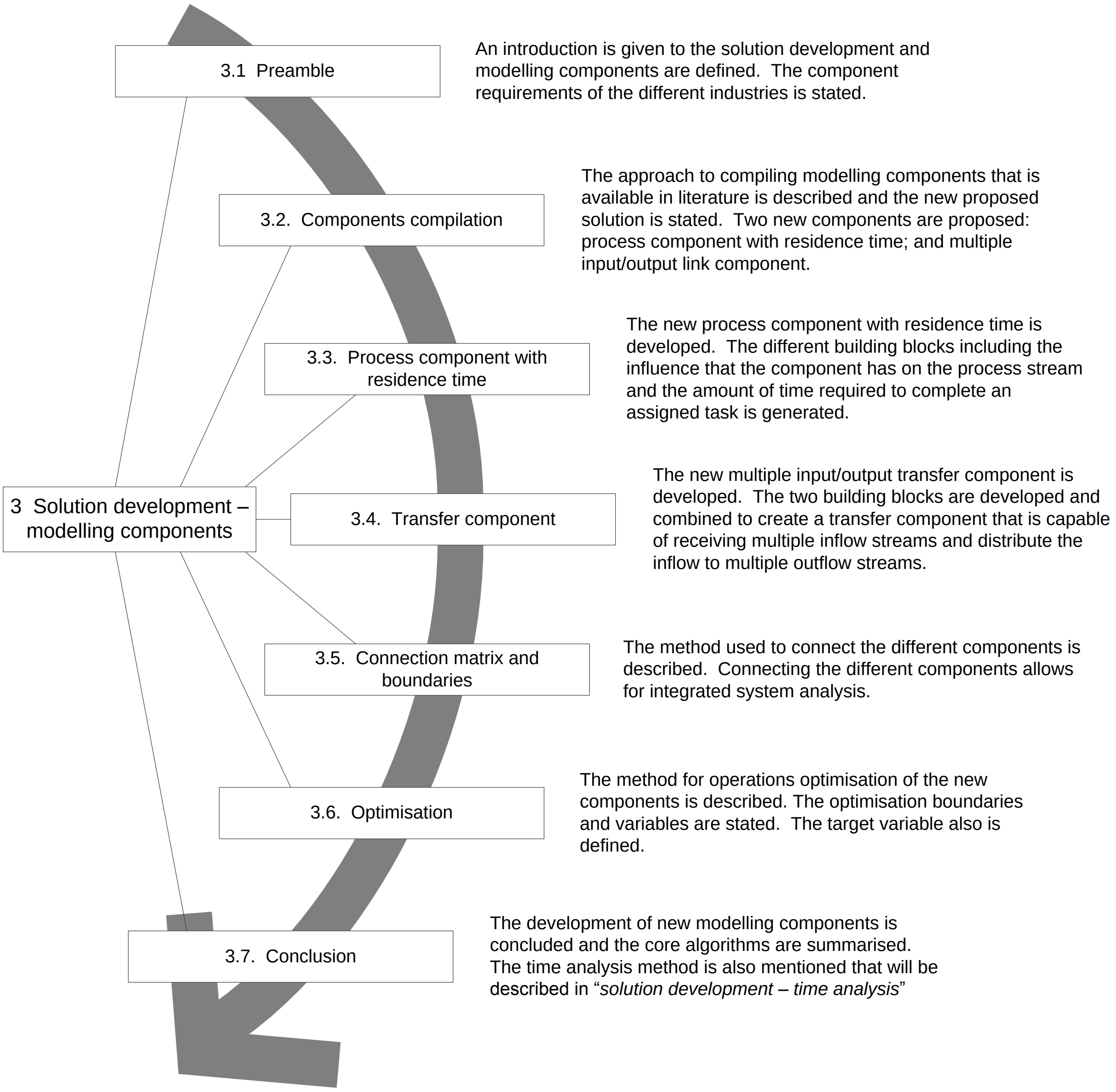
Gold mining

The components that are considered in the gold mining industry are the underground ore storage buffer/ore passes, the winders, the surface storage silos, the transport systems, the ore reception silos at the gold plant, the comminution (milling) circuits and the thickeners. All the mining activities preceding the underground storage volumes and all components following the thickening underflow control pump are not considered in the analysis. The mining targets are used as inflow boundary values into the underground storage silos. The outflow boundary value is also limited to a control range, as not to affect downstream chemical processing, with a constant relative density as constraint.

Platinum mining

The components that are considered in the platinum industry are the surface storage silos at the shafts, the transport system, including trucks, the ore reception silos at the concentrator plants, the milling circuits at the concentrators and the surge tank following the milling circuits. The mining activities and the ore extraction from underground are not considered. The flotation and any other processes following the flotation are not considered in the analysis. Similar to gold production, the target production/call at the shafts is taken as input value. The output is limited by flow constraints.

Chapter 3 develops modelling components that satisfy the different requirements of the three considered systems. The modelling components are developed by generating new core building blocks that are combined to accurately represent the physical installation in a virtual environment. The development of these components and the layout of Chapter 3 is summarised in Figure 3-1.



An introduction is given to the solution development and modelling components are defined. The component requirements of the different industries is stated.

The approach to compiling modelling components that is available in literature is described and the new proposed solution is stated. Two new components are proposed: process component with residence time; and multiple input/output link component.

The new process component with residence time is developed. The different building blocks including the influence that the component has on the process stream and the amount of time required to complete an assigned task is generated.

The new multiple input/output transfer component is developed. The two building blocks are developed and combined to create a transfer component that is capable of receiving multiple inflow streams and distribute the inflow to multiple outflow streams.

The method used to connect the different components is described. Connecting the different components allows for integrated system analysis.

The method for operations optimisation of the new components is described. The optimisation boundaries and variables are stated. The target variable also is defined.

The development of new modelling components is concluded and the core algorithms are summarised. The time analysis method is also mentioned that will be described in "*solution development – time analysis*"

Figure 3-1: Layout of solution development - modelling components

3.2. COMPONENT COMPILATION

A model is developed that is used in day-to-day operations planning for extended time intervals. The model utilises both discrete-time and aggregate-time approaches, combining fixed and rolling horizons to make industrial application possible. Most operations models of either batch- or continuous processes are subdivided into three basic components which are:

- Process components

  When modelling the operations of a set system of components, process components are defined as components that are used to facilitate the alteration of the state or characteristics of the processing materials or fluid. An example of process components are mills (reduce the particle size of the processing material), thickeners (increasing the relative density of the process fluid), or separators (separating a material into groups of acceptable particle size and particles that are to be recirculated).

- Buffer components

  Buffer components are used to absorb system- or process shock or rapid changes in fluid characteristics. In most cases, when modelling buffer components, the component is simply modelled as a set residence time, either dependant on the fill level or a fixed period of processing time.

- Distribution- or transfer components

  Distribution components are physical components that transport the processing fluid from one component to another (either buffer- or process components). When modelling these components, in most cases transfer- or distribution components simply link process outputs to process inputs.

The components discussion provides a sound foundation for specific model compilation, but are, however, not conducive for the construction a more generic approach. These basic component definitions are re-evaluated to improve the widespread application of the modelling method. Two novel basic components are generated.

It is accepted that most process components also represent a set or variable period of residence time. In addition, it is accepted that certain buffer components also have an effect on the processing fluid, be that homogenisation, or in other basic forms. Deductively, these two definitive components are uniquely combined into a single process item with variable residence time. This simplifies the construction of a process model for less experienced personnel.

Additionally, the new transfer components are extended. Logistic tasks require transfer component optimisation with multiple inputs and outputs. To achieve this, a simple novel process output to process input link will be insufficient. Two basic link entities are generated which are in turn combined to create the required modelling component. This includes firstly a summation entity (combining multiple inputs into a single output), and secondly a distribution entity (distributes the input process fluid to multiple outputs by using an output factor/fraction).

3.3. PROCESS COMPONENT WITH RESIDENCE TIME

To generate a unique process component with residence time, a simple lagging component is added to the generalised process unit. The combination is shown in Figure 3-2.

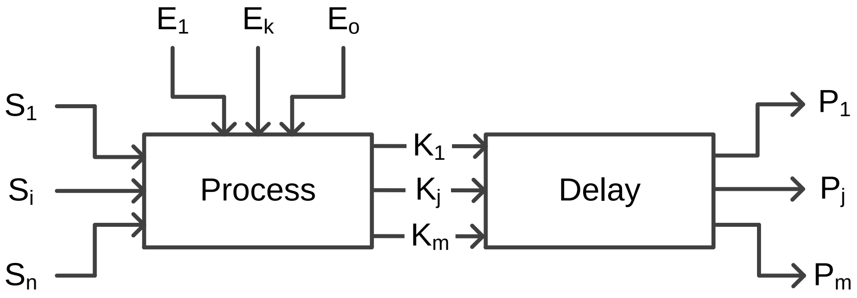


Figure 3-2: Representation of the process components with residence time

PROCESS COMPONENT

The process component constitutes a change in the processing fluid in different forms (temperature, particle fineness, relative density [RD], etc.). A product matrix is compiled with product description and reference. In addition to the product matrix, a variable or set number of variables is added to determine the state of a certain product. An example of this is water as the product with temperature as variable, or a solid-fluid mixture with RD as variable. The process definition of the process component is shown in Figure 3-3.

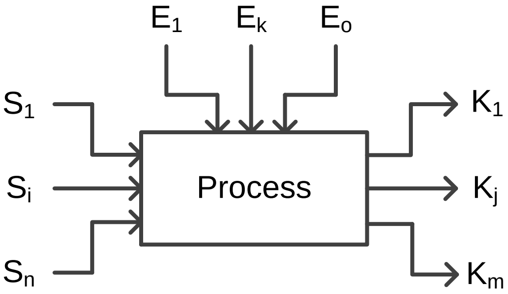


Figure 3-3: Representation of the process definition of the process component with residence time

The process component is compiled to be supplied with multiple process fluids (S) and to produce multiple process fluids (K), as shown in Figure 3-3. Considering a resource task description approach, the process component contains two physical concepts. The first is the machine or resource used to execute a process task, and the second the process task being accomplished. A resource-task approach separates these two concepts. In the developed modelling approach, the different processes that can be performed by a specified resource are included in the process component. Examples of such resources are finishing mills or blending facilities on a cement plant.

Each of these tasks produces certain process outputs. With the mentioned examples, only a single output can be produced during a specified time period. However, there are cases where multiple outputs are produced. A good example is a process where an off-gas of a task can be used as fuel or energy source for another task. Compiling a single component that incorporates both of these cases simplifies the construction of a model (enabling research contribution 1 to hold).

PROCESS FUNCTION

Keeping to the definition of a process function, the process component simply alters the state of a fluid. This presents two possible modelling approaches. Considering the pyro-process in a cement plant, the alteration of the fluid is complete – changing the fluid from one definitive product to another (in the considered example, from raw meal to clinker). In this case the process components simply need to assign a new product reference and calculate the production flow rate as function of the supply flow rate.

Equation 1

$$K_{j,t} = \sum_{i=1}^{n} S_{i,t} * D_{K,j,t}$$

With:

$K_{j,t}$ – Produced product flow rate at stream j

$S_{i,t}$ – Supplied product flow from stream i

$D_{K,j,t}$ – Distribution factor between outflow streams for stream j

j – Produced product index

i – Supplied product index

t – Time interval

The total inflow is distributed to the outflow ports by multiplying the total inflow by a distribution factor with:

Equation 2

$$\sum_{i=1}^{n} D_{K,j,t} = 1$$

Another case is a simple mixing or heat-exchange process task. The process fluid's state change, in this case, does not justify a reference change between two products. Considering a heat exchanger, two process flows exchange energy and alter a variable state in the two fluids temperature yet the process fluid remains definitively the same. A similar case is gravity sedimentation, where the process fluid's relative density is increased.

Both of these cases are considered in the modelling technique. A product matrix is compiled that defines process fluids and declares a set of variables that are altered during the process. The number of variables subject to change is not limited, as different processes require different state alteration variables. These variables include grade (gold processing – g/t), temperature (cooling systems), relative density (RD) and other examples not considered.

Changing the state of a product by altering a variable presents a problem in two forms. The variable of the processing fluid is linked to the process performed in the component. Additionally the variable is subject to change as a result of the buffer effect of the component (homogenisation). To keep the mathematical model as simple as possible, these two forms in which the state change variable is altered are separated once again.

Considering energy-related state variable change and conforming to the technique of developing simplified modelling building blocks from physical installations, a boiler is considered. In a boiler, electrical energy is used and converted with a specified efficiency function to alter the temperature of a process fluid. In this case, considering the first law of thermodynamics, equation 2 is developed in generic form.

Equation 3

$$\Delta V_{P-S,i,t} = \frac{E_t * C_{K,i,t}}{M_{S,i,t}}$$

Stated differently:

Equation 4

$$E_t = \frac{\Delta V_{P-S,i,t} * M_{S,i,t}}{C_{K,i,t}}$$

With:

$V_{S,i,t}$ – Supplied product variable
$M_{i,t}$ – Supplied product mass
$V_{P,j,t}$ – Produced product variable
$M_{j,t}$ – Produced product mass
$C_{K,j,t}$ – Inflow to Outflow conversion factor
E_t – Energy consumption at time t
j – Produced product index
i – Supplied product index
t – Time interval

Energy consumption is also divided into operational energy consumption and base-load energy consumption. To further describe the influence of scheduling on a system, an operation input is considered. The operation input is a fuzzy variable which, in most cases with normal operation, remains binary. The energy consumption of the component is extended to deliver an expected energy consumption output during modelling

Equation 5

$$E_t = O_o \left(\frac{\Delta V_{P-S,i,t} * M_{S,i,t}}{C_{K,i,t}} \right) + E_{bl}$$

With:

$V_{S,i,t}$ – Supplied product variable

$M_{i,t}$ – Supplied product mass

$V_{P,j,t}$ – Produced product variable

$M_{j,t}$ – Produced product mass

$C_{K,j,t}$ – Inflow to Outflow conversion factor

O_o – Operational input

E_t – Energy consumption at time t

E_{bl} – Base-load energy consumption

j – Produced product index

i – Supplied product index

t – Time interval

A homogenisation and a mixing process is considered. Initially, the resulting flow is calculated by weighing the product of the supply stream variable and the mass of that supply stream with the total mass of the inflow streams. The degree of homogenisation varies to create a homogenising region in plug flow if the component includes a storage capacity. The following expression is derived for complete homogenisation of an instantaneous mixing of different product streams:

Equation 6

$$V_{K,j,t} = \frac{\sum_{i=1}^{n} M_{S,i,t} * V_{S,i,t}}{\sum_{i=1}^{n} M_{S,i,t}}$$

For any losses in the production flow due to evaporation, dust, chemical conversion factors and various other losses, the mass of the outflow is the sum of the inflow masses multiplied by an inflow-to-outflow conversion factor and the distribution factor between the outflow streams:

Equation 7

$$M_{K,j,t} = \sum_{i=1}^{n} M_{S,i,t} * C_{K,j,t} * D_{K,j,t}$$

With:

$V_{S,i,t}$ – Supplied product variable of stream i

$M_{S,i,t}$ – Supplied product mass of stream i

$V_{P,j,t}$ – Produced product variable of stream j

$M_{K,j,t}$ – Produced product mass of stream j

$C_{K,j,t}$ – Inflow-to-Outflow conversion factor for stream j

$D_{K,j,t}$ – Distribution factor between outflow streams for stream j

j – Produced product index

i – Supplied product index

t – Time interval

RESIDENCE TIME

The second part of the process component with residence time is a simple delay component. The objective is for the processing portion of the component to calculate and represent all the state changes and energy influences that the component has on the process fluid. The delay part of the component then simply delays the result output to a different time slot, effectively implementing a residence time. This residence time may be fixed or transient. The representation of the residence part of the process component is shown in Figure 3-4.

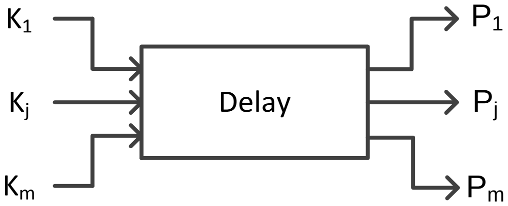


Figure 3-4: Representation of the delay definition of the process component with residence time

Fixed-/Steady-state residence time

A fixed or steady state residence time for the process components represents a lag constant. The time representation of this lag is derived simply by Equation 8:

Equation 8

$$P_{j,t} = K_{j,t-T}$$

With:

$P_{j,t}$ – Outflow product flow rate j at time t

$K_{j,t}$ – Inflow product flow rate at stream j at time t

j – Produced product index

t – Time interval

T – Time delay constant

Transient/Unsteady residence time

When considering most processes, this time delay experienced by the flow stream may vary with different characteristics. This is seen as a transient residence time. The delay is also simply represented by Equation 8. The time delay constant T is, however, a function of the characteristic that influences the delay experienced in the flow stream. An example of this delay and the most common in production facilities is simply a variable storage capacity. This example is displayed in Equation 9:

Equation 9

$$\mathrm{T}_t = \mathrm{F}(\mathrm{l}_t)$$

With:

T_t – Time delay constant at time t

l_t – Volume capacity at time t

In most cases this delay function is not simply represented by a function of a single variable, and may be influenced by various system characteristics. The challenge still remains to calculate this linking function between the time delay and the influencing factors. In most cases this will be represented by a simple empirical relationship.

The transient delay is that some components will also have an influence on the quality of the product. As mentioned earlier, this is as a result of homogenisation. Two cases are considered. Firstly a case where the homogenisation of the storage volume is complete, and secondly where there is no homogenisation present, i.e. plug flow.

Mixed flow/ homogenising flow

When homogenisation of the control volume is assumed, the entire volume is assumed to have an equal distribution of quality V(x) (in the case of gold plants: the ore grade in the form of g of gold per ton ore).

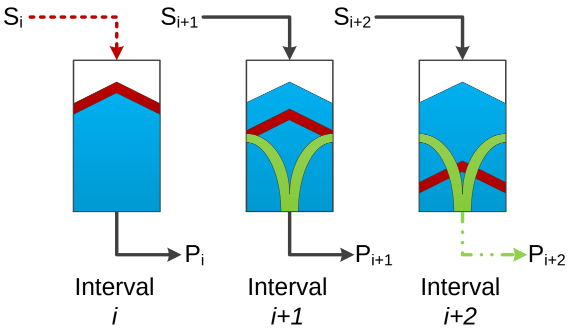


Figure 3-5: Buffer extraction pattern assuming homogenisation

The quality of the product extracted from the buffer is thus always the quality of the entire buffer volume at the time of the extraction event.

Present silo quality value (Homogenising)

Equation 10

$$G_{P,j,t} = G_{Silo,t} = \frac{V_{Silo,t-1} * G_{Silo,t-1}}{V_{Silo,t-1} + S_t} + \frac{S_{i,t} * G_{S,i,t}}{V_{Silo,t-1} + S_t}$$

With:

$G_{P,t}$ – Feed quality from stream P at time t

$G_{S,t-T_t}$ – Feed quality from stream S at time $t - T_t$

$V_{Silo,t-T_t}$ – Silo content at time $t - T_t$

P_t – Inflow rate at stream P at time t

T_t – Delay or residence time at time t

t – Analysis time indicator

Plug flow

When plug flow is assumed, the quality of the incoming flow steadily moves through the buffer volume at the rate of product extraction, as indicated in Figure 3. The quality of the flow extracted is the same as the supply quality of j time intervals preceding the extraction event, where j is the amount of time required to extract all the volume of the buffer at rate Pn (with Pn varying with time).

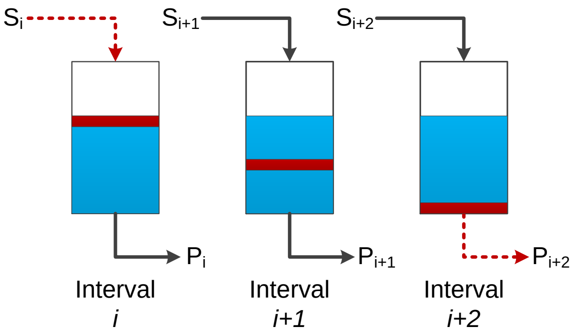


Figure 3-6: Buffer extraction pattern assuming plug flow

Extraction quality:

Equation 11

$$G_{P,t} = G_{S,t-T_t}$$

With:

Equation 12

$$T_t = \frac{V_{Silo,t-T_t}}{\int_{t-T_t}^{t} P_t dt}$$

And:

$G_{P,t}$ – Feed quality from stream P at time t

$G_{S,t-T_t}$ – Feed quality from stream S at time $t - T_t$

$V_{Silo,t-T_t}$ – Silo content at time $t - T_t$

P_t – Inflow rate at stream P at time t

T_t – Delay or residence time at time t

t – Analysis time indicator

Homogenizing region in plug flow to represent non-ideal plug flow

Though the above-mentioned theories are mathematically accurate, most practical applications require a combination of the two. Product quality diffuses into surrounding material with varying magnitude. The two concepts, homogenizing- and plug flow, are thus combined to create a more accurate description of the quality distribution through a field of analysis. The extent and value of the combination of the two theories remain variable to account for real-world variances between the different components.

Consider a hypothetical case where material of a specific grade (no specific attribute) is fed into a buffer. Figure 3-7 shows the response of the grade at upper surface of the material in a buffer to a step function in the supply grade.

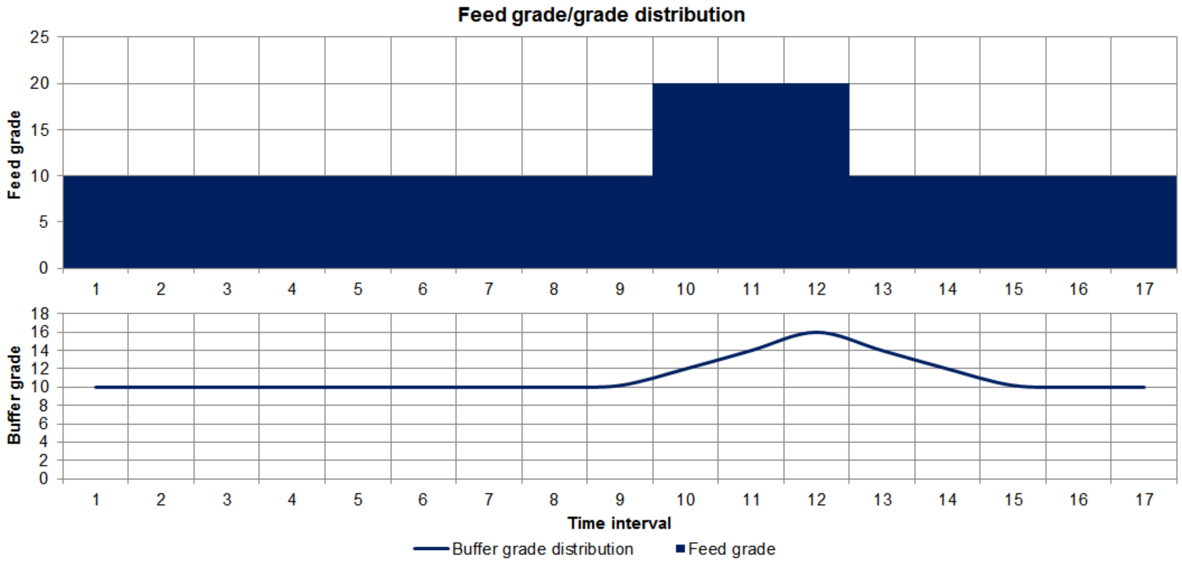


Figure 3-7: Quality response to a step function with a homogenising region in plug flow

Figure 3-7 shows that the grade contamination creates a distribution of this attribute in a buffer that combines homogenizing- and plug flow. The two formulae developed for homogenizing flow and plug flow are combined to develop a simple transfer function. The function describes a limited homogenization effect that occurs during the contamination period, denoted by a contamination constant $C_{P,j}$. The contamination effect is described by Equation 13.

Equation 13

$$G_{P,t} = (1 - C_{P,t})G_{S,t-T_t} + C_{P,t} * \frac{V_{Silo,t-1} * G_{Silo,t-1}}{V_{Silo,t-1} + S_t} + \frac{S_{i,t} * G_{S,i,t}}{V_{Silo,t-1} + S_t}$$

With:

$G_{P,t}$ – Feed quality from stream P at time t

$G_{S,t-T_t}$ – Feed quality from stream S at time $t - T_t$

$V_{Silo,t-T_t}$ – Silo content at time $t - T_t$

P_t – Inflow rate at stream P at time t

T_t – Delay or residence time at time t

t – Analysis time indicator

T_t is described by Equation 14:

Equation 14

$$T_t = \frac{V_{Silo,t-T_t}}{\int_{t-T_t}^{t} P_t dt}$$

With:

$G_{P,t}$ – Feed quality from stream P at time t
$G_{S,t-T_t}$ – Feed quality from stream S at time $t - T_t$
$V_{Silo,t-T_t}$ – Silo content at time $t - T_t$
P_t – Inflow rate at stream P at time t
T_t – Delay or residence time at time t
t – Analysis time indicator

A CONJOINING REPRESENTATION FOR THE PROCESS COMPONENT

Bringing all the above-mentioned factors into a conjoining process component will solve most of the restrictions in present modelling techniques in terms of component allocation. The new formulation is also flexible and can consider a multitude of different scenarios for different processing components without altering the algorithmic core. The resulting component delivers the following generic formulae:

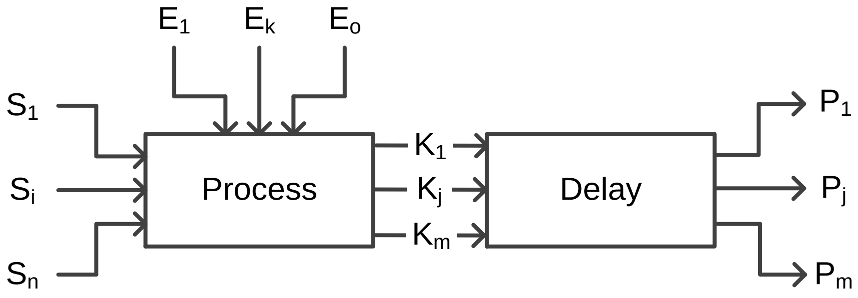


Figure 3-8: Schematic representation of the process component with residence time

Parameters:

n - Number of inputs
m – Number of outputs
o – Number of energy inputs
$D_{K,j,t}$ – Output distribution factors for 1 to m
$C_{K,j,t}$ – Inflow-to-outflow conversion factor
T_t – Time delay function
E_{bl} – Base load energy consumption

Inputs:

O_o – Operational input
$G_{P,t}$ – Feed quality from stream P at time t

In transient states additional inputs can be provided to assist in solving the transient effect on the residence volumes as described above. These additional inputs are:

$S_{i,t}$ – Supplied product flow from stream i
$P_{j,t}$ – Outflow product flow rate j at time t

Processing:

The processing component is summarised by Equation 1 to Tt is described by Equation 14:

Equation 14 and can be solved using simultaneous equation solutions.

Outputs:

$G_{S,t-T_t}$ – Feed quality from stream S at time $t - T_t$
E_t – Energy consumption at time t

Assuming steady state operation, the following outputs are also provided:
$S_{i,t}$ – Supplied product flow from stream i
$P_{j,t}$ – Outflow product flow rate j at time t

State alteration function and the product matrix

A product matrix is compiled for the simplified computerisation of the mathematical modelling. In order to compile the product matrix, the different products in the considered process are defined. In addition, variables representing the states of the different products are included. Finally a product reference is included to link these products with different components of the model. Examples of the product matrix process are shown in Table 3-1 and Table 3-2

Table 3-1: Example 1 of a product matrix

Reference	Product	Variable 1	Variable 2	Variable 3
P1	Ore slurry	RD	Temperature	Grade

Table 3-2: Example 2 of a product matrix

Reference	Product	Variable 1	Variable 2	Variable 3
P1	Lime stone	-	-	-
P2	Gypsum	-	-	-
P3	Magnetite	-	-	-
P4	Raw meal	-	-	-
P5	Clinker	-	-	-
P6	Cement	-	-	-

3.4. TRANSFER COMPONENT

Logistic optimisation requires the capacity to combine multiple inputs and distribute these inputs to multiple outputs. This is achieved by combining two different approaches. The first component is a summation component, and the second is a controllable distribution component. The ability to optimise the distribution of the process fluid requires a variable distribution component to be included in the link component. The two different link components are further described in the following sections.

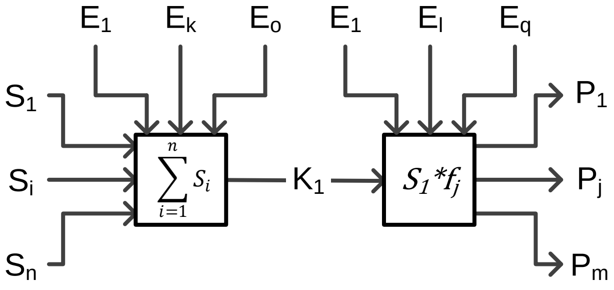


Figure 3-9: Schematic representation of the combined summation and distribution link component

SUMMATION COMPONENT

The first component is a summation component. This component simply combines all the flows of similar process fluids to a single output. This is done by summing all assigned inflows of similar composition (Refer to the product matrix). This component is shown in Figure 3-10.

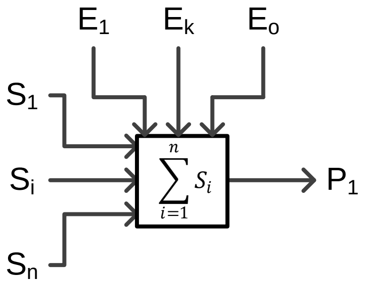


Figure 3-10: Schematic representation of the summation part of the new link component

The component flow is simply represented by:

Equation 15

$$P_1 = \sum_{i=1}^{n} S_i \qquad i \in \mathbb{N}$$

With:

P_1 – Summation component outflow

S_i – Summation component inflow of supplied products at i

i – Supplied product index

n – Number of supplied products

Transferring product quality of a summation component presents a simple homogenisation equation. The transfer of product quality is shown in Equation 16

Equation 16

$$V_{P,t} = \frac{\sum_{i=1}^{n} M_{S,i,t} * V_{S,i,t}}{\sum_{i=1}^{n} M_{S,i,t}}$$

With:

$V_{S,i,t}$ – Supplied product variable of stream i

$M_{S,i,t}$ – Supplied product mass of stream i

$V_{P,t}$ – Produced product variable of stream j

$M_{K,j,t}$ – Produced product mass of stream j

i – Supplied product index

t – Time interval

DISTRIBUTION COMPONENTS:

A second part of the link component, specifically when considering a logistical problem, is the distribution component. The distribution component distributes a single input volume to m different outputs. The total input volume is distributed by multiplying the input volume with a distribution factor f_j. During optimisation, this distribution factor is set as a variable. Deductively, the sum of all the distribution factors equals unity. The distribution component is depicted in Figure 3-11.

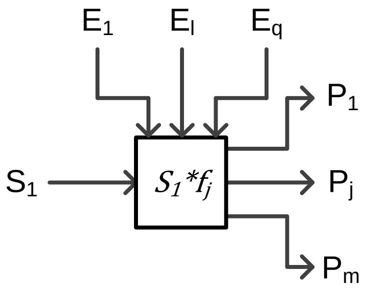


Figure 3-11: Schematic representation of the distribution part of the new link component

The flow through the distribution variable is calculated using Equation 17:

Equation 17

$$S_1 = \sum_{j=1}^{m} P_j * f_j \qquad j \in \mathbb{N}$$

With:

Equation 18

$$\sum_{j=1}^{m} f_j = 1 \qquad j \in \mathbb{N}$$

And:

S_1 – Total supplied process fluid volume

P_j – Produced process fluid output volume at j

f_j – Output distribution factor

j – Output flow stream index

m – Number of produced process flow streams

The product quality of the produced stream is equal to the quality of the summed supply stream.

Equation 19

$$V_{P,i,t} = V_{S,t}$$

With:

$V_{S,t}$ – Supplied product variable of stream i

$V_{P,j,t}$ – Produced product variable of stream j

j – Produced product index

t – Time interval

To create a target variable during optimisation, a specific cost is allocated to each of the outputs. This cost can be defined as fuel cost, energy cost or any other form not included in the analysis. The cost influence is assigned to each of the process outflows j. The cost component is taken as a function of the volume that is distributed through the distribution output P_j. The total cost allocated to the distribution component is simply the sum of all the process outflows' specific costs. The cost is calculated by:

Equation 20

$$C_t = \sum_{j=1}^{m} C_j \qquad j \in \mathbb{N}$$

With:

Equation 21

$$C_j(P_j) \quad j \in \mathbb{N}$$

This can be taken as a linear relationship in most cases with large distribution volumes:

Equation 22

$$C_j = P_j * C_{sj} \qquad j \in \mathbb{N} \cup [1, m]$$

With:

C_t – Total cost allocated to the distribution component

C_j – Cost allocated to output *j*

P_j – Produced process fluid output volume at *j*

C_{sj} – Specific cost of distribution at output at *j*

j – Output flow stream index

m – Number of produced process flow streams

A CONJOINING SUMMATION AND DISTRIBUTION COMPONENT:

The two distribution components are combined to for a comprehensive distribution component. The distribution component combines multiple inflows to produce multiple outputs. The combined distribution component is shown schematically in Figure 3-12.

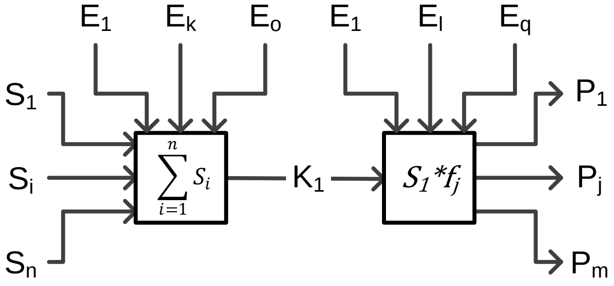


Figure 3-12: Schematic representation of the combined new link component

Combining the description of the summation component and the distribution component, the process flow reduces to:

Equation 23

$$P_j = \frac{\sum_{i=1}^{n} S_i}{f_j} \qquad j \in \mathbb{N} \cup [1, m], i \in \mathbb{N}$$

With:

P_j – Produced process fluid output volume at j

S_i – Summation component inflow of supplied products at i

f_j – Output distribution factor

j – Output flow stream index

i – Supplied product index

m – Number of produced process flow streams

n – Number of supplied products

3.5. CONNECTION MATRIX AND BOUNDARIES

The layout of the connection matrix as it is used in the analysis is shown in Figure 3-13.

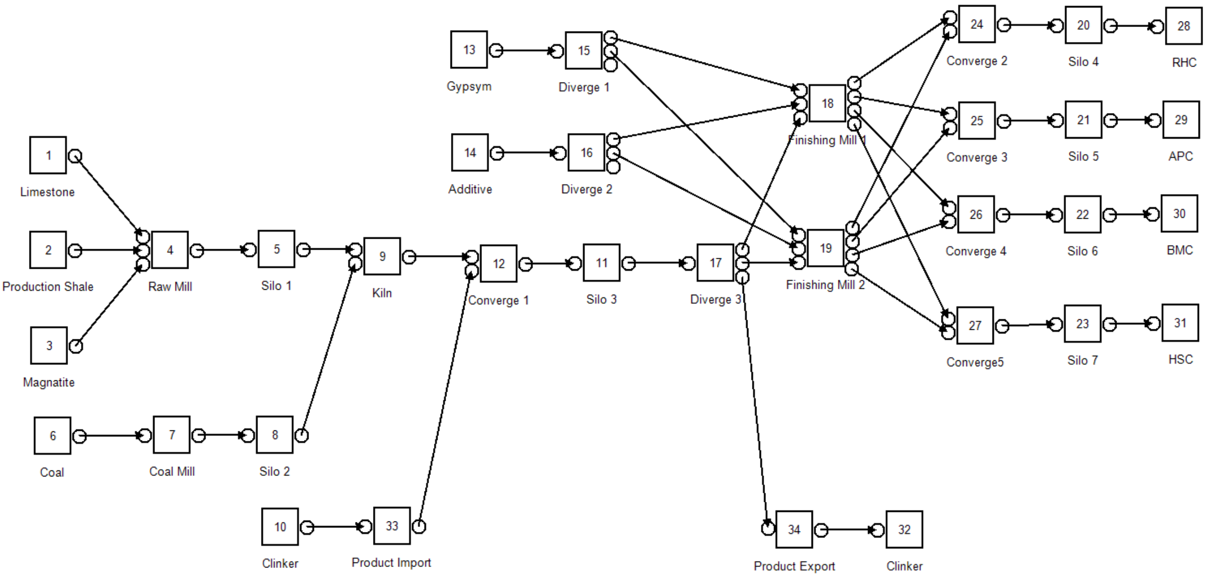


Figure 3-13: Model component connection representation

The operations model is compiled for the integrated system of components. This allows for all the components to be analysed at once, in turn increasing the accuracy and flexibility of the modelled result. The interlinked nature of a continuous process plant can be investigated and buffer volumes can be managed to realize optimal cost of operation.

3.6. OPTIMISATION

Optimisation of the operations of a system of components is done over time. Within bounds, the series of equations defined in this chapter are optimised to reduce the cost of operation. In literature the optimisation of an operations model is focused on one specific characteristic, such as energy, whereas this does not provide a global optimum. When deriving a global optimum for operation, cost is an accurate measure to unify the different target characteristics. When optimising for cost, the entire system is compared, and different influences are combined to produce a global optimum that does not unbalance a solution to the focus characteristic.

Operation as variable

The variable that is considered is operation, as denoted above by O_o. O_o represents a fuzzy variable instead of considering a simple binary variable to plant components. The input can be limited to simple binary inputs in the case that a component is either operational or idle. However, providing a fuzzy variable allows the modelling system to consider different production settings, such as variable speed pumps and other variable components.

Cost as target

Using cost as optimisation target enables different characteristics to be combined and minimised in unison. Cost is allocated to different model outputs, including energy cost and raw material inputs, at model boundaries. Assigning cost to boundary values also enables the model to consider risk, such as loss in sales etc. Considering the combined cost of the entire system provides an integrated target to find a global optimum for a complex system of components and operations.

The system of components is analysed over time to consider the effects of scheduling on the global cost of operation. A unique time modelling approach is used to simplify the optimisation of the model to reduce processing time. Using a mixed integer solver with the complex models will increase the complexity of the solution and significantly increase processing time. Thus the new linear analysis approach that combines continuous and aggregate modelling approaches is developed. This time modelling approach is discussed in Chapter 4.

3.7. CONCLUSION

To develop a solution, the methodology was subdivided into two concepts: components development/modelling and time analysis/simulation. The first part of the methodology was discussed in Chapter 3. Traditional modelling components as outlined in the literature, was discussed. These modelling components were a process component, a buffer component and a transfer component. Since most components found in real-world systems represent process components with a form of residence time and a transport component with multiple inflows and outflows, these components were re-evaluated.

The new methodology developed two new modelling components that represented real-world systems better. These components were a process component that also represents a set or variable residence time, and a transfer component with multiple process inflows and outflows. The process component with residence time was developed to also account for multiple fluid characteristics such as temperature, relative density, or other process variables. Additionally, the process component accounted for a set or variable residence time, represented simply as a delay in the outputs of the component.

The transfer component incorporated a summation section and a distribution section. The summation section added all the different fluid inflows from the different components and summed the total process flows. The variables of the process flows (including temperature and RD) was calculated by using the process fluid volume as scaling factor. The distribution section subdivided the total flow by using a distribution factor. The distribution factor was derived from the process requirements (from downstream components or an optimisation derived variable), or used a set distribution factor.

These two new components allowed for accurate simulation of real-world systems. The two new components are simple and can be used to describe a multitude of different systems, not only focussing on the flow volumes, but also on the flow characteristics. Compiling a simulation is, however, required to effectively use the new components to derive operational schedules and settings to reduce operational costs. The new time analysis of these components is described in Chapter 4.

CHAPTER 4

Solution development – time analysis

Chapter four

Chapter four will continue the solution development by describing how the new modelling components will be analysed over time. Different time periods, analysed in a new continuous-time analysis, will be used to reduce the processing requirements of the system.

4 SOLUTION DEVELOPMENT – TIME ANALYSIS

4.1 PREAMBLE

Various time modelling approaches are presented in literature. The different time modelling approaches are suited to different applications of schedule optimisation. The different time models are discrete-time, aggregate-time and continuous-time modelling. Once again, the aim is to widen the application of the operations modelling approach. It is necessary to either combine the three time modelling approaches in such a way as to unify all of the strengths, or to create a new time-modelling approach that is widely applicable to different industries and applications.

Aggregate-time modelling holds various advantages. Analysing a system in aggregate-time simplifies a statistic planning of operations with reduced processing requirements. Using a statistic planning method assists the production manager/planner to easily incorporate breakdown and preventative maintenance hours into the proposed operational schedule. However, compiling this statistical operation plan into real time schedule is difficult. Additionally, planning for buffer volumes and possible risk remains a cumbersome manual task.

Using a discrete-time approach simplifies the planning of storage volumes and assists in risk management. Conversely, discrete-time analysis for scheduling also poses various limitations. The operational variance is limited to the analysis intervals, i.e. if the analysis intervals are one-hour periods; the cycling limitation (on/off command) is once hourly. Secondly, discrete-time optimisation is often unstable and produces unfeasible results, unless the results are manipulated for specific desired outcomes (cycling from time interval to time interval).

Continuous-time modelling offers an accurate and comprehensive approach; however, it also limits the statistical method of operations planning. Continuous-time modelling also involves large processing requirements to optimise. A continuous-time model however enables the user to evaluate the system more accurately and is better suited to real-time analysis.

4.2 WATER DROP FORMULATION (WDF) FOR CONTINUOUS AND AGGREGATE SCHEDULE OPTIMISATION

A new continuous-time optimisation method is developed that eliminates these limitations whilst reducing processing requirements. The new optimisation approach is defined as the Water Drop Formulation (WDF). The new WDF method for continuous schedule optimisation is fundamentally derived from the natural optimisation effect of water settling on a surface (curved or flat). Due to gravity and the potential energy of the water, the considered droplet will automatically settle on the lowest point on the surface. Secondly, the surface tension in the water forms a *discrete* area where the droplet will settle. For visual conception, Figure 4-1 shows the effect of water settling on a surface.

Figure 4-1: The settling of water drops on the lowest point of a considered surface

When considering the electricity cost profile, operation can be seen as water settling on the lowest point (point of least resistance, or cost). By implementing the new WDF, aggregate-, discrete- and continuous-time modelling approaches can be derived and the various strengths of each approach can be unified. The WDF method of optimisation is further developed by considering different cases when scheduling the operation of machines.

The WDF is developed by considering five cases of increasing modelling complexity. These cases are:

- WDF and a continuous cost profile
- WDF and a discontinuous cost profile
- WDF and multiple modes of operation
- WDF with varying storage capacity

4.3 WDF AND A CONTINUOUS COST PROFILE

Consider a continuous cost profile $E_c(t)$, charged on a machine with a single operational mode, i.e. only binary on/off settings. A desired analysis period utilisation is received from the aggregate optimisation of a higher time level. The desired outcome of the optimisation is to generate an on/off schedule for the component being analysed. The continuous specific cost profile is given by:

$$E_c(t) = F(t)$$

With:

E_c – Electricity cost profile

t – Time

A maximum cost line $[C(t) = MC]$ is generated to determine the optimal operation for the desired utilisation. This line is increased from $MC = \min\ E_c(t)$ to $\mathrm{MC} = \max\ E_c(t)$. Where the maximum cost line $[C(t)]$ is larger than the continuous specific cost function $[E_c(t)]$, the machine is seen as on. Where the continuous cost profile $[E_c(t)]$ is larger than the maximum cost line $[C(t)]$, the machine is seen as off. This can be represented by:

Equation 24

$$O(t) = \begin{cases} 1\,, C(t) \geq E_c(t) \\ 0\,, C(t) < E_c(t) \end{cases}$$

And:

Equation 25

$$Utilisation = \frac{\int_0^e O(t)dt}{(e-0)}$$

To determine the point where maximum cost is large enough to obtain a predetermined utilisation, the maximum cost line value $[MC]$ is increased iteratively. The continuous cost profile $[E_c(t)]$ and the iteration of the maximum cost line $[C(t)]$ is illustrated in Figure 4-2.

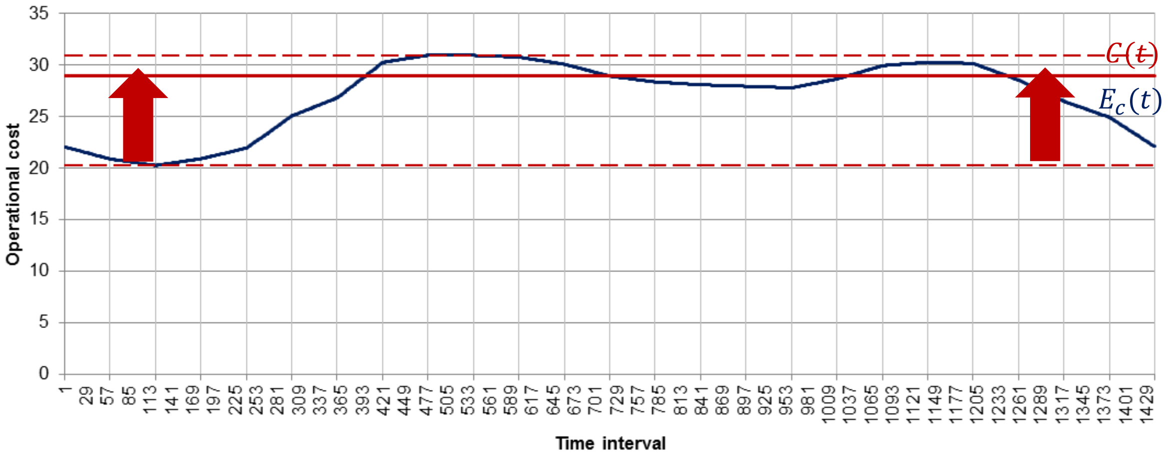


Figure 4-2: Example of continuous electricity cost profile

From this operation, different aggregate and discrete profiles are generated. Minimum cost utilisation for the time interval is denoted by Equation 24. Considering a specific uitlisation value (a single iteration value of $[MC]$), an operations profile is generated. The resulting binary operational profile $[O(t)]$ is depicted in Figure 4-3.

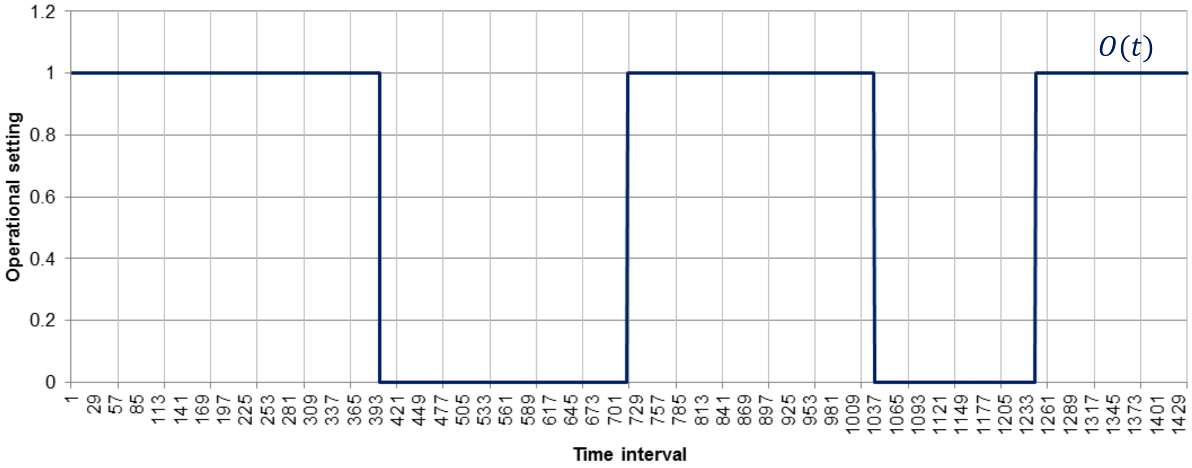


Figure 4-3: Example of an operational profile

Equation 24 is used to compile a statistic cost with utilisation profile. For a specific value of MC, the utilisation is calculated as:

Equation 26

$$Utilisation = \int_0^e O(t)dt$$

Figure 4-4 depicts the specific cost profile [values generated by iteratively increased $C(t)$ from min $E_c(t)$ to max $E_c(t)$] with utilisation generated, for example the continuous electricity cost profile shown in Figure 4-2. The specific cost profile represents the cost value of $C(t)$ with the coresponding utilisation.

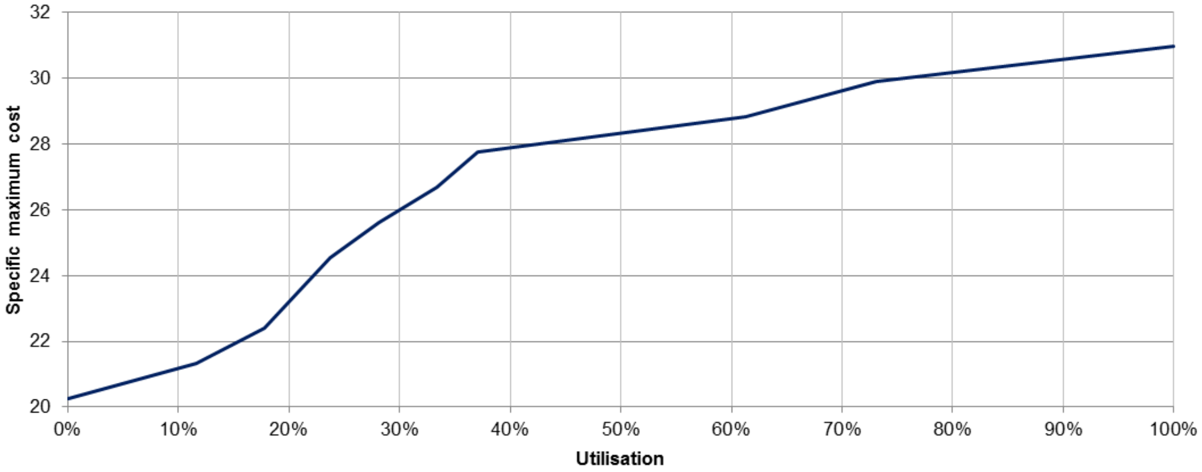


Figure 4-4: Example of a specific cost profile with utilisation

Using the utilisation, the optimal cost of operation for a specific utilisation, or *aggregate cost profile* with utilisation for the analysis period, is calculated. This is done by integrating the continuous electricity cost profile where $C(t) \geq E_c(t)$, i.e. $O(t).E_c(t)$ or:

Equation 27

$$Min\ cost\ of\ operations_{Utilisation} = \int_0^e O(t)E_c(t)dt$$

The resulting aggregate cost profile with utilisation is depicted in Figure 4-5. The aggregate cost profile is a diagram that indicates the optimal cost of operation at a specific utilisation for the considered component in the specific analysis period $[0 \leq t \leq e]$.

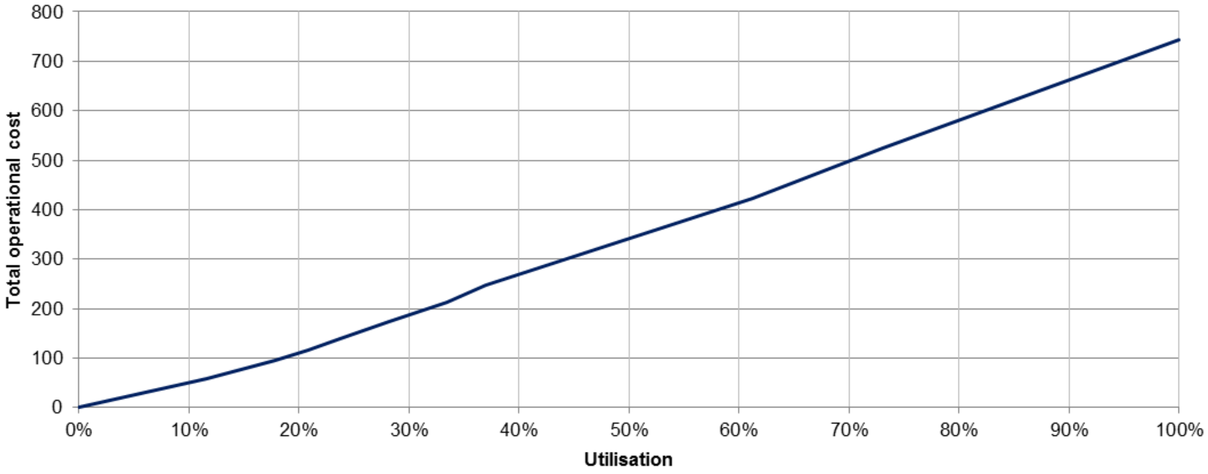


Figure 4-5: Example of an aggregate cost profile with utilisation

The derived operation and supporting profiles work well with continuous cost profiles. However, when implementing the methodology on a TOU costing profile or a discontinuous cost structure, the methodology will fail. The new WDF is expanded to incorporate this cost profile.

4.4 WDF AND A DISCONTINUOUS COST PROFILE

When considering a discontinuous cost profile, as depicted in Figure 4-6, the WDF methodology will be ill-defined at a point where $\frac{dE_c(t)}{dx} = 0$. A filling mechanism is incorporated following the water drop analogy. At points where the methodology is ill-defined, the operation is filled from t=0 to t=e according to the required utilisation. This mechanism is also depicted in Figure 4-6.

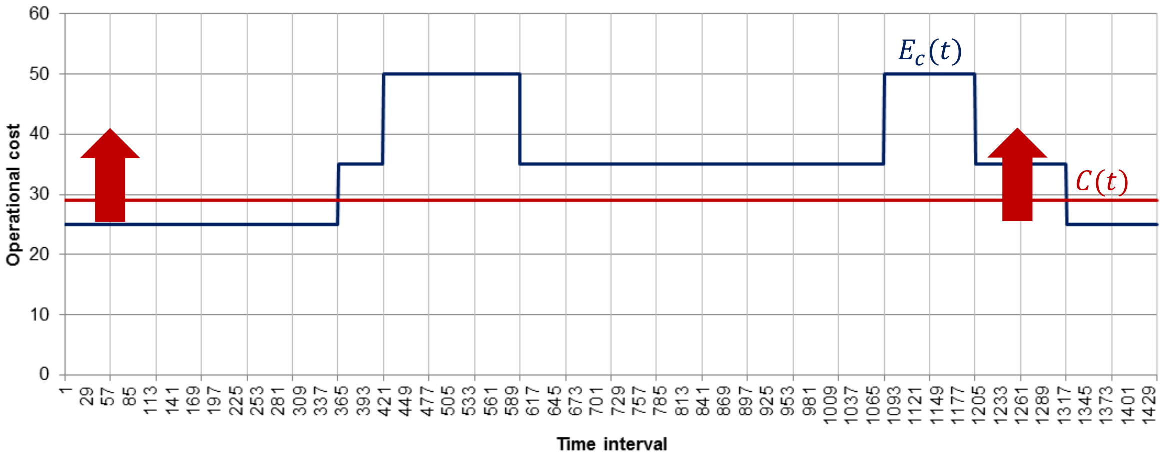


Figure 4-6: Example of a discontinuous cost profile with the WDF methodology

Similar to the continuous cost profile analysis, a specific cost profile is generated. It is noted that the specific cost remains constant with increasing utilisation at points where the discontinuous cost profile gradient is zero. The resulting specific cost profile is depicted in Figure 4-7.

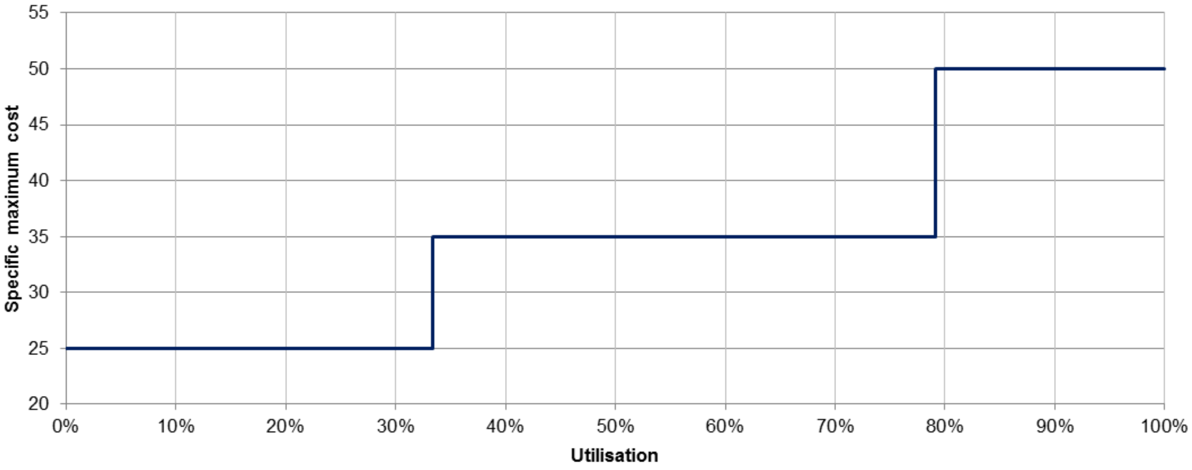


Figure 4-7: Example of a specific cost profile with utilisation for discontinuous cost profile

Once again, an aggregate cost profile is generated that depicts the minimum cost of operation for a corresponding utilisation. When considering a discontinues or TOU cost profile, the resulting aggregate cost profile is stepwise continuous. The resulting stepwise continuous aggregate cost profile is shown in Figure 4-8.

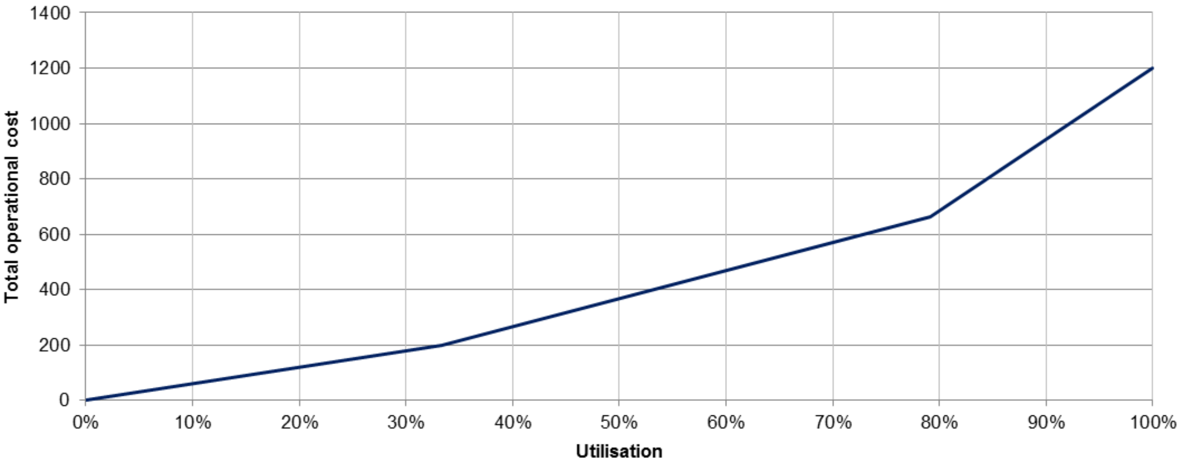


Figure 4-8: Example of an aggregate cost profile with utilisation for discontinuous cost profile

Using a water drop analogy, an optimal operations profile can be generated for discontinuous or TOU tariff structures. The components considered comprised of a single mode of operation, i.e. binary on/off settings. The unique WDF is further developed to include components with multiple modes of operation or continuously-variable operation capacity.

4.5 WDF AND MULTIPLE MODES OF OPERATION

The WDF is conducive to components with a single mode of operation. However, most new components, such as variable speed pumps, have either multiple or continuously-variable modes of operation. Adding an axis to the cost profile $E_c(t)$ provides the capability to incorporate these additional modes of operation to the WDF. The addition of the modes of operation dimension to the cost profile is shown in Figure 4-9.

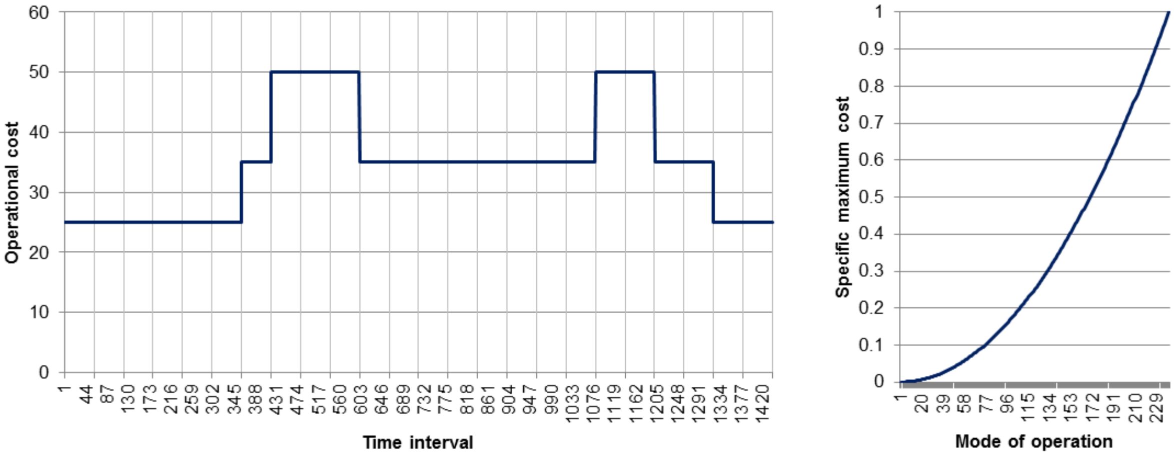


Figure 4-9: Example of a discontinuous cost profile with the WDF methodology, with the modes of operation dimension

The modes of operation are considered to be a simple fuzzy logic variable function of operational energy requirement with operational setting (i.e. flow rate or feed rate) where the max operational capacity is unity. This fuzzy logic variable energy consumption variable is subsequently multiplied with the energy profile to create an operational energy profile plane, as shown in Figure 4-10.

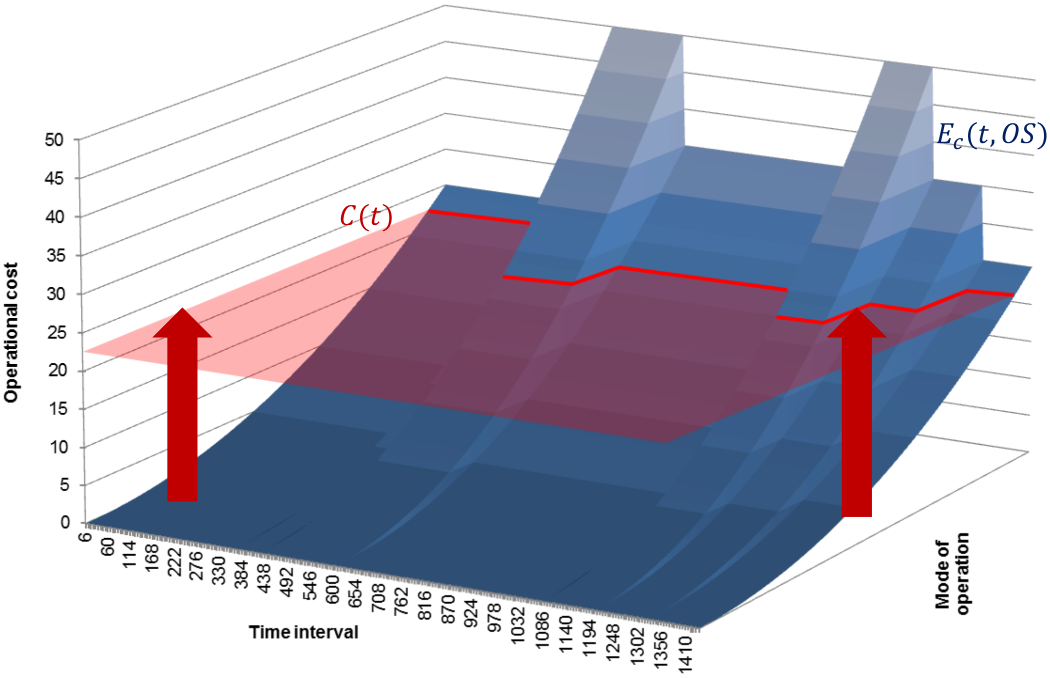


Figure 4-10: Example of a discontinuous cost profile with maximum cost plane intersection with the modes of operation dimension

The maximum cost line is extended to form a maximum cost plane. Similar to the original formulation, the maximum cost plane is increased iteratively to generate an operations schedule. The intersection between the maximum cost plane and the cost profile represents the mode setting for optimal operation. The maximum cost plane and the cost profile with continuous modes of operation is depicted in Figure 4-10.

The mode-with-time plane depicts the optimal operations setting for the component with variable modes of operation. This operations setting is depicted in Figure 4-11.

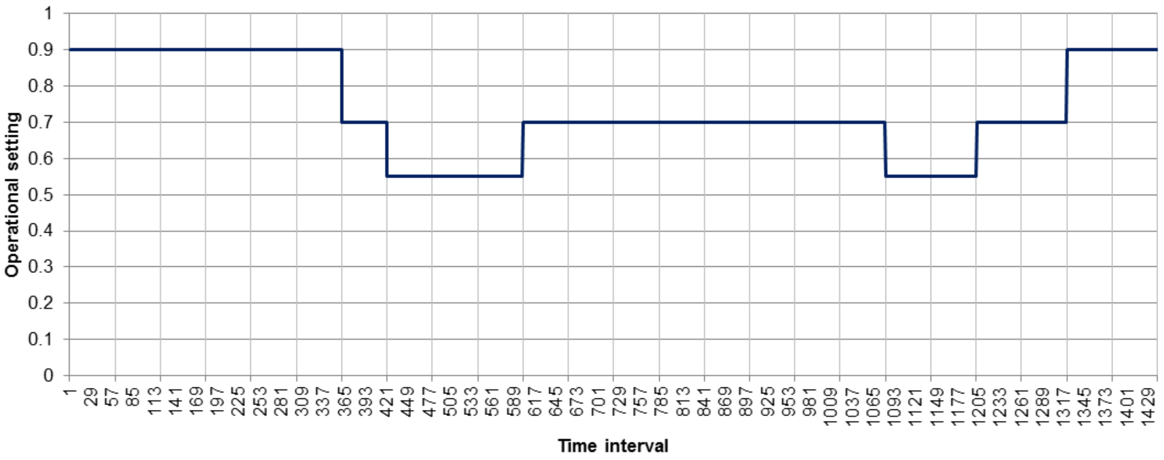


Figure 4-11: Example of an operational setting with time profile for discontinuous cost profile, with components of continuously variable operational settings

The new WDF works well for optimisation in various cost-analysis scenarios. It enables the user to analyse the operation of a machine in different time-analysis forms. Optimal aggregate cost profiles depict an accurate statistical representation of the operational cost with machine utilisation. This approach uniquely combines all of the required approaches in a single iteration, which dramatically reduces processing requirements. The WDF, however, only considers a single component, whereas analysing an entire system of components in unison is required. The impact of different interlinked components is further investigated.

4.6 WDF WITH VARYING STORAGE CAPACITY

The goal of the study includes the combined analysis of multiple components in an interlinked plant. Altering the maximum cost line to account for the residence or buffer level of the components directly linked to the considered component will enable the WDF to optimise multiple components simultaneously, generating a global optimal operation of the interlinked system. All the components' maximum cost line iteratively increases simultaneously. In other words, a single value for the maximum cost value is applied on all the considered components.

To include the buffer or storage influence on the different components, a virtual induced cost for buffer level is assigned to the level that is calculated to the different components that are connected. The virtual cost represents the priority of mill operation with regards to the energy cost during that period, for example it is higher priority for the mill to operate when the silo level is below the minimum than any cost period during the analysis period. The virtual silo level cost is therefore higher than the maximum operating cost during the analysis period. The adjusted maximum cost line with buffer levels is represented in Figure 4-12.

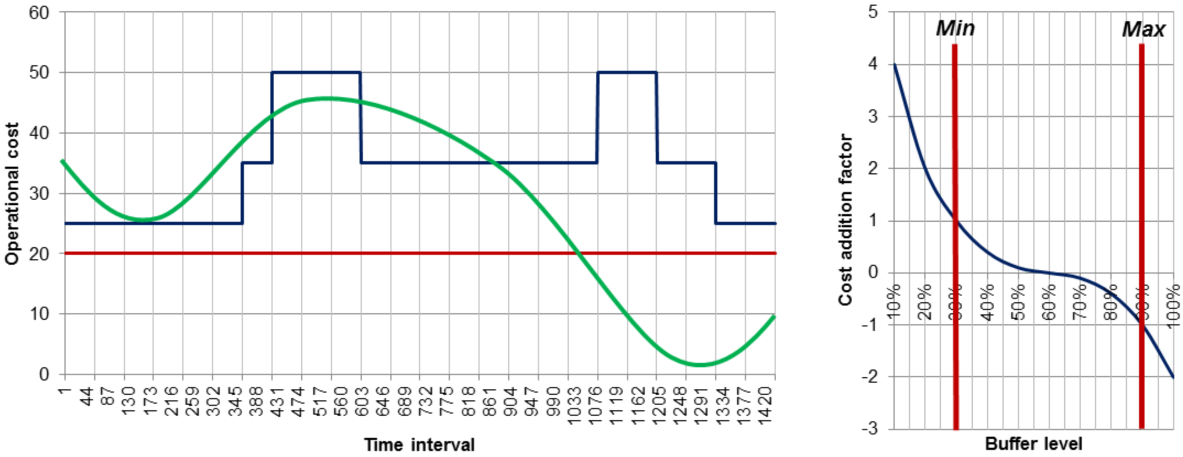


Figure 4-12: Example of a discontinuous cost profile, with buffer level altered maximum cost profile

The same approach is followed with buffers on the supply side and the demand side of the considered component; however, the supply side is negative to that of the demand side. All the relevant altered buffer-level virtual costs that are directly connected to the considered component are summed to generate a final adjusted maximum cost profile.

This adjusted maximum cost profile is represented by:

Equation 28

$$C_{ad}(t) = C(t) + \sum_{i=1}^{n} V_{C,i}(t)$$

With:

Equation 29

$$V_c(t) = S(t) * A_{C,S}(l)$$

From this new adjusted maximum cost line, the same methodology is followed to calculate the operations profile. The operations profile is simple represented by:

Equation 30

$$O(t) = \begin{cases} 1\,, C_{ad}(t) \geq E_c(t) \\ 0\,, C_{ad}(t) < E_c(t) \end{cases}$$

The operations profile for the adjusted buffer-level cost profile and the example shown in Figure 4-12 are shown in Figure 4-13.

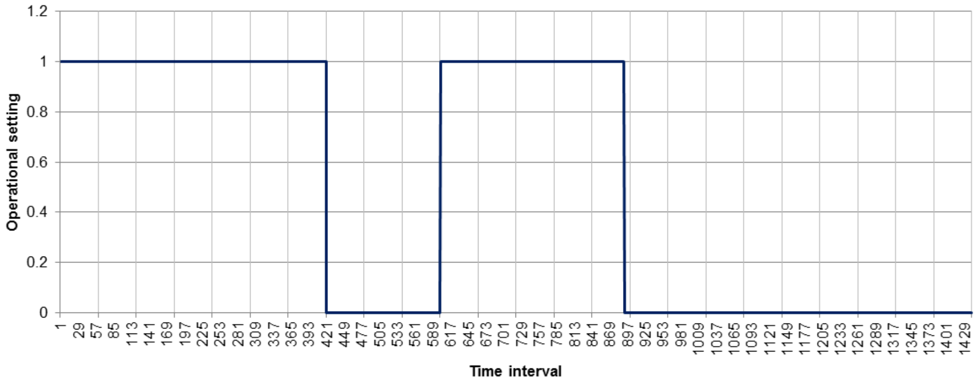


Figure 4-13: Example of an operations schedule for altered maximum cost line with buffer level

The cost induced by the buffer volume is added to the maximum cost profile, with time to prioritise operation of different time intervals. The different components iterate the same maximum cost line that is adjusted to the individual interacting buffer levels to recalculate the optimal operations. The operations are then used to recalculate the maximum cost profile and the process is repeated until the result is within error values. The iteration of operations is shown in Figure 4-14. The resulting optimal schedule then represents the global optimum for the system of component operations.

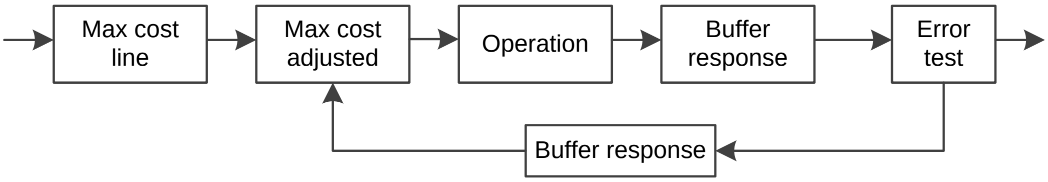


Figure 4-14: Buffer-level operations schedule iteration

4.7 APPLYING WDF WITH MULTIPLE PRODUCTS

Extending the buffer volume monitor enables the WDF to include multiple products. The multiple products buffer virtual induced cost is projected to the maximum cost line as shown in Figure 4-15. In the case of multiple products, the maximum between the different products that are higher than the energy cost profile are operational, as shown in Figure 4-15.

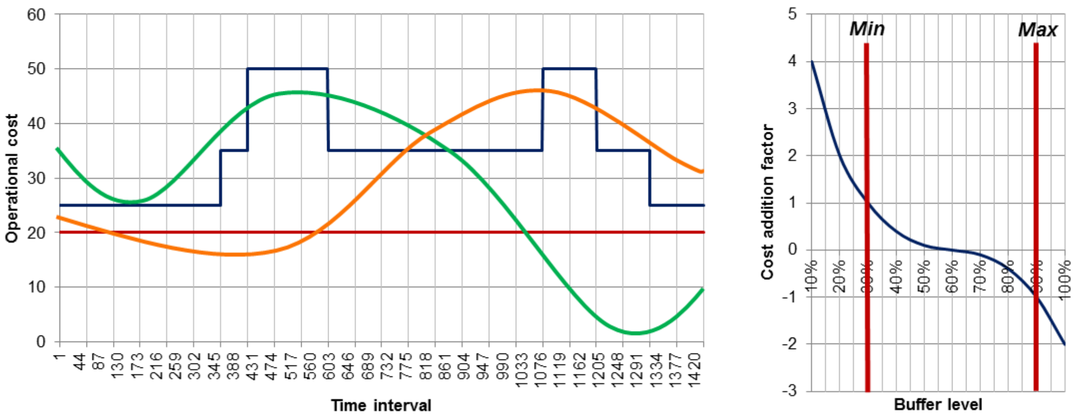


Figure 4-15: Example of a discontinuous cost profile with buffer level altered maximum cost profile for multiple products

The operational profile is generated for each product. Where the adjusted virtual maximum cost line is the highest and larger than the energy cost profile, the operation for that product is seen as on. This is simply represented as:

Equation 31

$$O_1(t) = \begin{cases} 1\,, C_{ad,1}(t) \geq E_c(t) \cup C_{ad,1}(t) \geq C_{ad,2}(t) \\ 0, C_{ad,1}(t) < C_{ad,2}(t) \\ 0\,, C_{ad,1}(t) < E_c(t) \end{cases}$$

The resulting operational profile for the example cost profile in Figure 4-15 is shown in Figure 4-16.

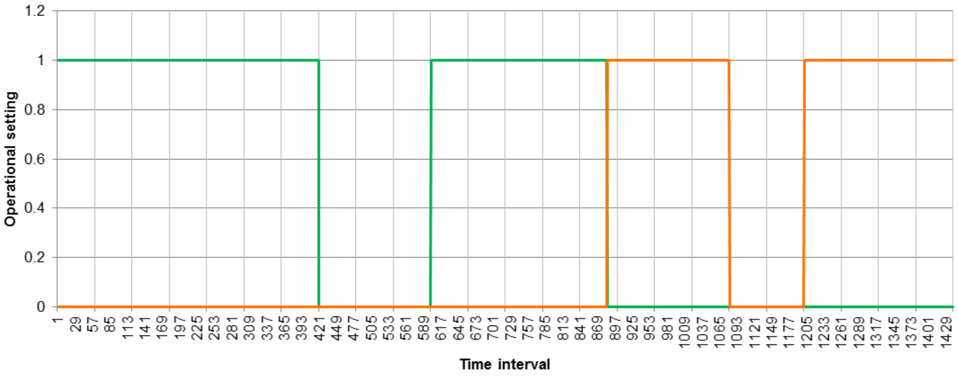


Figure 4-16: Example of an operations schedule for altered maximum cost line with buffer level for multiple products

Once again these profiles can be combined with multiple modes of operation to create a three-dimensional cost figure that generates both product and machine setting profiles. The generated profiles are also subjected to the iterative calculation technique shown in Figure 4-14 to generate a final operational schedule.

4.8 COMPUTERISED CONTROL SYSTEM

The modelling and simulation method is applied in real-time using the existing computerised control and communication system. The existing control system is expanded to incorporate the added complexity of operations modelling and the added input variables. Expanding and existing control system improves the sustainability of the solution as it is a tried and test technique to implement direct control. The original control system with information map is shown in Figure 4-17.

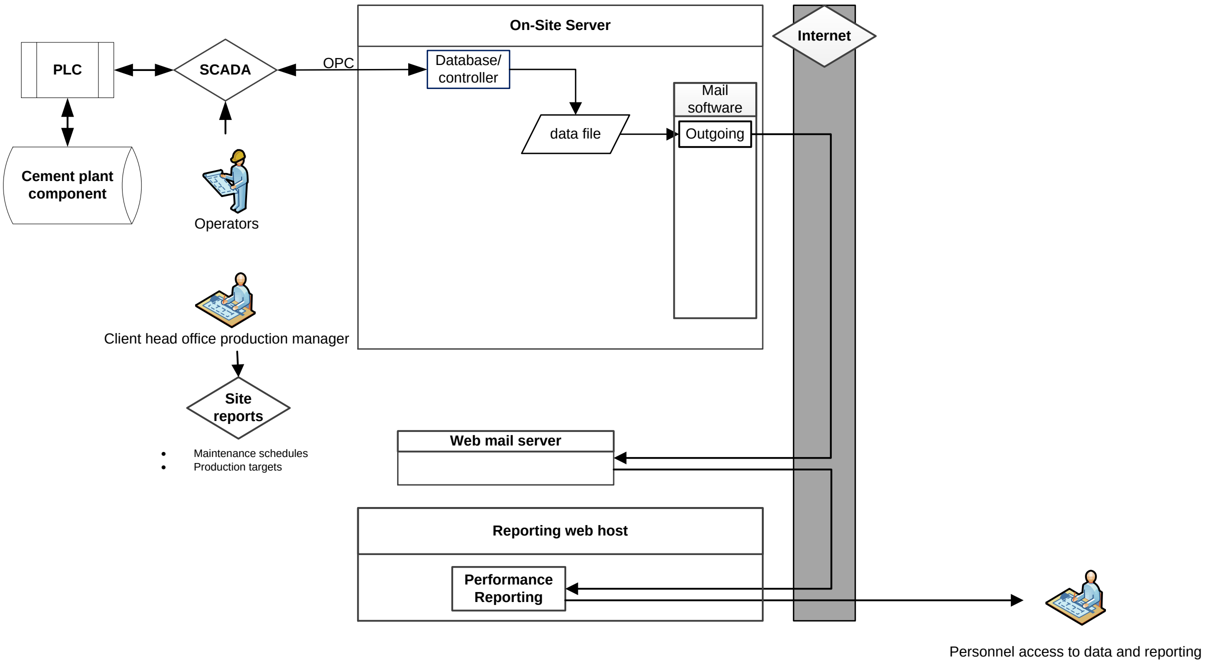
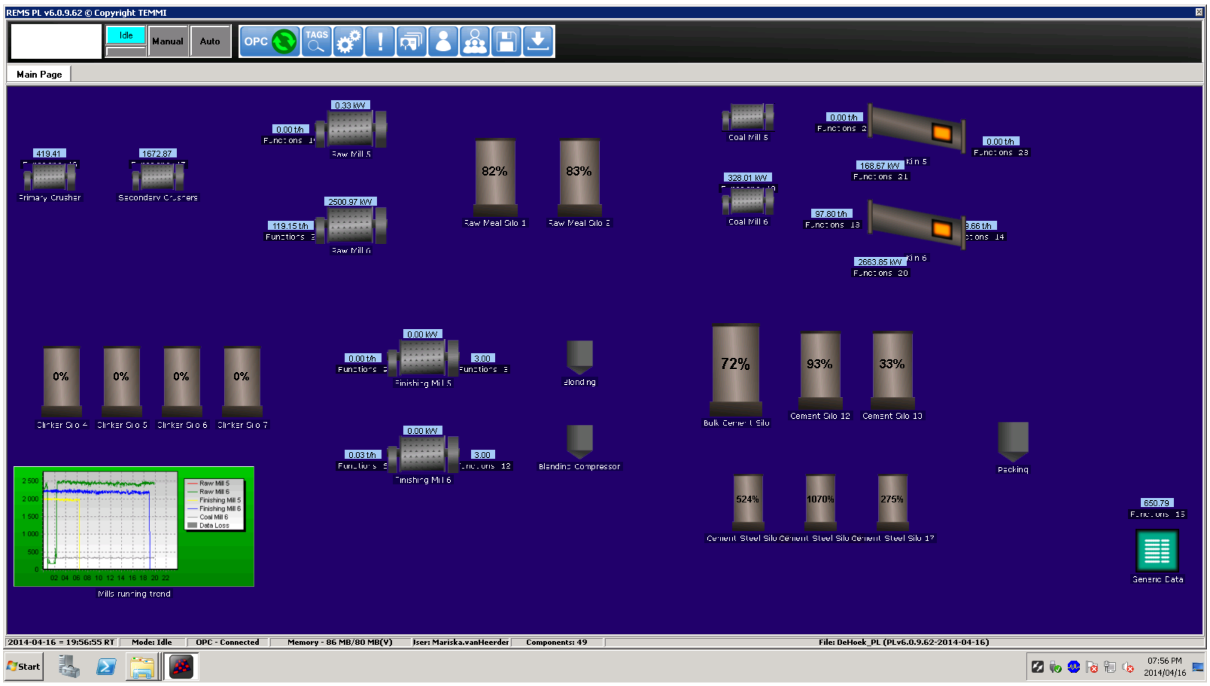


Figure 4-17: Real time energy management system layout

The existing control system comprises of a simple database controller that connects to the site SCADA via OPC. The controller is installed on a local server connected to the site process control computer network. Recorded data is sent to a web-based reporting system via automated mail software. From the web-based reporting system custom reports are generated and sent to client personnel to manage the sustainability of the projects. The in-site database controller's interface is shown in Figure 4-18.



REMS PL v6.0.9.62 © Copyright TEMMI

2014-04-16 = 19:56:55 RT | Mode: Idle | OPC - Connected | Memory - 86 MB/80 MB(V) | Jser: Mariska.vanHeerder | Components: 49 | File: DeHoek_PL (PLv6.0.9.62-2014-04-16)

Figure 4-18: Database construction interface on client server

The operations model requires a specialised server and a controlled network and data environment to account for the added processing requirements. Additionally, to ensure a stable and sustainable solution, a secondary local modelling server is used to compile operations model and simulation. The existing mail software is also expanded to assist the with the added data requirements. The new control system is shown in Figure 4-19.

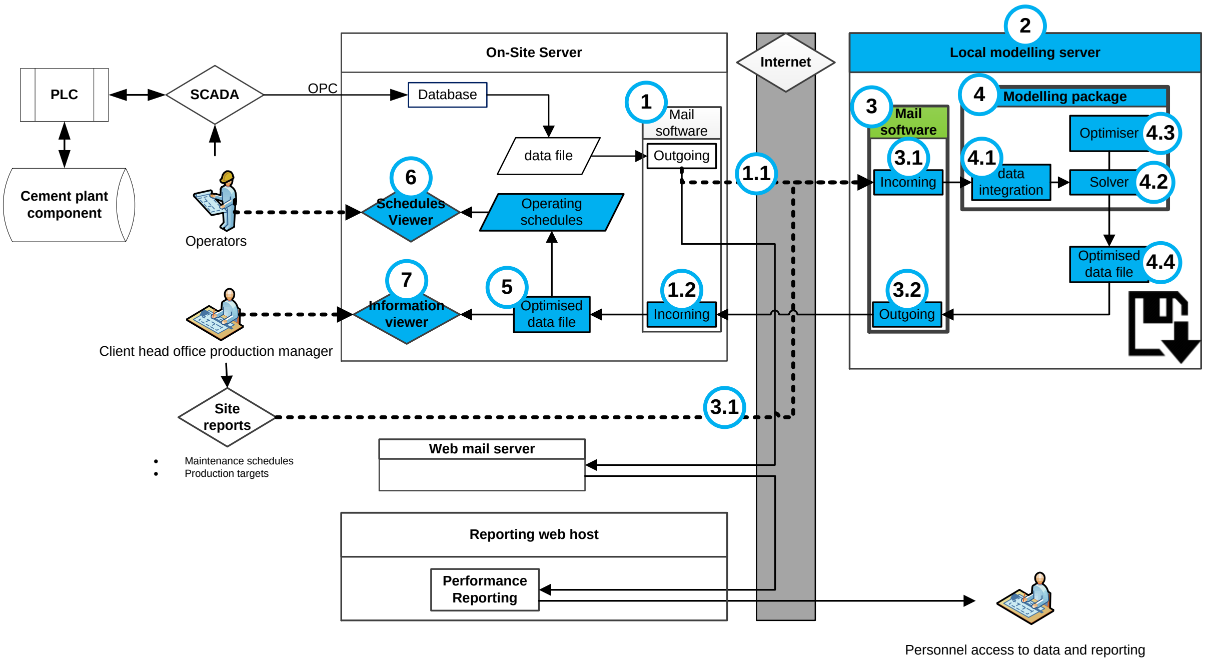


Figure 4-19: Proposed layout for additions to the real time energy management system

1. The mail software that is used in the existing real time energy management system for reporting is expanded.
    1.1. The mail software is expanded to include a second local modelling server address to which the recorded plant data is sent.
    1.2. The installed mail software on the on-site server is expanded to receive e-mails and store these emails in a designated location on the client network

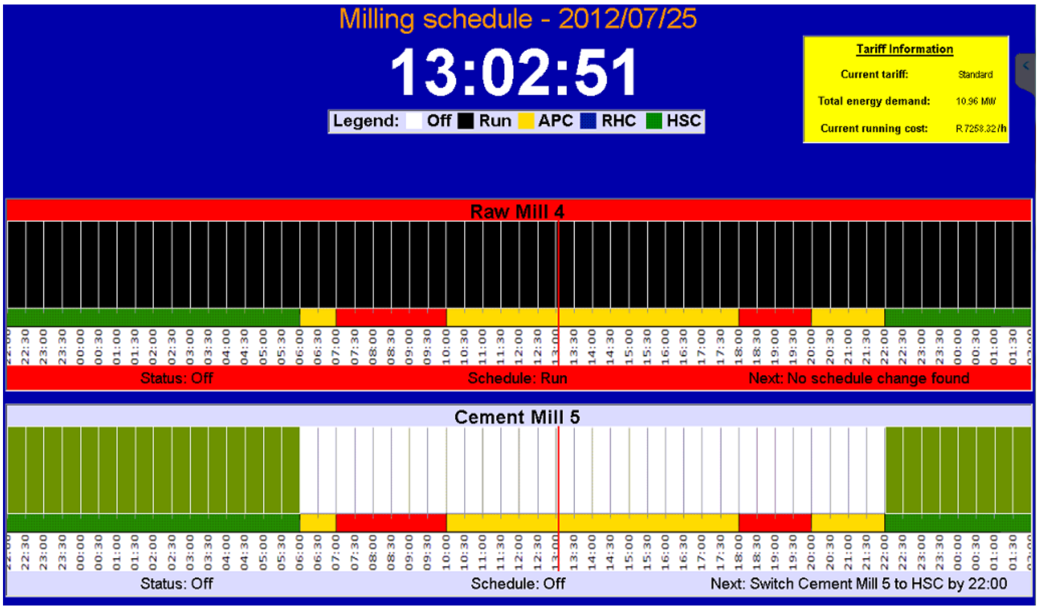
2. A new local modelling server is setup to manage and maintain the addition processing required to solve the real time operations modelling.

3. The original e-mail software is used to receive and store the different data files that are used to compile the operations model.
    3.1. Since the operations model uses a multiple variable scenario, different maintenance and production reports are obtained from site personnel and maintenance databases. The reports include preliminary sales and production forecasts, scheduled maintenance tasks and various other site specific reports.
    3.2. The e-mail also sends solved data files back to the site server including the production schedules and forecasted silo levels.

4. A modelling data handling package is developed that receive, process and compile the required data files and schedules.
    4.1. The received data is reformatted to a standard format and combined to generate a single data file that can be processed. The data file in integrated into the existing plant model and the present responses are simulated.
    4.2. A solver package compiles the model alters the variables to generate a solution to the present operational constraints and circumstances.
    4.3. A numeric optimiser extracts the modelling variables and simulation and iteratively alters the variables to reduce the target variable, which in most cases represents total operational cost.
    4.4. The optimised schedules are exported and stored as a generic data file. This ensures that data traffic during system communication is reduced and a stable and sustainable solution is generated. The data file is also stored in a local database for future reference.

5. The optimised data file is sent to site and store in a local reference folder.

6. The optimised data file is used to display the relevant operational schedules to machine operators. A simple user interface is used to display these schedules. Direct control via OPC communication and PLC control is possible, however, using the operators provides and additional factor of safety to machine operation. The operator user interface is shown in Figure 4-20.



Milling schedule - 2012/07/25

13:02:51

Legend: ☐ Off ■ Run 🟨 APC 🟦 RHC 🟩 HSC

Tariff Information

Current tariff: Standard

Total energy demand: 10.96 MW

Current running cost: R 7258.32 /h

Raw Mill 4

Status: Off

Schedule: Run

Next: No schedule change found

Cement Mill 5

Status: Off

Schedule: Off

Next: Switch Cement Mill 5 to HSC by 22:00

Figure 4-20: Operator interface to display operations schedules

7. An additional data file viewer is compiled to display more intricate operations management information to plant personnel (including production and maintenance personnel. This information includes operational schedules for extended periods of time, buffer response, required raw materials and other site specific information. The detailed user interface is shown in Figure 4-21.

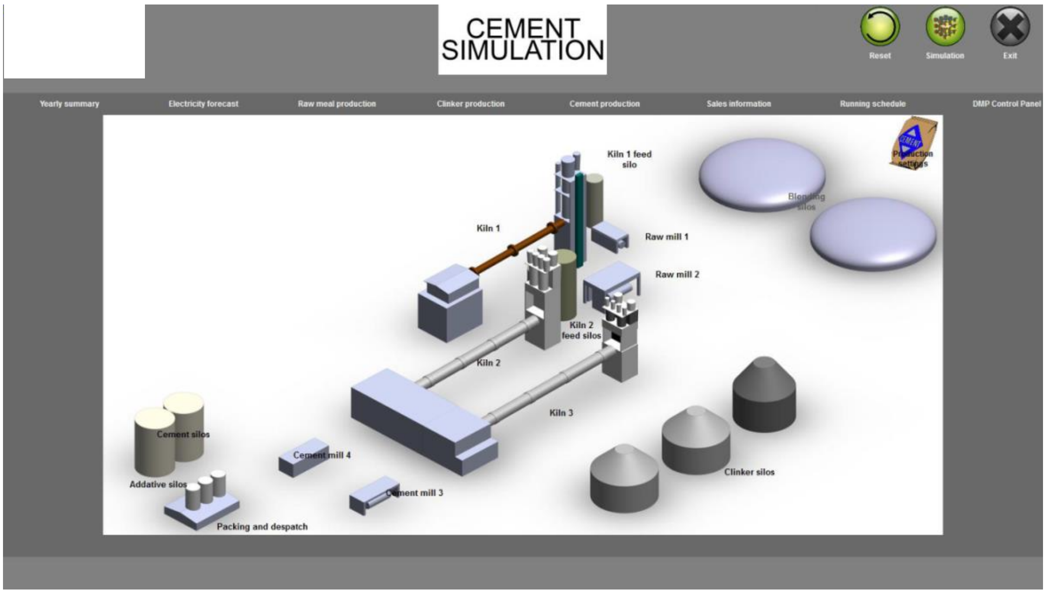


Figure 4-21: Detailed data file display for plant personnel

4.9 CONCLUSION

The second section of the methodology, simulation/time analysis, is set out in Chapter 4. A new analogy is developed and transcribed into a simulation approach. The analogy follows that in nature, water always settles on the lowest point of a given surface. Applying this analogy, referred to as the water drop formulation (WDF), to cost optimisation will generate a new approach to simulating the operations of a given system. The analogy was transcribed into an optimisation approach by using different simple mathematical concepts.

Three functions were developed to transcribe the optimisation effect of water on a surface to any cost- and operational environment. These functions are: A cost profile $E_c(t)$; a maximum cost line $C(t)$, and an operational profile $O(t)$. A maximum cost line is iteratively moved across the cost profile to generate an operational profile. Extending the analysis to three dimensions allows the WDF to analys different operational settings of a component in a real-world system (such as VSD control). Silo levels are added to the WDF to allow different components in a system to interact and in so doing, integrate the analyses of multiple components.

From the WDF approach, an optimal agregate cost profile can be derived. The aggregate cost profile gives the user an indication as to what the optimal operational cost is at a given machine utilisation. This aggregate profile can be used to analyse longer periods of time or more complex systems. The application of the new simulation technique is further explored in Chapter 5.

CHAPTER 5

Implementation and results

Chapter five

The implementation of this method for three different applications will be described in chapter five. This description will include the results of the implementation in the form of savings achieved over extended periods of time.

5 IMPLEMENTATION AND RESULTS

5.1 PREAMBLE

A new modelling technique was developed to simplify the implementation of operations planning on real-world systems. The new modelling technique was subdivided into two subcategories. These categories are a new component representation and a new time-modelling approach called the *Water Drop Formulation* (WDF).

The new component description combines a process effect with a time delay to account for residence time in production components and process effects encountered in buffer volumes. Additionally, a new link component was generated that can accumulate multiple flow inputs and distribute these flow inputs to multiple components. These two component descriptions simplify the construction of a component model for modelling of operations.

The new WDF time-analysis technique simplifies the in-time modelling of operations and propagates the component response throughout the system to unify the simulation of multiple components. The WDF presents a unique approach to minimising operations cost by monitoring the schedules and rate settings of multiple components. The WDF also iterates the response of residence volumes of different adjacent components that, in turn, propagate the influence of the operation schedules of specific components to the larger system of interdependent components.

The developed modelling techniques are used to plan operation schedules at three different types of industrial systems. These systems are cement production plants, gold mining ore handling and platinum ore handling. The modelling techniques are verified to validate the effectiveness and efficiency of the implementation. The model is set up for the specific applications components, and the impact of the time modelling is analysed. The cement process is used to validate the real-world impact of the modelling technique by altering the operations schedules and monitoring the operational costs.

The modelling technique is then used to model the gold- and platinum mining industry to identify further savings potential. The gold- and platinum industries represent different modelling challenges that are used to validate the flexibility of the modelling technique. The different applications will validate and verify that the goals of the thesis, as stated in Chapter 1, are comprehensively satisfied and prove the novelty of the applied solution.

Different mills and buffers are analysed during the implementation of the modelling techniques. To better clarify the operation of these components, a basic description of a mill, silo and thickener is given below.

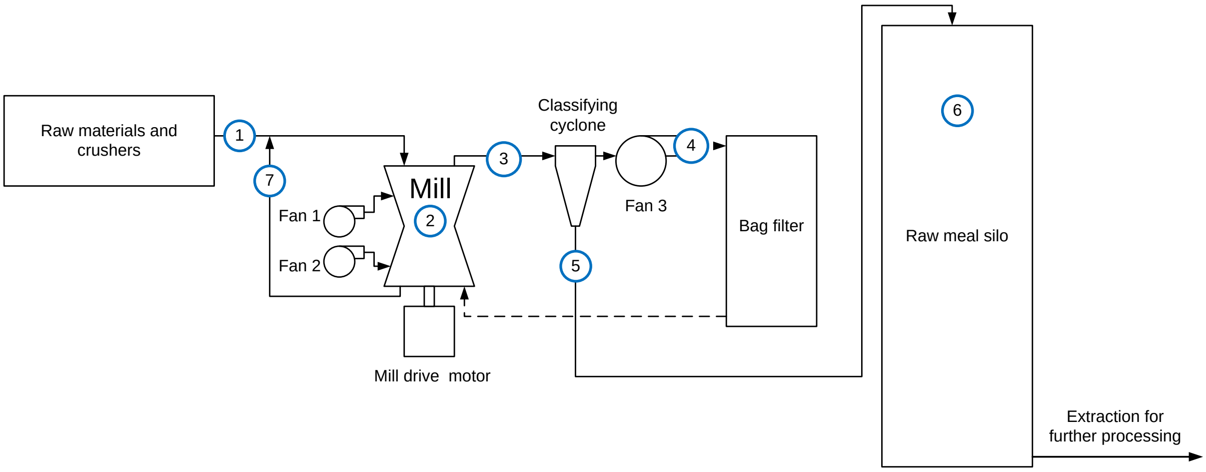


Figure 5-1: Operational diagram of a mill and silo circuit

From Figure 5-1, the descriptions as indicated by the numbers are further described:

1. Raw material is fed to a grinding mill using a combination of vibrating feeders, conveyor belts and air lift/pump systems. The raw materials are fed into the mill at an electronically controlled rate.

2. The raw material is fed into the mill. The mill uses different means to grind the raw material to a reduced particle size. These means include metal grinding balls in multiple chambers, grinding rollers or grinding presses. The temperature and air flow through these mills are controlled using large draught inducing fans.

3. After grinding in the mill, the raw material exits the mills suspended in the air draughts and enters a cyclone classifier. The classifier uses centrifugal forces to separate oversize particle from particles that are at an acceptable particle size.

4. Oversize particles exit the centrifugal classifier and are fed back into the grinding mill with the raw feed. These particles are re-ground until an acceptable particle size is achieved.

5. Particles of a correct particle size are fed into a storage silo known as buffers. The transport of the ground raw materials is facilitated by either airlift, conveyor or bucket elevator systems

6. The particles are stored in large buffers. The function of these buffers includes stabilising the flow between two adjacent component to reduce the impact of either scheduled or unscheduled shut downs of the components.

   An example of this in a cement plant is the raw meal silo. Should the mill be shut down for maintenance, the raw meal can still be fed to the down-stream kiln without unnecessary interruptions or fluctuations.

   Additional function of the silos includes homogenisation of the raw material to ensure that a stable quality and particle size can be fed to the down-stream components. These functions of the buffer components make them essential during a load management intervention.

7. In some mill configurations known as self-classifying mills, the interior of the mill acts as a classifier and re-directs oversize particles back to the raw material feed of the considered mill.

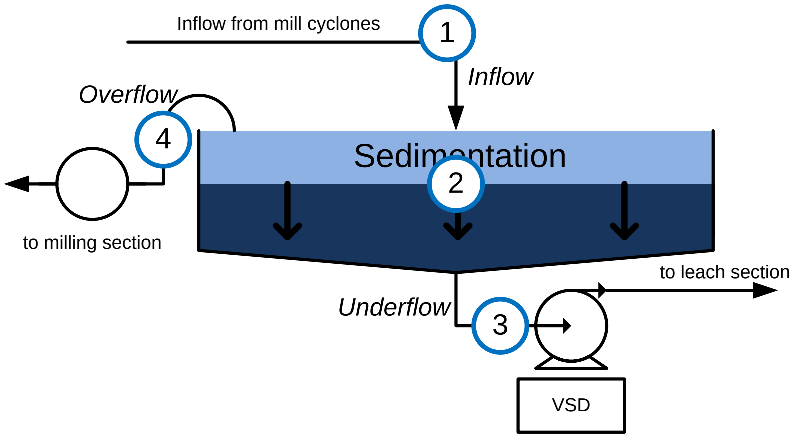


Figure 5-2: Operational diagram of a thickener

From Figure 5-2, the descriptions as indicated by the numbers are further described:

1. Gold plants utilise a wet milling process. This process mixes the raw material with dilution water when it is ground in the mills. Downstream from these mills, a thickener is use to increase the relative density of the fluid.

2. The relative density is increased by a process of sedimentation. A flocculent is added to the inflow of the thickener to assist the sedimentation of the fluid.

3. Over time, solid particles drop to the bottom of the thickener and is extracted by a VSD controlled pump.

4. Additional water, drifting to the top of the thickener overflows and is pumped back to the mill to be used as dilution water.

5.2 CEMENT PLANT IMPLEMENTATION

Before multiple different cement plant layouts are considered, the components are configured for a cement plant. A basic single process line using coal and electricity as energy sources is considered. The basic layout is depicted, using the component configuration as described in Chapter 3. It can be noted that coal is a product that is processed before being used as fuel in the kiln. The raw material cost depicts the cost allocated to the energy allocated to the coal that is used for pyro-processing in the kiln. The layout is shown in Figure 5-3

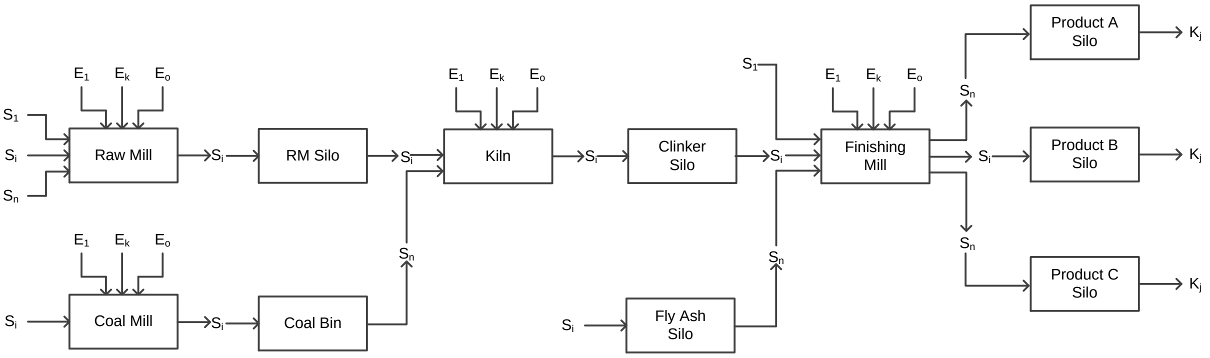


Figure 5-3: Basic cement plant components model setup

The description of the components is done using an example of a Raw Mill found in the cement production process. The original component does not limit the amount of energy inputs, inflow or outflow products for the processing component. The original representation of the new combined process component, as shown in Figure 5-4, is used to describe the considered raw mill component.

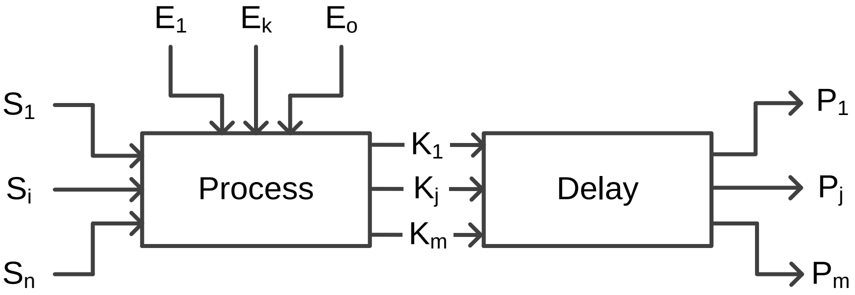


Figure 5-4: Representation of the process components with residence time

The different constants and inputs that are used in the new component description are aligned with the physical raw mill component found at cement production components. These show three inputs at the considered plant, a single output, no residence time and a single energy source. The component representation for the raw mill is shown in Figure 5-5.

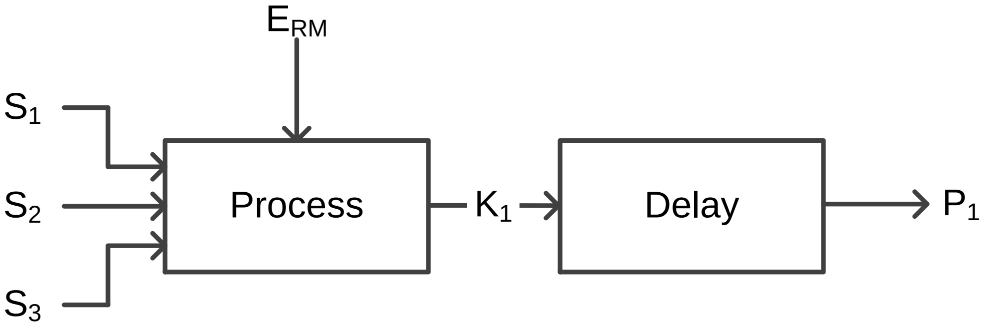


Figure 5-5: Representation of the process components with residence time for a cement raw mill

Figure 5-5 shows the setup of a Raw Mill component according to the component description laid out in Chapter 3. Considering a Raw Mill, three flow inputs are assumed. These flow inputs are Limestone (S_1), Magnetite (S_2) and additives (S_3). A single output is assumed. This output is Raw Meal. A single energy input is assumed. Energy is consumed in the form of electricity and is denoted by E_{RM}. The energy consumed is multiplied by the energy tariffs applicable to the component to generate a cost profile. This cost profile is used to generate an optimised operation profile with the *Water Droplet Formulation* (WDF). The delay part of the process component is assumed to be zero.

As a second example, a silo used on the cement production process is described. The silo is modelled using the component description discussed in Chapter 3. When considering a silo, no operational effect is assumed and a zero energy input is also assumed. The silo is also assumed to have a full homogenisation effect on the production fluid; however, product quality will not be monitored in this example. The silo level is monitored to calculate the optimal operation of the plant. The silo displays a dynamic response to the flow rate to- and from the silo to the other surrounding components. The component representation of the silo is shown in Figure 5-6.

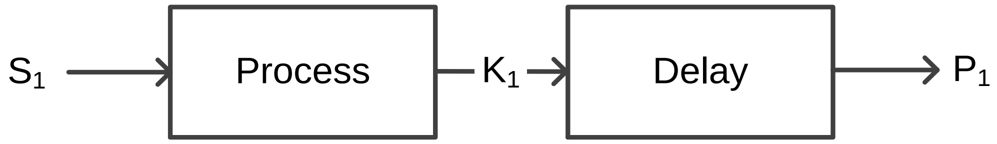


Figure 5-6: Representation of the process components with residence time for a cement silo

A dynamic response is assumed with inflow and outflow as data inputs, and the calculated level as the data output. The level is propagated to the other adjacent components using the WDF with varying storage capacity, as described in Chapter 4. The plant layout, such as the example shown in Figure 5-3, describes which components these levels are propagated to. The new silo description shows only a single inflow and a single outflow. In a case where the silo feeds from or to multiple components, the new link component description, as outlined in Chapter 3, will be used. The link component either sums the inflows to the silo, or distributes the outflow according to the component requirements.

Four plants are considered to validate and verify the new modelling techniques. The different cement plants pose different challenges and scenarios to evaluate the effectiveness of the new modelling techniques. The generated components described above are further investigated to confirm that the goal statement is satisfied by the developed methodology. The optimisation algorithm is also applied to the different plant layouts and implemented on the real-world systems to further prove that the generated operational solution is practical.

5.2.1 PLANT A

The first cement plant considered, cement Plant A, is a South African cement plant with two parallel clinker production lines and a single finishing line. The two clinker production lines share a common homogenisation raw meal silo and a common clinker silo. The two production lines were built during different periods and are thus not equally efficient. The older line requires a higher electrical intensity (kWh/t) and higher coal intensity ($\text{tonne}_{\text{coal}}/\text{tonne}_{\text{clinker}}$). The layout of the cement plant is compiled using the new component description, as described in Chapter 3. The generated layout of cement Plant A is shown in Figure 5-7.

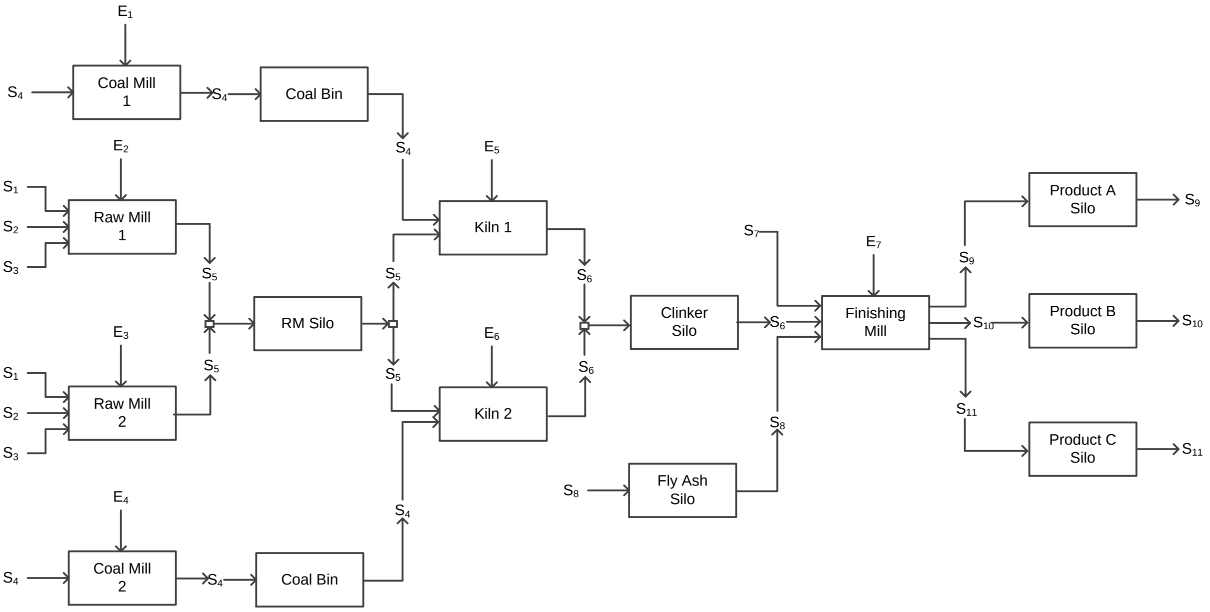


Figure 5-7: Component layout for cement Plant A

As stated, the boundaries considered in the analysis of the cement production process are the raw mill, the coal mill and the finished product silos. The raw material stockpiles, the coal stockpile and the secondary blending and packing are not included in the analysis. The boundary values preceding the raw mill and coal mill are seen as infinitely large. The boundary values following the product silos are fixed, in-time extraction as forecasted in sales figures by plant personnel.

The plant layout compiled for Plant A depicts the different products used at the plant. The products are assumed to stay definitively the same, thus no product characteristic is included in the analysis. Al process stages that are undertaken at Plant A are assumed to be complete, i.e. changing the product definition wholly from one product definition to another. The different products considered are summarised in Table 5-1.

Table 5-1: Product matrix for the cement production process at Plant A

Product label	Product description
S_1	Raw limestone
S_2	Magnetite
S_3	Raw meal additives
S_4	Raw dry coal
S_5	Milled raw meal
S_6	Clinker
S_7	Gypsum
S_8	Fly ash
S_9	Finished cement, product A
S_{10}	Finished cement, product B

S_{11}	Finished cement, product C

Using this component description, or *Virtual System Representation* (VSR), the WDF can be implemented on selected operations schedules at Plant A. The components that are considered for operations management are the large milling circuits. At Plant A these are Raw Mill 1, Raw Mill 2, Coal Mill 1, Coal Mill 2 and the Finishing Mill. The two kilns are not considered in this analysis as the cycling time and start-up costs are much greater than that of the milling circuits. When considering longer time periods, these components will be included, as is the case with Plant C.

VERIFICATION AT PLANT A

A time-of-use tariff structure is used to charge the client at Plant A for electricity consumed. This tariff structure is Eskom's MegaFlex tariff scheme. In the MegaFlex tariff scheme, a working week is subdivided into three tariff periods, viz. off-peak, standard and peak times. The tariff structure also considers two seasons during which these three tariffs also differ. These seasons are High Demand Season (1 June to 31 August) and Low Demand Season (1 September to 31 May). These tariffs are used to compile a cost curve for the WDF.

The cost curve is normalised by evaluating the cost per tonne of final product that is produced. Since there are multiple final products with different compositions, the volume of raw material required is propagated back through the VSR to quantify the normalised operational cost of downstream components. This scale is linked to the specific cost, or cost per ton of final product produced. The normalised cost per component is thus simply linked to the conversion factor of the component itself. This provides a simple form of scaling of the maximum cost curve when analysing a system of components.

Two different curves are compared when compiling the WDF, as described in Chapter 4. These are the cost curve and the maximum cost line. The maximum cost line is kept equal between the different components while the operation is iterated as described in Chapter 4. This ensures that parallel components are compared in efficiency and cost-effectiveness through all the considered tariff periods. The normalised cost curve for the different components that are considered at Plant A is shown in Figure 5-8.

The unifying control variable during optimisation is total cost. Each iteration monitors the specific cost of operation during the different periods of the time interval to account for TOU tariffs. During iteration the total cost as encountered by the relative silo adjusted cost risk is recalculated. The example depicted in Figure 5-8 uses a specific target production to calculate the most efficient operating schedule.

The operating schedules are calculated as a simple binary variable (on/off). Figure 5-9 depicts the operating schedules for the generated solution. The coloured areas represent the time periods during which the component is operational and the uncoloured areas represent periods when the component is not operational. It can be seen that the WDF only uses the Mega-Flex off peak periods to produce the required cement.

The simulation calculates the silo response to the operation shown in Figure 5-9. The inflow to the different silos from the operational components changes the related silo volumes. At the start of the next iteration, the model uses the calculated buffer volume feedback and shifts the operation of the components to keep the buffer volumes within acceptable levels within 10 iterations. Figure 5-10 shows the predicted storage response to the operational schedules calculated and shown in Figure 5-9.

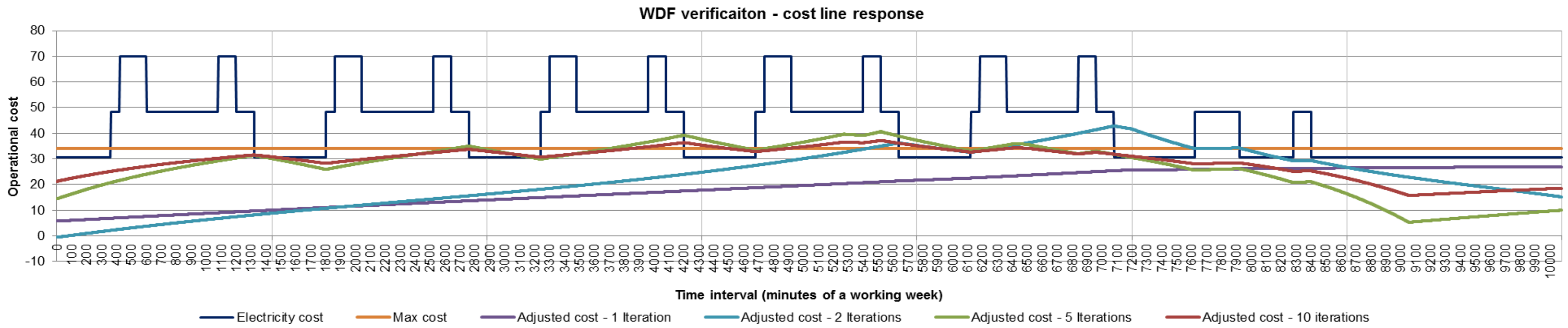


Figure 5-8: Cost curve with adjusted maximum cost curves for the three mills at Plant A after 10 iterations

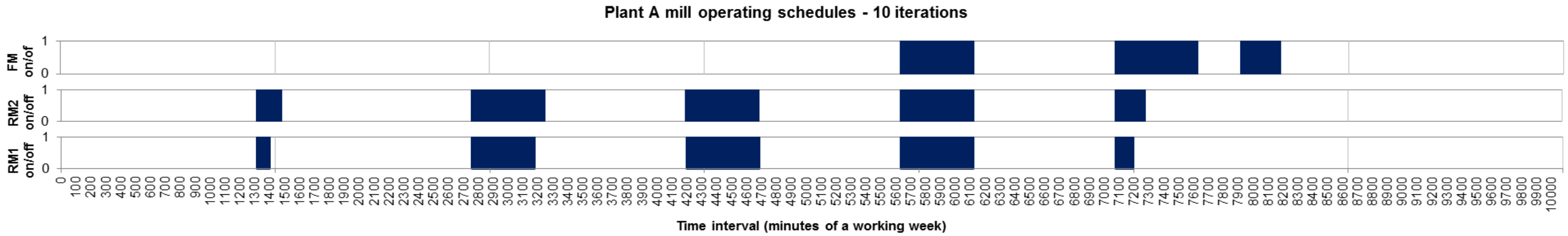


Figure 5-9: Component operational schedules after WDF optimisation at Plant A after 10 iterations

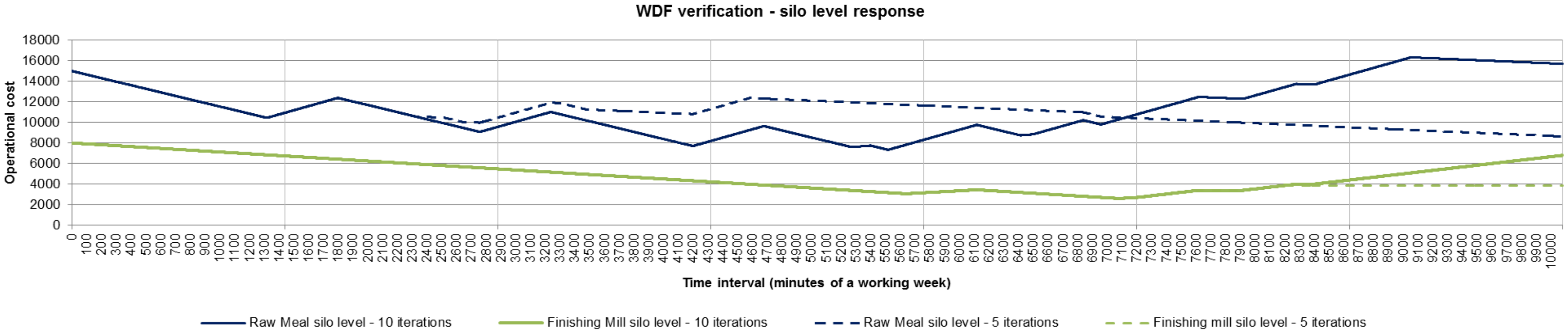


Figure 5-10: Storage response to operating schedule at plant

VALIDATION AT PLANT A

The electricity savings for the project for the period from 01 June 2012 to 01 June 2013 are shown in Figure 5-12, Figure 5-13 and Figure 5-14. The South African electricity utility, Eskom, uses a time-of-use tariff structure to bill clients for electricity during different periods of the week. These tariff periods are divided into peak, standard and off-peak periods. The different tariff periods and associated times are shown in Figure 5-11

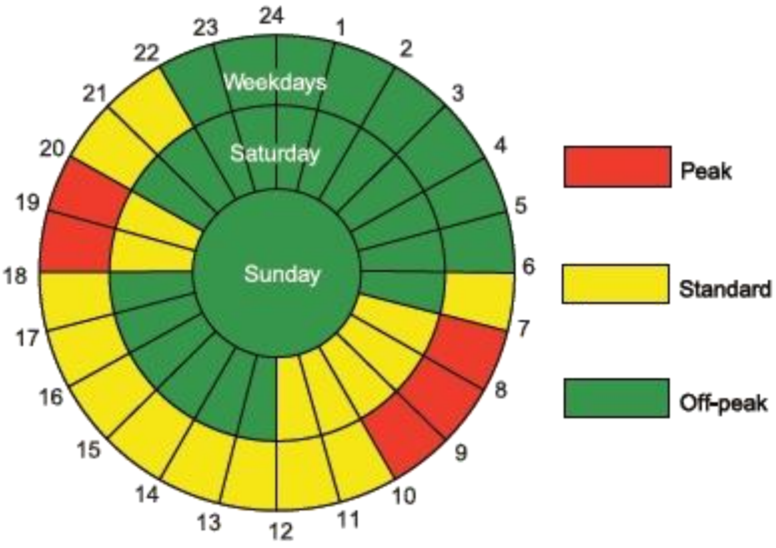


Figure 5-11: Eskom time-of-use tariff periods

Figure 5-12 shows the weekly average power consumption profile for Plant A. This graph shows the baseline electricity consumption, a scaled baseline, and the actual post-implementation electricity consumption profiles. The baseline electricity consumption is the average plant electricity consumption before the scheduled optimisation was implemented. The actual post-implementation electricity consumption shows the demand after the schedule optimisation was implemented. Due to production variation, a scaled baseline is compiled to alter the original baseline to represent present production figures.

Figure 5-12 shows the reduction in peak period power consumption during weekdays. Additionally, the weekly average power consumption graph shows an increase in weekend electricity demand. Figure 5-13 shows the average power that has been shifted to less expensive weekend periods. Weekends comprise of only MegaFlex Off-peak and Standard periods. Shifting load from Weekdays to Weekends reduce the specific cost of operation. In Figure 5-13, the scaled baseline entries represent what the plants operating power consumption was before the load management intervention was initiated. The actual entries represent what the specific electric demand of production was after the load management intervention was implemented.

Similar to Figure 5-13, Figure 5-14 displays the influence that the simulation system had on the electricity demand of Plant A. OP, S and P represent the Off-Peak, Standard and Peak MegaFlex periods respectively. The scaled baseline entries represent what the plants operating power consumption was before the load management intervention was initiated. The actual entries represent what the specific electric demand of production was after the load management intervention was implemented.

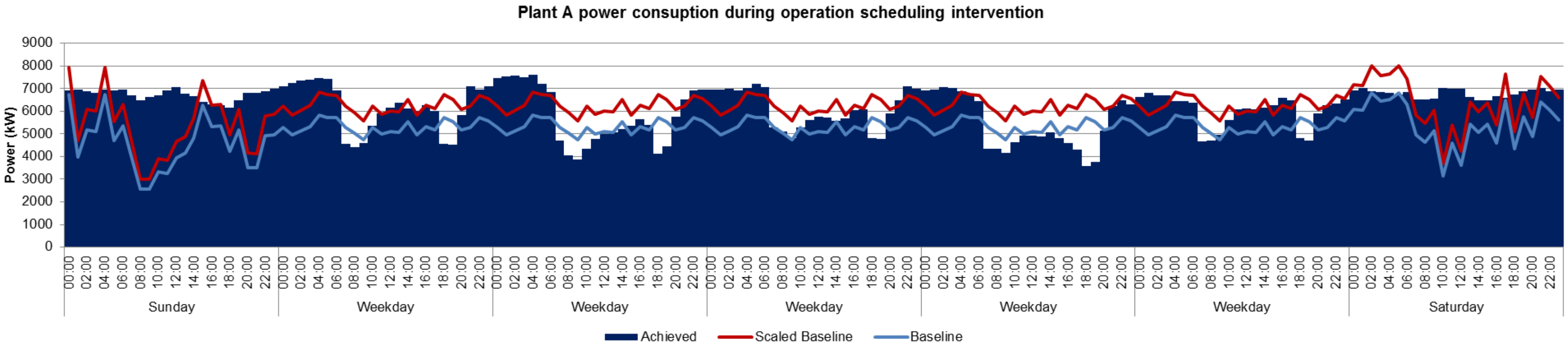


Figure 5-12: Weekly electricity demand during operations scheduling intervention at Plant A

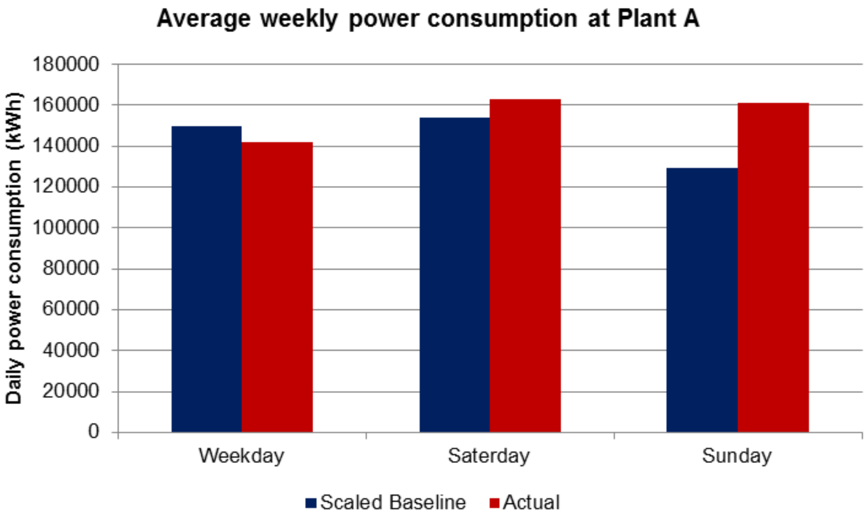


Figure 5-13: Weekday to weekend load shift trend at Plant A

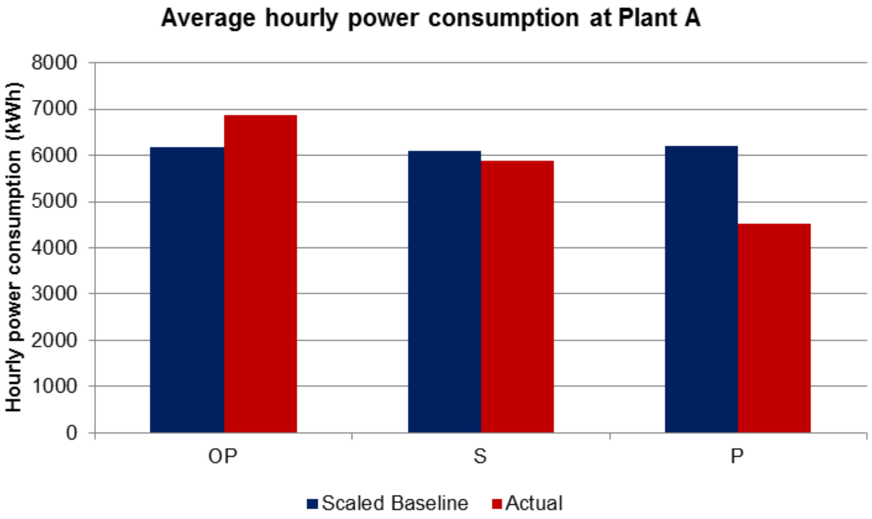


Figure 5-14: Load shift trend between tariff periods at Plant A

5.2.2 PLANT B

Plant B is the second plant analysed to test the efficiency of the new component description and the WDF. This South African cement plant consists of a single clinker production line with two parallel finishing mills. Though the two finishing mills are identical, a single high-efficiency separator is installed on Finishing Mill 1. The high-efficiency separator allows Finishing Mill 1 to use less clinker than Finishing Mill 2 to produce the same quality finished cement. Finishing Mill 1 is the preferred mill during cement production, since clinker is more expensive than the other raw materials used in cement finishing. The component layout of Plant B is shown in Figure 5-15.

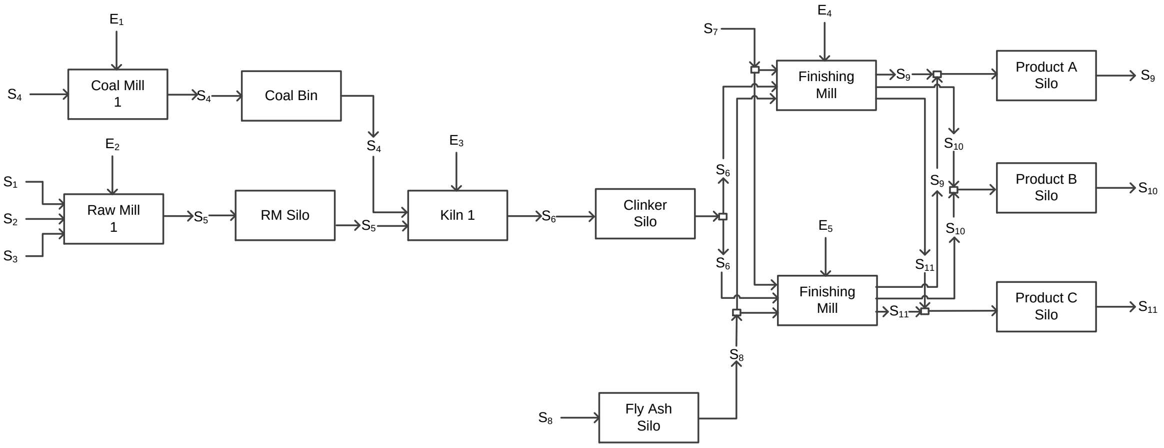


Figure 5-15: Component layout for cement Plant B

Plant B tends to favour using Finishing Mill 1 during the production of cement due to efficiency of the separator. Favouring Finishing Mill 1 does not, however, represent the most cost-effective solution. Comparing the cost implication of the raw materials with the different energy costs during the operation of the mills will allow the user to determine an operations schedule with a global optimum cost. The raw material requirements are noted in the component setup of the new model. Including the raw material costs in the adjusted maximum cost line allows the new model to include the raw material costs in the analysis.

VALIDATION AT PLANT B

The electricity savings for the project for the period from 01 June 2012 to 01 June 2013 are shown in Figure 5-16, Figure 5-17 and Figure 5-18. Figure 5-16 shows the weekly average power consumption profile for Plant B. This graph clearly shows the reduction in peak period power consumption. Figure 5-17 also shows that the average power consumption has been shifted to less expensive weekend periods. Figure 5-18 shows the average hourly load was shifted out of the MegaFlex peak periods to less expensive off-peak periods, in turn signifying an electricity cost reduction.

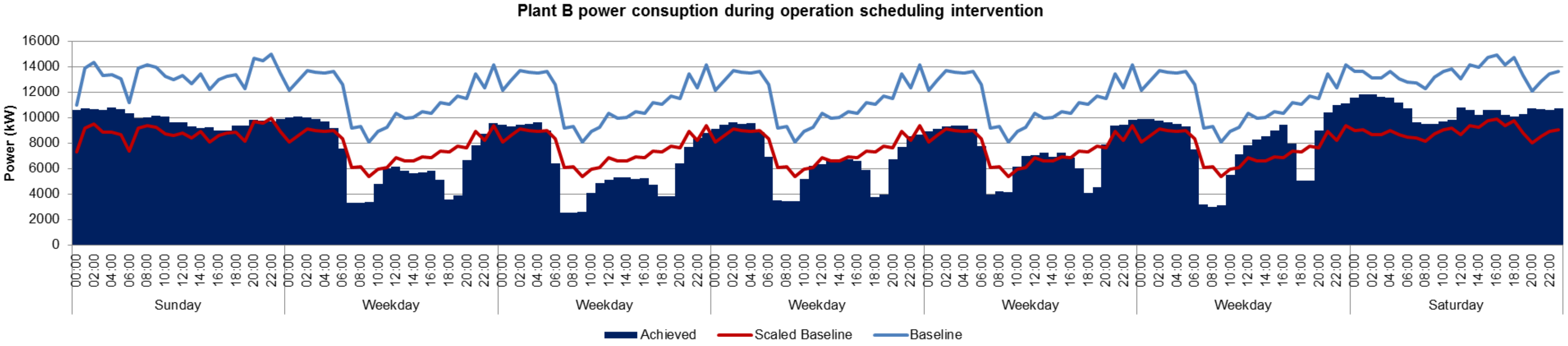


Figure 5-16: Weekly electricity demand during operations scheduling intervention at Plant B

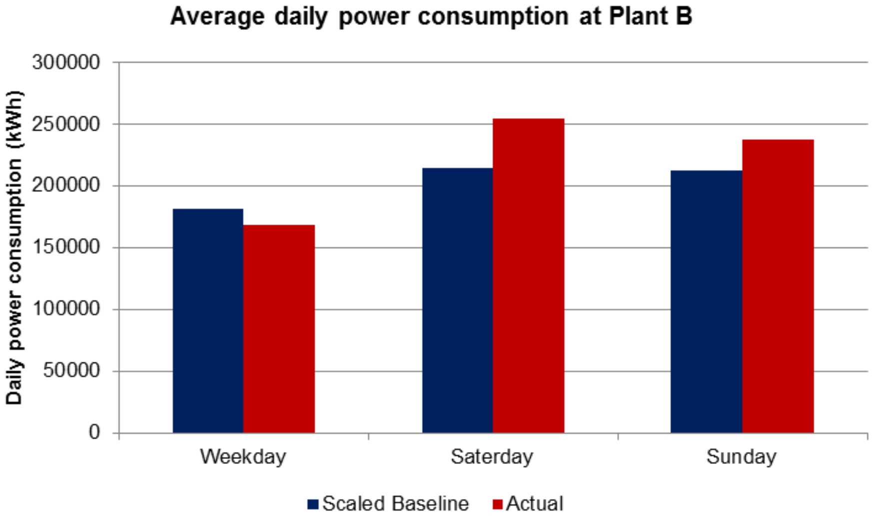


Figure 5-17: Weekday to weekend load shift trend at Plant B

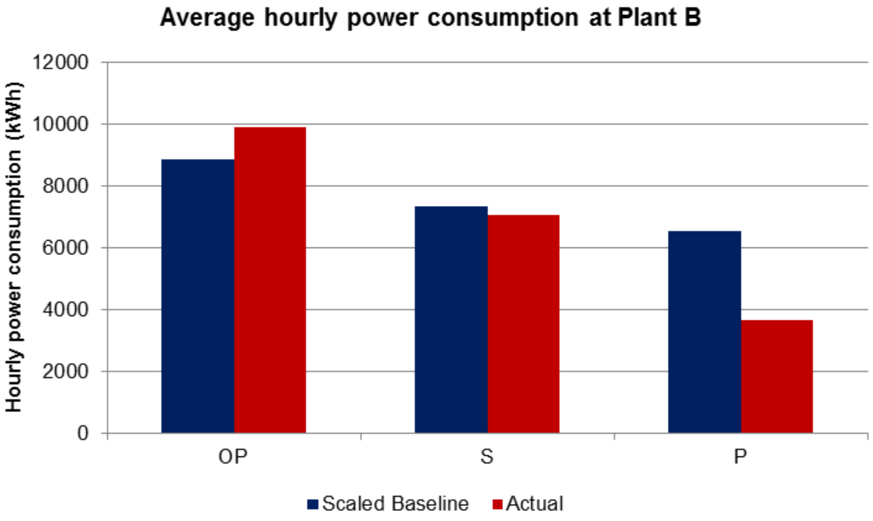


Figure 5-18: Load shift trend between tariff periods at Plant B

5.2.3 PLANT C

Plant C acquires clinker from another larger clinker production line in South Africa. Plant C thus consists of only two parallel finishing mills. The two finishing mills are identical and produce three different products. The plant only consumes energy in the form of electricity. The plant is located in an industrial suburb and is subject to higher electricity tariffs than the other competing cement plants. Plant C is therefore subject to closing down unless the energy cost, and more specifically electricity costs can be reduced. The layout of the plant is shown in Figure 5-19.

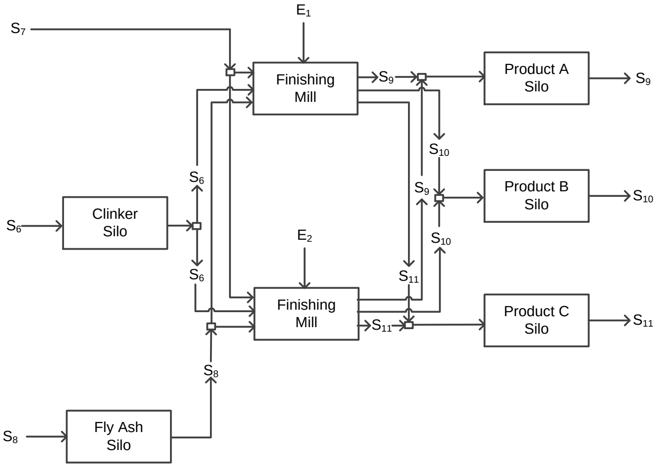


Figure 5-19: Component layout for cement Plant C

Increased energy efficiency has formed the primary focus at Plant C. However, rescheduling operations to decrease the specific energy cost (R/t) instead of specific energy consumption (kWh/t) gives the plant the opportunity to remain productive in the competitive South African cement market. This can be achieved by ensuring that the plant only operates during less expensive tariff periods. The plant is in most cases referred to as a “swing plant”, as it is only used to fill market capacity that cannot be achieved by other more efficient plants. This occurs during unscheduled stops, market sales surges or other unpredictable production influences.

VALIDATION AT PLANT C

Manually scheduling the operations at Plant C is limited by junior personnel assigned to the plant and generally unpredictable sales targets. Real-time adapting of a modelling system is thus imperative to reduce the plant’s electricity costs. The modelling technique, including the WDF, was implemented at Plant C from 5 December 2013 to 28 April 2014. The weekly load profile shows the peak period energy consumption in Figure 5-20. The weekday to weekend load shift trend is shown in Figure 5-21, with the peak period to off-peak period load shift depicted in Figure 5-22.

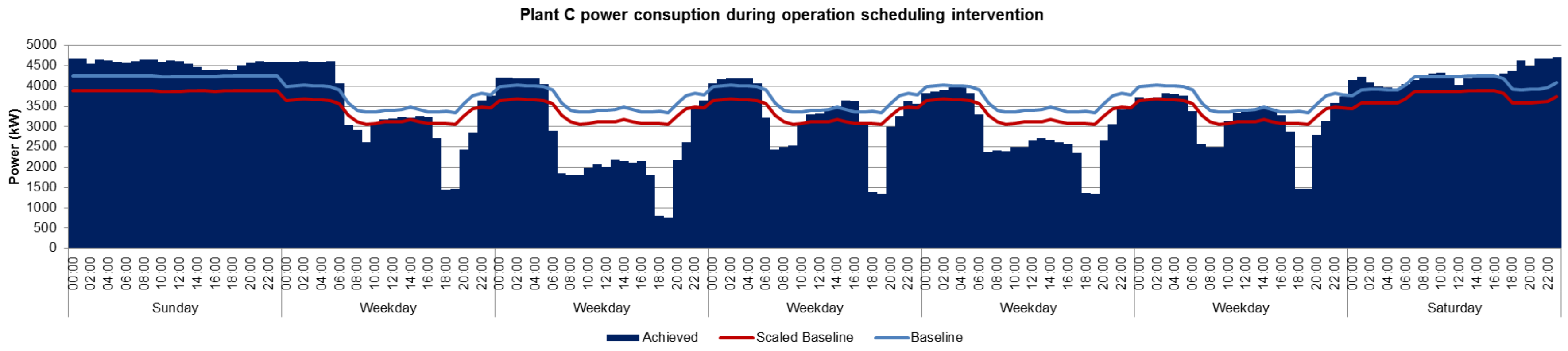


Figure 5-20: Weekly electricity demand during operations scheduling intervention at Plant C

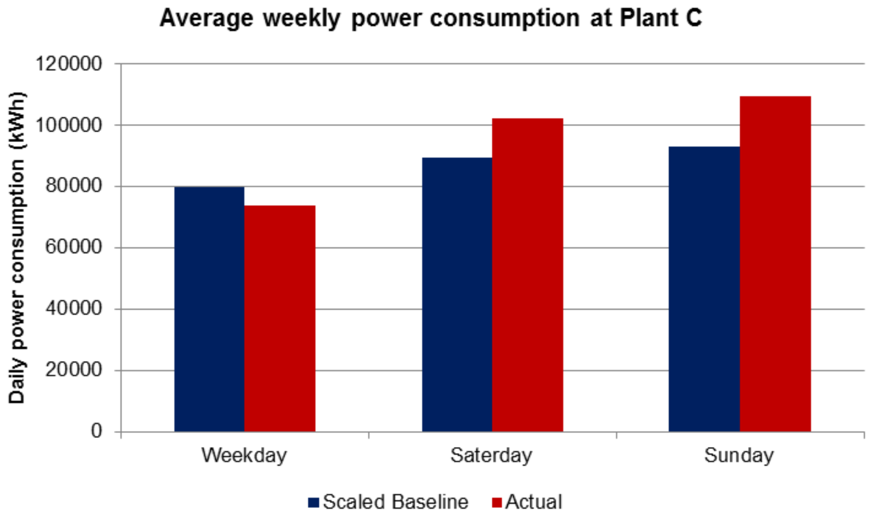


Figure 5-21: Weekday to weekend load shift trend at Plant C

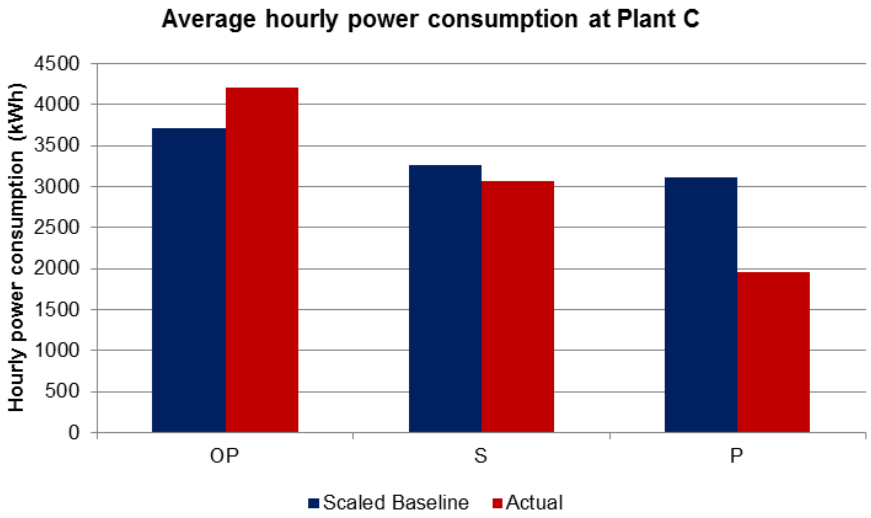


Figure 5-22: Load shift trend between tariff periods at Plant C

5.2.4 SUMMARY OF CEMENT IMPLEMENTATION

The new modelling techniques were implemented at three cement plants in South Africa. A baseline energy usage was recorded before the intervention was undertaken. The cement plants' energy usage was monitored for a performance tracking period, during which the electrical demand of the plant was compared to the baseline. The results showed that the average electricity consumption trend changed after the new modelling techniques were used to compile operating schedules. The results showed that the electricity consumption was shifted according to electricity cost.

The three plants showed a peak period demand reduction. Considering the weekly energy consumption, it was shown that the production demand was shifted from expensive weekday periods to less expensive weekends. The hourly energy consumption also showed that production load was shifted from expensive peak periods to less expensive off-peak periods. In general, the hourly electricity consumption showed a stacked demand trend, with highest demand in off-peak periods, reducing to the lowest demand in off-peak periods, according to plant production demand.

The total savings achieved by these projects, when comparing the post-implementation electricity consumption to the baseline, are summarised in Table 5-2:

Table 5-2: Summary of cement projects implementation

Plant	Annual baseline electricity costs	Annual electricity cost savings (pa)	Total savings impact
Plant A	R 31.83 Million	R 2.33 Million	7.3%
Plant B	R 37.93 Million	R 2.16 Million	5.7%
Plant C	R 17.07 Million	R 1.26 Million	7.3%
Total	***R 86.83 Million***	***R 5.75 Million***	***6.6%***

5.3 GOLD MINE INVESTIGATION

The cement plant investigations proved that savings can be achieved by implementing the developed modelling techniques. The new modelling technique is also applied to the gold industry. In South Africa, gold is mined in ultra-deep mines and is then extracted using a series of mechanical and chemical processes. In the gold plant that is considered, ore is received from various shafts and is stored in large reception silos. The ore is fed from the reception silos to a wet milling circuit, where dilution water is added. Gold ore in a fineness range is then passed on to a thickener section, where the gold slurry is thickened to a specific relative density for further processing.

Excess production capacity is available at the gold plant. Additionally, different forms of ore are processed, with a large variance in characteristics, including hardness, abrasiveness, particle size and gold content or grade. Chemical treatment of the gold extraction process requires a specific RD to be able to function. Due to the varying ore characteristics and the process dependence on a stable RD, the milling process is closely monitored to ensure a stable RD from the underflow of the thickener. Figure 5-23 depicts the layout of the gold plant.

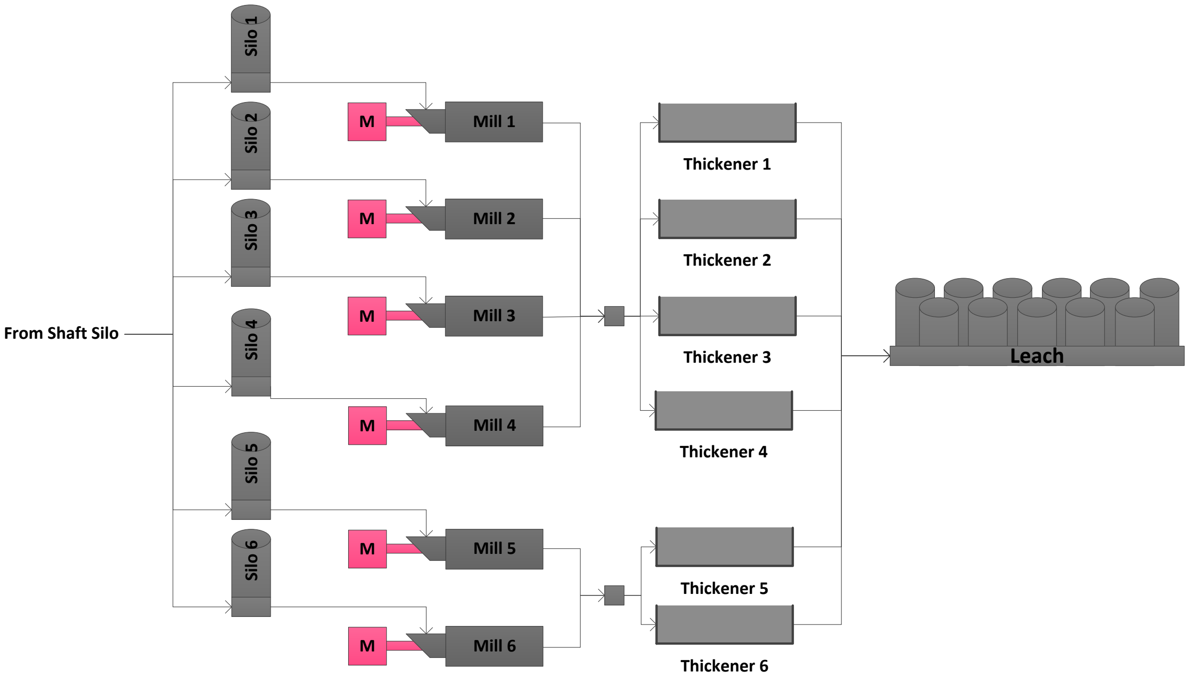


Figure 5-23: Gold plant layout

The gold plant is modelled using the modelling component descriptions. Two sections of the gold plants are considered with the aim of reducing electricity cost at the milling components, as these components are the largest electricity consumers at the gold plants. Figure 5-24 shows the component layout for the gold plant. The two sections are the milling circuits with the preceded ore storage silos and the thickening section. The system is modelled for flow of process fluid and RD of that processed fluid. The electricity consumption of the milling components is the cost function that is considered.

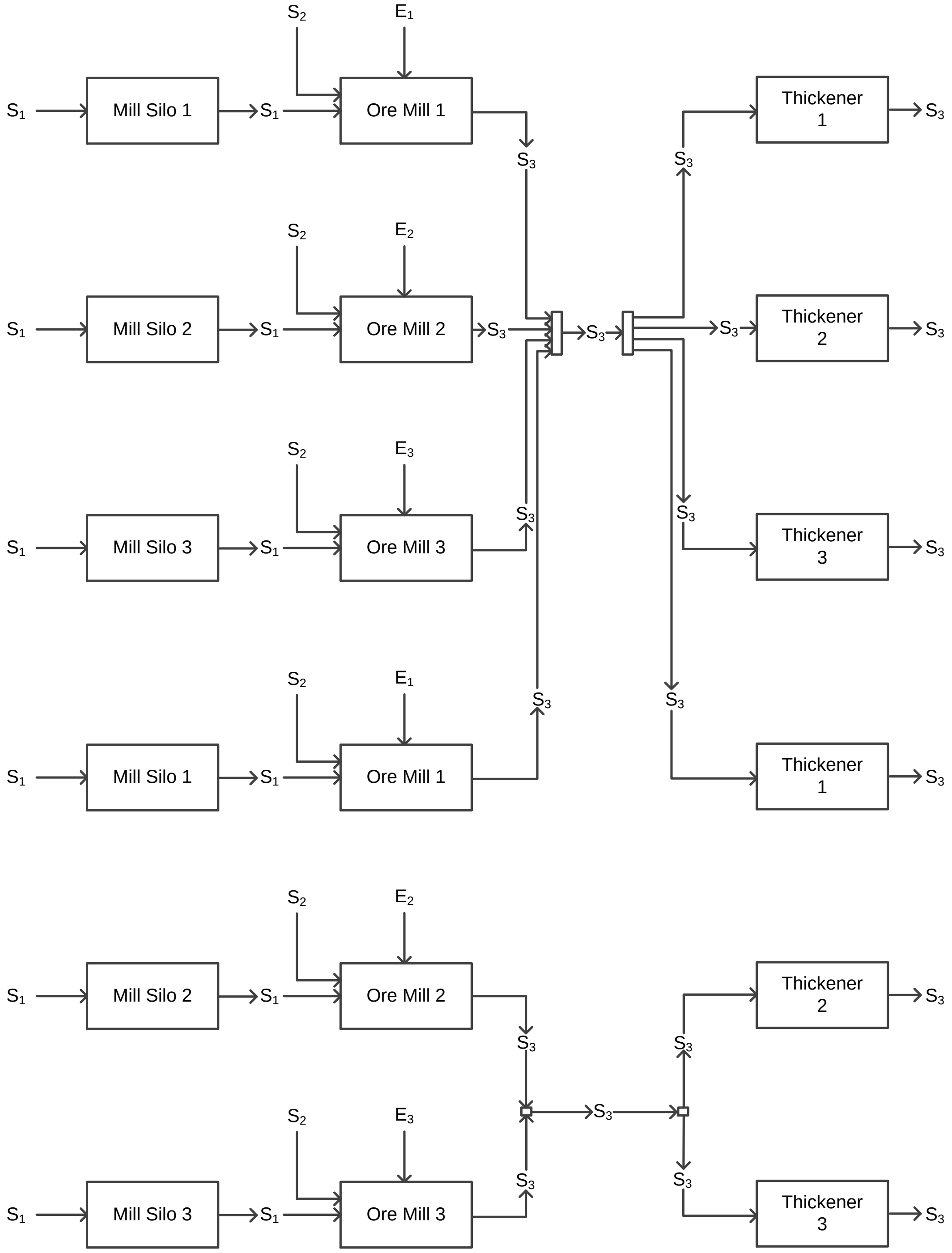


Figure 5-24: Component layout for Gold Plant

The simulation is compiled by monitoring the inflow of ore from the shafts into the mill silos and by maintaining a control RD in the underflow from the thickener. The control variable is monitored throughout the system. It is assumed that the gold ore and the dilution water maintain a constant RD. The product matrix for the gold plant simulation is shown in Table 5-3.

Table 5-3: Product matrix for the gold plant model

Reference	Product	Variable 1
S_1	Ore dry	RD – Fixed
S_2	Dilution water	RD – Fixed
S_3	Ore slurry	RD – Variable

The operations of the gold mills can be controlled by either varying the feed to the mill, or by applying a simple on/off schedule. The most effective way to reduce electricity costs, however, is to use the excess production capacity to shift milling load from expensive peak periods of the TOU tariff structure to less expensive off-peak periods and weekends. The operations of the mills are, however, limited to the underflow RD of the thickener. The thickener RD must be closely controlled to ensure a stable inflow to the leach section and to optimise the recovery obtained from the chemical processing.

VERIFICATION AT THE GOLD PLANT

To ensure that the simulation accurately models the response of the gold plant system, various characteristics of the system are compared with recorded data. Figure 5-25 shows the simulated RD when compared to the achieved RD at the gold plant. The simulated RD closely follows the actual RD that is recorded and remains accurately between the bounds of the underflow RD. This proves the accuracy of the simulations. Singular deviations from the simulated RD represent breakdowns of auxiliary components, but do not have a large effect on the accuracy of the simulated results.

Additionally, the control of the mills also needs to be monitored well to ensure a stable underflow particle size. The mill power consumption gives a strong indication of the mill load in tonnes. An accurate controlled mill load ensures that the mills grind remains effective and stable. Figure 5-26 shows the simulated power consumption compared to the actual power consumption. PLC control ensures that the mill controls well; however, the forecasting of the component response assists operations personnel to plan plant shut-downs or start-ups for minimum electrical cost.

The simulated power consumption accurately follows the actual power consumption, also indicating that the simulation is accurate enough for control of the milling section. *Area A* in Figure 5-26 represents an unexpected breakdown on the mill feeder belt and shows a deviation from the simulated values. Unplanned maintenance stops can be considered by incorporating a reliability factor into the simulation method to still obtain the target production.

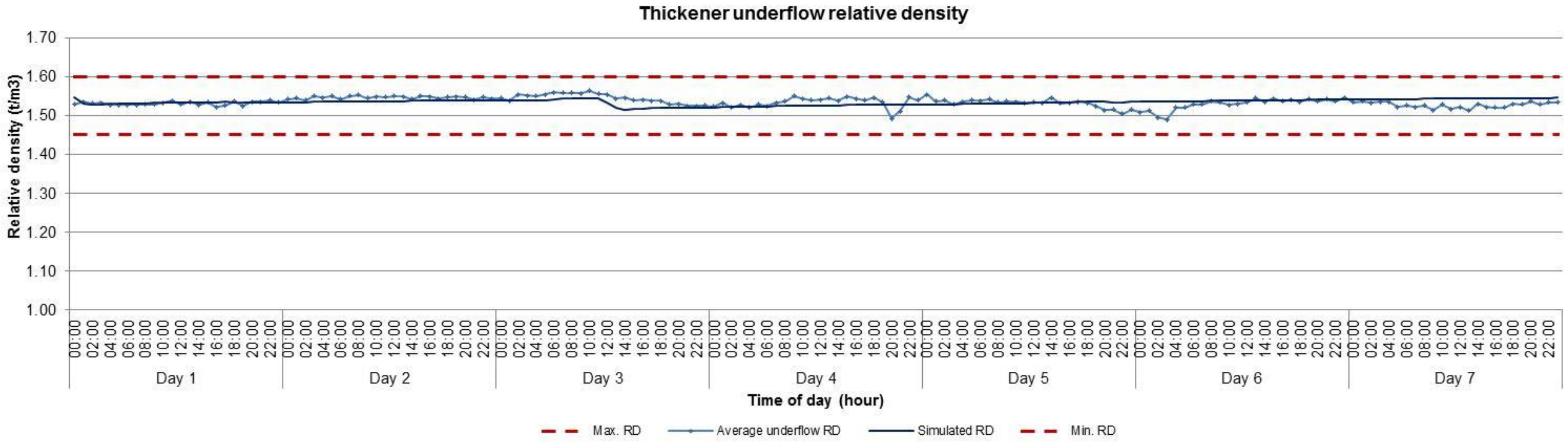


Figure 5-25: Gold plant thickener underflow RD simulation accuracy

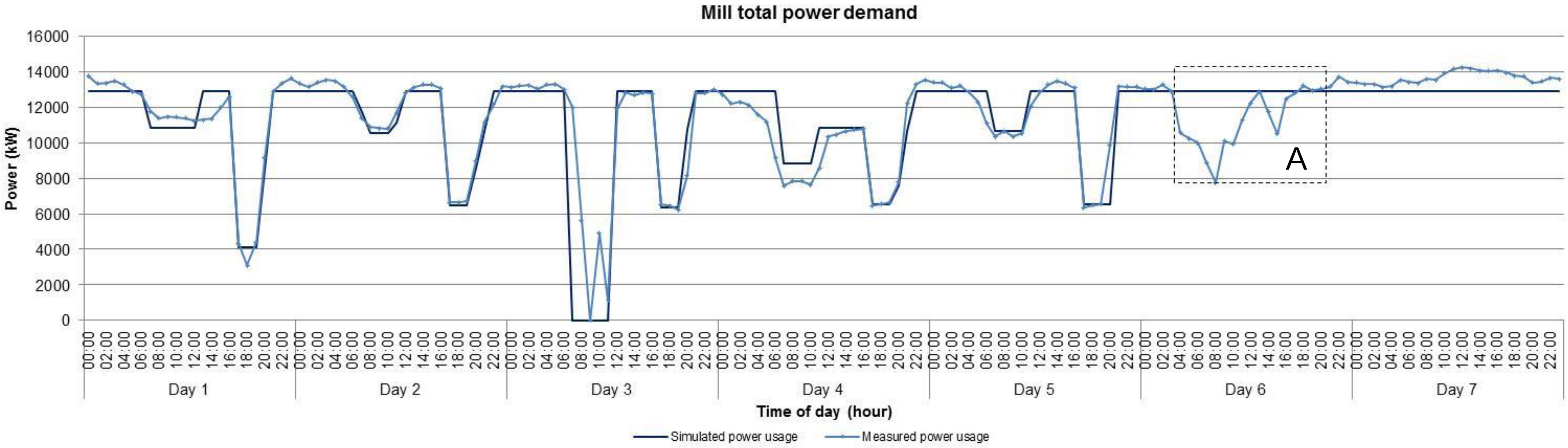


Figure 5-26: Gold plant mills power consumption simulation accuracy

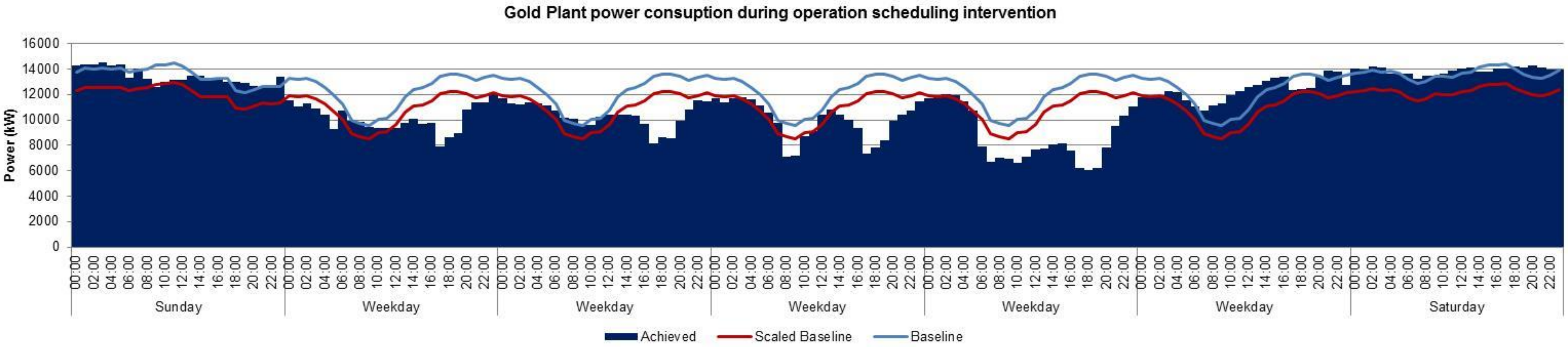


Figure 5-27: Weekly electricity demand during operations scheduling intervention at the gold plant

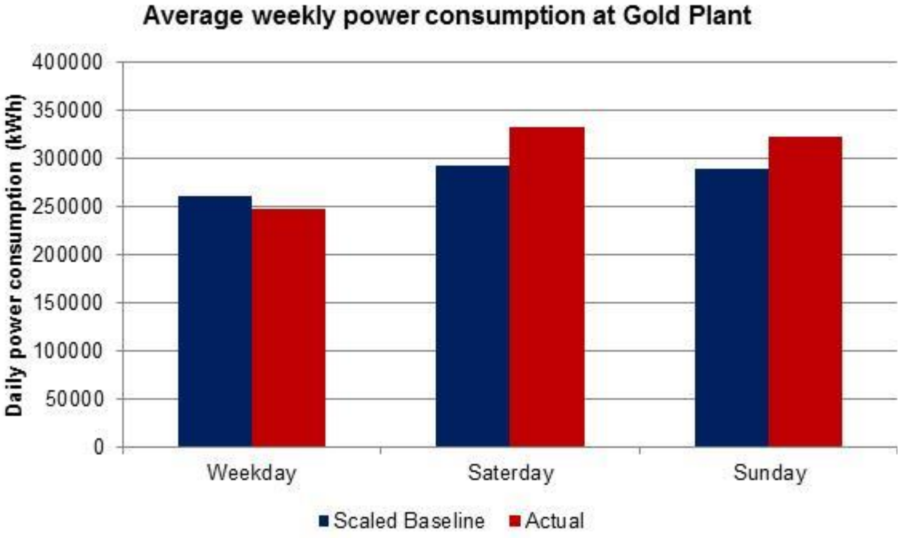


Figure 5-28: Weekday to weekend load shift trend at the gold plant

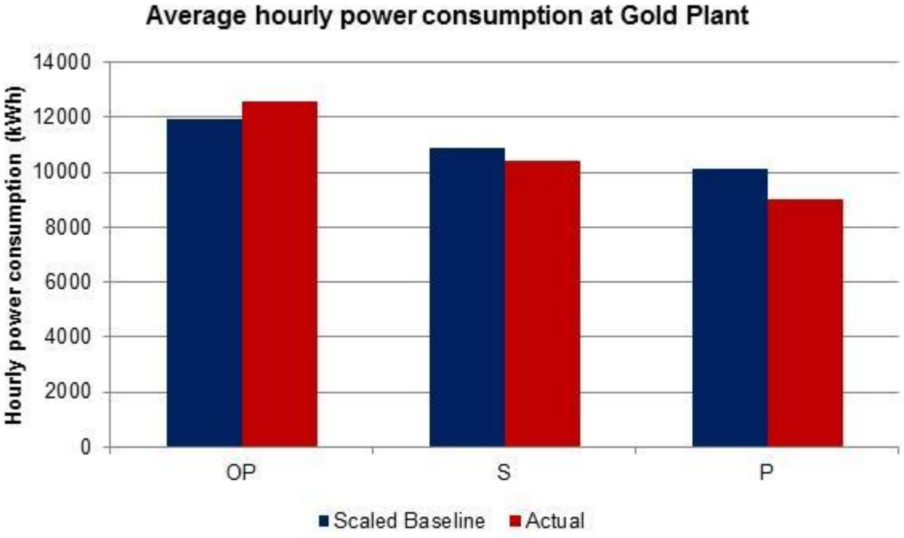


Figure 5-29: Load shift trend between tariff periods at the gold plant

VALIDATION AT THE GOLD PLANT

The new modelling method allowed the operations of the gold plant to be accurately simulated, and for an optimal running schedule to be compiled for the milling components. The storage silos preceding the mills and the thickener components were used to manage the mill loads and in so doing, implemented a mill operations optimisation. Figure 5-27 shows the baseline, the scaled baseline and the actual operations power consumption during the performance assessment period at the gold plant. From the average power consumption figure, a reduction in peak- and standard time power consumption can be seen.

An increase in the weekday off-peak power consumption and the weekend power consumption is also shown in Figure 5-27. Figure 5-28 shows the average power consumption of the average weekly operations that is shifted to Saturdays and Sundays. Figure 5-29 also shows that peak electricity consumption was reduced when implementing the new modelling method. As a result, the energy management intervention showed a R 3.4 million p.a. improvement, amounting to a 6.8% reduction in energy costs on the considered components.

5.4 PLATINUM MINE INVESTIGATION

A platinum group is used to further test the capabilities of the modelling techniques. A scenario is investigated where the logistics aspect of a scheduling problem is studied. Though the platinum group also presents plant operations optimisation potential, the logistical aspect of production allocation will be considered.

The platinum group consists of multiple shafts and multiple ore concentration plants. The ore is transported from the different shafts to the different plants by using trucks. The planning of production allocation, i.e. the quantity of ore that each plant processes, is presently done according to a predetermined planning schedule that only considers ore quality. Electricity costs and transport costs, however, also need to be considered when compiling an optimal solution. A larger global solution will be obtained if all the above-mentioned factors are included in the analysis. The distribution of plant utilisation is therefore optimised while considering transport costs and individual plant utilisation.

The platinum group extracts two types of ore in the mining shafts namely Merensky ore and UG2 ore. The two types of ore have different chemical compositions and require different processes to concentrate the ore. The platinum group mines the two different types of ore at multiple shafts and concentrates the ore at multiple concentration plants. The concentration plants cannot process both types of ore without undergoing process alterations. The concentration plants are dedicated to processing specific types of ore. The shaft and concentration plant group is simplified in Figure 5-30.

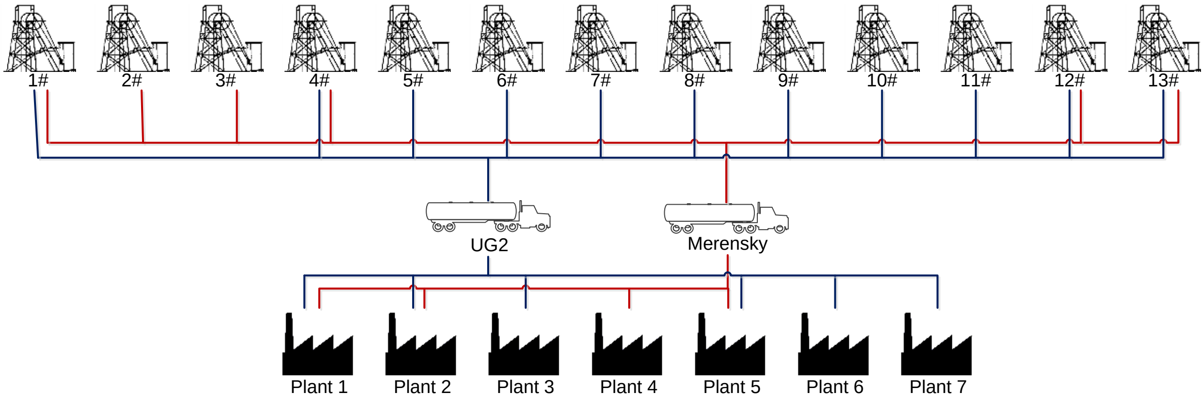


Figure 5-30: Platinum group simplified layout

The mine group has developed over time, which has resulted in multiple plants with varying efficiency. The efficiency can be observed in both recovery rate (quality of PGMs in the concentrate) and electrical efficiency used in grinding the ore. The mine group operates the plants with higher efficiency at full capacity, while the plants with lower efficiency are used to recover the remaining ore. Production allocation is done without considering the cost of electricity during different periods of a working week, or the distance the trucks have to drive to deliver the ore to the plants.

The present production volumes and average utilisation for the different concentration plants are shown in Table 5-4. This table clearly shows that plant 5's line 2 is utilised to a much lower capacity than the other plants considered.

Table 5-4: Monthly production distribution before operations schedule optimisation

Plant description	Design capacity (tonnes per month)	Allocated production (tonnes per month)	Utilisation
Plant 1 - Line 1	140000	140000	100.00%
Plant 1 - Line 2	125000	125000	100.00%
Plant 2 - Line 1	130000	130000	100.00%
Plant 3 - Line 1	200000	200000	100.00%
Plant 4 - Line 1	120000	120000	100.00%
Plant 5 - Line 1	86000	86000	100.00%
Plant 5 - Line 2	81000	40000	49.38%
Plant 6 - Line 1	174000	174000	100.00%
Plant 7 - Line 1	106000	106000	100.00%

The WDF is used to compile a cumulative cost with utilisation graph for concentration Plant A. The cumulative cost graph is shown in Figure 5-31. It is seen in Figure 5-31 that if the operations at a concentration plant are optimised, the cumulative cost of electricity with utilisation is not linear. The higher the utilisation of a concentration plant, the higher the specific electricity cost will be (R/tonne), though the specific electricity consumption will remain constant (kWh/tonne).

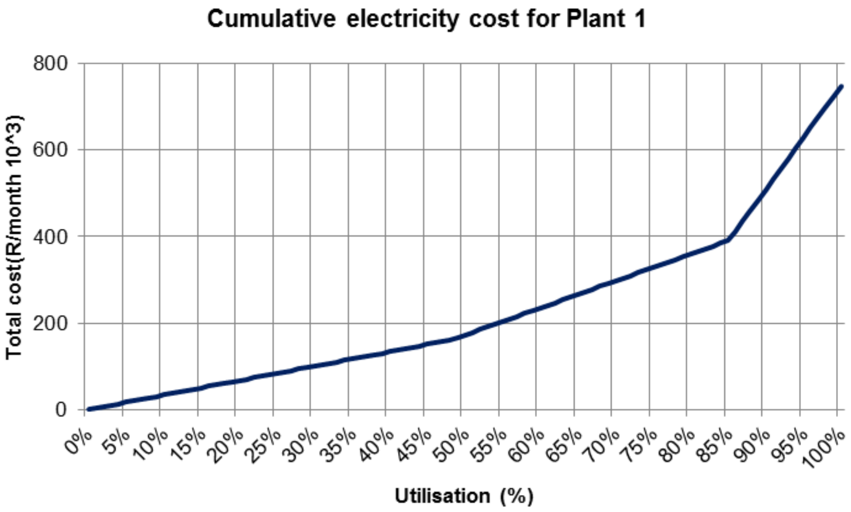


Figure 5-31: Cumulative cost for increasing utilisation of concentration Plant A

The total electricity cost will be reduced if the total production demand for the concentrator plants is distributed evenly in accordance to the specific electrical cost of the plants. However, the transport costs and the PGM recovery of the considered plant must also be included in the analysis. The WDF can be used to optimise this distribution while accounting for all three these cost influences. The general cost line can be adjusted for the different plants to optimise the ore distribution. The new distribution component developed in Chapter 3 can be used to optimise this ore distribution.

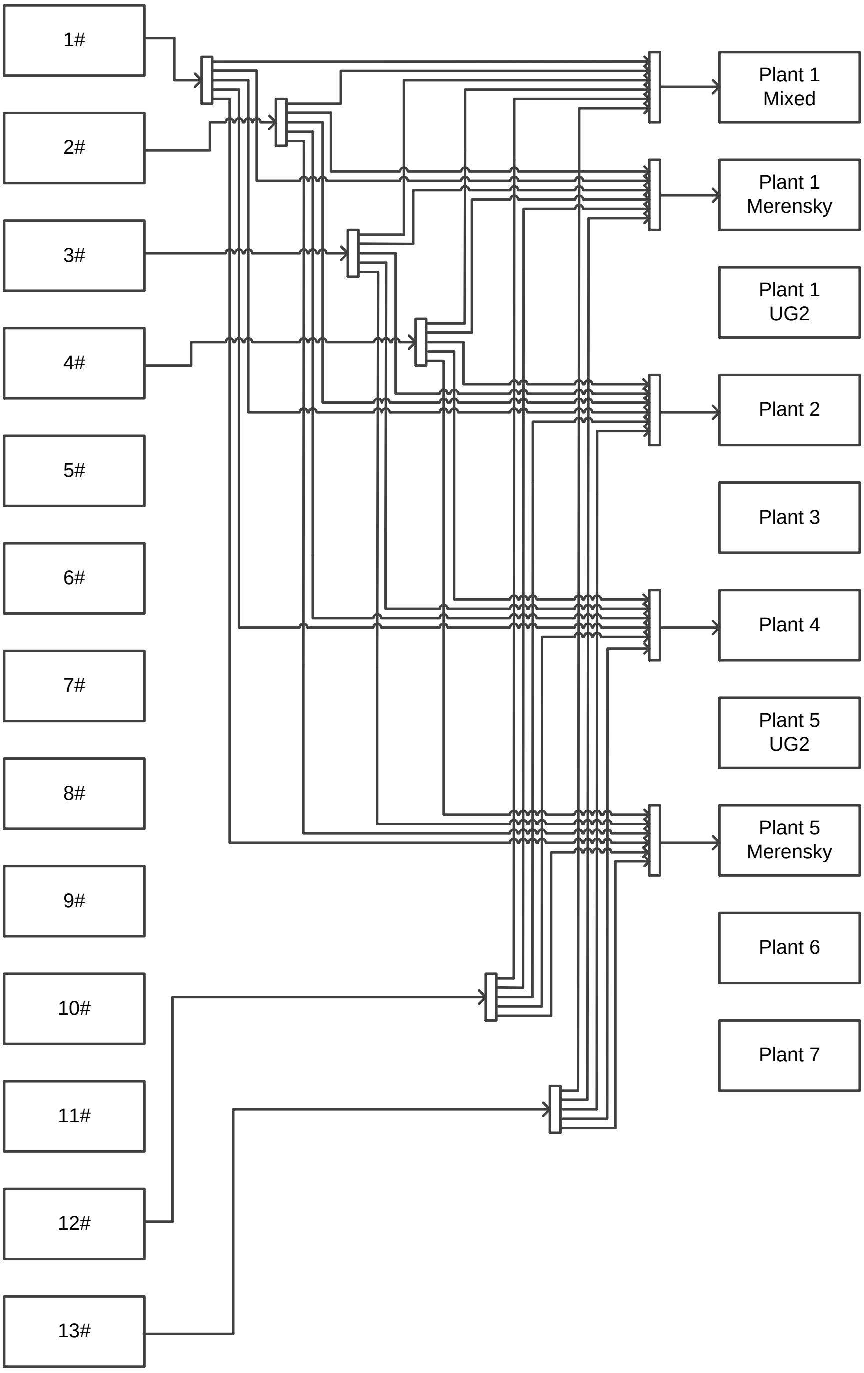


Figure 5-32: Virtual system representation for the platinum group distribution allocation for Merensky ore

The distribution of Merensky ore from the shafts to the concentrating plants is set up as shown in Figure 5-32. A similar VSR is compiled for the UG2 ore. A link component is used for every supply point, which is the mining shaft. The different volumes of ore are then distributed to the different plants in accordance with the different transport costs. A summation component is then used to combine the different supply lines or supply volumes to a single concentrator plant input. Using the link components to add the transport cost and the recovery rate of the different plants to the maximum cost line enables the user to combine the three considered cost components.

An optimal global solution that integrates all the associated costs in the system is generated by increasing the maximum cost line to the required ore volume. Different from the cement production plants, the platinum boundary values are infinite demand beyond the concentrator plants, and a set volume of ore that is produced at the shafts. The original distribution of ore from the mines to the shafts is shown in Table 5-5.

Table 5-5: Baseline ore distribution at the platinum mine group

		Plant 1 Line 1	**Plant 1 Line 2**	**Plant 2 Line 1**	**Plant 3 Line 1**	**Plant 4 Line 1**	**Plant 5 Line 1**	**Plant 5 Line 2**	**Plant 6**	**Plant 7**
	Recovery	88%	87%	84%	89%	87%	78%	84%	82%	85%
	Capacity	140000	125000	130000	200000	120000	86000	81000	174000	106000
1# Mer	116000	116000								
1# UG2	145000		125000	20000						
2#	15000	15000								
3#	24000	9000				14000				
4# UG2	85000			85000						
4# Mer	61000					61000				
5#	82000								82000	
6#	115000			25000	59000		31000			
7#	78000						24000		44000	10000
8#	48000								48000	
9#	40000									40000
10#	56000									56000
11#	15000						15000			
12# UG2	141000				141000					
12# Mer	45000					45000				
13#	40000						16000	40000		
Total	**1106000**	**140000**	**125000**	**130000**	**200000**	**120000**	**86000**	**40000**	**174000**	**106000**
Utilisation		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*49.4%*	*100%*	*100%*

It can be seen in the ore distribution matrix that Plant 5's line 2 only operates at 49.4% of its available production capacity. The platinum group operated at a very high production volume in the period that was used to calculate Table 5-5. The UG2 ore that was mined at the shafts forced the concentrator plants to operate at full capacity. Potential for electricity cost savings exists despite the high production volumes. The WDF is applied to the platinum group and generates an optimal solution. The generated solution is shown in Table 5-6.

Table 5-6 shows that the reserve utilisation of Plant 5's line 2 is distributed evenly between Plant 2, Plant 3, Plant 4 and Plant 5. A lower utilisation enables the plants to operate at a lower specific cost in terms of electricity consumption, as described in Figure 5-31. The fuel costs and recovery rates also showed a potential improvement. The improvement in recovery rate is unexpected as it forms the primary focus of production allocation planning at the mining group. This increase proves that automated planning of production allocation is helpful, not only in reducing energy costs, but also in optimising production outputs.

Table 5-6: Optimised ore distribution at the platinum mine group

		Plant 1 Line 1	**Plant 1 Line 2**	**Plant 2 Line 1**	**Plant 3 Line 1**	**Plant 4 Line 1**	**Plant 5 Line 1**	**Plant 5 Line 2**	**Plant 6**	**Plant 7**
	Recovery	88%	87%	84%	89%	87%	78%	84%	82%	85%
	Capacity	140000	125000	130000	200000	120000	86000	81000	174000	106000
1# Mer	116000	55000		10428						
1# UG2	145000		125000	20000						
2#	15000			15000						
3#	24000									
4# UG2	85000	85000								
4# Mer	61000					33571				
5#	82000									82000
6#	115000							25000	8000	24000
7#	78000								78000	
8#	48000								48000	
9#	40000								40000	
10#	56000							56000		
11#	15000						15000			
12# UG2	141000				141000					
12# Mer	45000						45000			
13#	40000					40000				
Total	**1106000**	**140000**	**125000**	**45428**	**141000**	**73571**	**60000**	**81000**	**174000**	**106000**
Utilisation		*100%*	*100%*	*34.9%*	*70.5%*	*61.3%*	*69.8%*	*100%*	*100%*	*100%*

Table 5-7: Total savings summary for the platinum mine group

	Present	**Proposed**	**Saving**
Fuel (kl)	2 492	2 437	54
Peak-period electricity (MW)	13.145	6.843	6.302
Average recovery rate	84.81%	84.91%	0.10%

The total savings at the platinum mine group is summarised in Table 5-7. Table 5-7 shows a 2% improvement in fuel used during transport (R 694 000), and a total reduction of peak electricity consumption of 47% (R 820 000). The largest improvement when quantified in cost was seen with the recovery rate of the concentrator plants, amounting to R17.5 Million.

5.5 RESULTS EVALUATION AND GOAL COMPARISON

Results showed that the new modelling method developed savings in various applications. To test the success of the developed solution, however, the original goal statement is reviewed and compared with the achieved results. The goal statement described the target for the research that was identified from literature. The practical application of the new method will provide measured and verified confirmation of the success of the solution. The goal statement specified that the following should be developed to solve the problem statement:

Goal statement:

Develop a generic model (1) *that accurately describes the system being modelled, supplying the information necessary to make sound operational planning and system settings decisions* (2) *on a frequent to constant basis and in real time* (3) *focussing on real-world application* (4)*.*

When comparing the four focuses of the goal statement with the application results, the research can be validated and verified. The savings reported on the applications of the new modelling method showed that the modelling method produced energy savings, but to verify the focus and success of the solution when considering the problem statement, the results must adhere to the goal statement. The different applications aimed at solving all four tiers of the goal statement and the achieved results are summarised with reference to these four tiers:

1. *Develop a generic model*;

   The new modelling approach was applied to three different industries and to different plant configurations. The different applications presented different problems, including the combination of different contradicting target variables, logistics planning, product quality monitoring and production limits controlling. All of the applications developed savings that was not possible by manual intervention methods. Additionally, the developed modelling components and the WDF simulation method were not altered to simulate the different industries.

2. *Accurate and comprehensive*

   The gold- and cement plant applications compared the results of the new modelling technique with real-world data and plant response. The generated simulation values stayed within the set accuracy limits and were therefore accurate. The gold plant application also not only accurately simulated the plant response to certain operational settings, but improved the prediction of quality of the process fluid, and in so doing gave a comprehensive feedback to the plant operational personnel.

3. *Frequently and in real time*;
   The simulation extracted data from the plant directly. This data was recovered and incorporated into the developed model in real time through computer systems. This real-time data was then used to re-optimise the solution to give frequent feedback to plant personnel. Thus the simulation method could extract data and re-simulat the optimal solution to give feedback to the plant personnel on a basis frequent enough to accurately follow the optimal operational schedule.

4. *Focussing on real-world application*;
   The results were extracted from real-world plant. Through a process of monitoring plant schedules and re-evaluating the optimal schedule, the real-world plants showed considerable savings in different forms of energy and operational costs. The multiple applications in industry prove that the new modelling technique is focussed on real-world application.

The application of the new modelling method proved to satisfy the goal statement. By satisfying the goal statement, the identified problem statement was satisfied and large energy savings were achieved, in turn reducing the operational costs of the plants that were considered. The modelling method is a viable solution to keep the platinum mining, the gold mining and the cement production industry in South Africa competitive in an international market.

5.6 SUMMARY OF VERIFICATION AND VALIDATION

The WDF is verified by monitoring the iterative response for the cement plant models. The WDF reaches a solution that remains within silo level constraints and maintains a minimum operations cost within ten iterations. The cost is proved to be optimal, as only the off-peak periods of the South African TOU tariff structure was utilised. Additionally, by using the sales targets and the silo level constraints, the WDF also calculates the optimal end silo level for the considered time interval, as shown in Figure 5-10.

The new modelling components are verified by considering the gold plant model. The RD of the underflow closely follows the RD that is experienced on the real-world site. The calculated electricity demand also accurately predicts the site electricity demand during implementation. The only deviation experienced from the modelled power demand was experienced during a large unscheduled maintenance event. However, this event is modelled by including a reliability factor into the production modelling of the milling equipment.

The new modelling technique is validated by monitoring various real-world applications of the modelling method. Each of the applications showed substantial cost reduction, with an average of 6.6% on cement plants, 6.8% at the gold plant. The results also satisfy the original goal statement, showing the hypothesis holds when applying the new modelling method to real-world industries. These results serve to accurately validate the approach generated to reduce operational costs.

5.7 CONCLUSION

The new modelling method was applied to three different real-world systems. These systems were the South African cement industry, a South African platinum group and, a South African gold plant. Each of the three systems served to verify a different functionality of the new modelling technique and delivered real-world results in the form of cost savings.

Three different South African cement plants were considered. A cement plant poses a simple binary operations strategy (the machines are either on or off). Operational savings were identified using the new modelling technique to simulate the buffer responses and the operational costs. The generated operational schedules were applied for an extended period of time and generated operational savings. The savings showed a 6.6% reduction in operational costs on the considered components.

The new modelling method was applied to a South African gold plant. The gold plant presented a product quality problem, which served to test the fluid characteristics simulation of the new modelling method. Monitoring the RD of the thickener underflow proved that the thickener components of the gold plant could be used as buffers. Operational management of the milling circuits generated large electrical savings with a better control of the system RD. An average cost saving of 6.8% was achieved on the considered components.

A South African platinum mine group was analysed as a logistics problem. The new modelling technique, with the developed aggregate cost profile, was used to integrate the analysis of the platinum group logistics problem. The distribution of ore from the mining shafts to the concentrator plants was re-calculated and developed a potential saving of 2% on considered components.

The results were evaluated and compared to the original goal statement. Every aspect of the goal statement was achieved. The results were also used to verify and validate the modelling technique. The goal, scope, methodology and results will be summarised and concluded in Chapter 6.

CHAPTER 6

Conclusion and recommendations

Chapter six

Chapter six will test the results of the implementation to the original hypothesis and draw a conclusion as to the success of the new approach. Advantages and shortfalls will be described, from which recommendations for further study will be made.

6 CONCLUSION AND RECOMMENDATIONS

6.1 PREAMBLE

Electricity- and other forms of energy costs are increasing at a rapid rate. This increase in energy costs is pressuring energy-intensive industries to reduce energy costs. This pressure is clear when considering three South African industries: gold mining, platinum mining and cement production.

South African gold production has shown an increase in operating costs and personnel costs. Additionally, the ore mined and the head grade of ore processed has decreased since 2003. The impact that these factors has on the South African gold industry can be seen in the major reduction in total gold produced, a sharp decrease in global market share and a decrease in personnel numbers as a result of forced personnel dismissals. The only area where possible operational savings can be obtained, apart from personnel layoffs, is by reducing costs allocated to energy.

Similarly, the South African platinum industry showed an even larger increase in personnel costs, caused by continuing wage unrest and strike action. As a result, the number of employees has decreased and the platinum sector in South Africa has also presented a decrease in global market share. To minimise the impact that the personnel unrest and forced unrest has on the global production share and stability of the South African platinum industry, energy- and operational costs must be reduced.

The South African cement demand peaked in 2007, as a result of increased infrastructure development and construction. However, after 2007 the South African cement demand decreased dramatically. Cement production is also experiencing increased pressure from international and local producers, including an additional local cement producer entering the market. To remain competitive and avoid losing market share, operational costs in the cement industry must be reduced. Reducing cost allocated to energy is an effective way to reduce these costs.

Energy costs can be reduced in various ways. Replacing old and outdated equipment will reduce energy consumption and, in so doing, also reduce energy cost. However, these installations require large initial capital expenditure and production downtime to implement. The saving gained from these installations is also limited, which extends the payback period of the intervention.

Apart from infrastructure upgrades, energy can also be reduced by altering operational strategies. Ensuring that the most optimal combination of existing equipment is utilised, and managing the operational periods of this equipment has been shown to also reduce energy cost. Operational interventions are most often subdivided into three sub-categories: load shift, peak clip and; energy-efficiency improvement. Managing operational practices can, however, combine these strategies to reduced cost in all three forms.

Automating the operations intervention provides a solution, with larger savings than manual interventions. An automated solution also provides a more sustainable solution. Automating the operations management intervention is also limited to the effectiveness of the control strategy and/or the modelling technique used. Literature discusses different operations modelling techniques. These techniques are, however, suited to specific applications and are not designed to operate in real time in an automated control environment.

The application-specific nature of these modelling techniques also makes the construction of such a model cumbersome. The restricted number of skilled personnel limits the application volume of automated operations management interventions, whilst this intervention method has been proven to be the most cost-effective energy cost reduction approach. The development of a more generic modelling technique that is widely applicable, and with automated control capabilities, is required.

The goal of this thesis was to develop a new modelling technique that can be applied to multiple different systems without altering the algorithmic core, as well as enabling this modelling technique to be applied in an automated control environment. This goal was subdivided into four different pillars: generic application, accurate and comprehensive, frequent and in real time, focussing on real-world application. The novel contributions of the thesis arise from this four-tiered approach. The novel contributions set out are: a generic approach, integrating the analysis of multiple components simultaneously and, the model to operate in real-time in an automated environment.

The thesis focussed on a modelling technique, i.e. the mathematical- and algorithmic core. The novelty of the study is based on the development of a widely applicable approach to modelling. This thesis therefore did not consider the programming of the computer systems that implement this new modelling technique. Start/stop time was not considered. The components analysed were directly production related. The modelling technique also developed operational principles from practical operations of real-world machinery and plants.

The thesis was set out by analysing relevant literature, developing a new modelling technique and applying this technique to real-world plants to validate and verify the success of the new method. The solution development was subdivided into two subsections namely: modelling components and; time analysis. The method was applied to operating cement plants, a gold ore processing plant and; a platinum mining group.

6.2 LITERARY BACKGROUND

Automating the control of operations is a well-researched field. Different levels of automated control has been developed and implemented in industry. These range among relay control, closed loop PI control (in PLCs), set-point based control systems and simulation-based intelligent control. Each of these automated control strategies presents different advantages and disadvantages. The different interventions were investigated and these advantages and disadvantages were listed. The different interventions were compared to the goal statement to identify which interventions are better suited to the problem statement.

Most modern machines are controlled via PLC networks and can be remotely started and stopped. Since these machines comprise of multiple subcomponents such as motors, fans and belt feeders, some of the integrated control is done automatically. For instance, a mill circuit is prompted to start, after which the sub-components are started automatically by a relay circuit or a PLC. Using these capabilities, the PLCs can be used to control certain set-points in a component. By managing these set-points with control variables, such as mill load, the efficiency of the component can be optimised. These systems are known as advanced process control.

PLC networks can also be used to control the components from a real-time control system. These control systems read control variables from instrumentation via a SCADA system and start and stop large energy consuming components. Since this control system is more variable than a PLC, these set-points can be altered dynamically to reduce total energy cost. Using these control systems, however, limit the amount of variability of the control system and can thus only achieve limited amounts of energy savings. More comprehensive modelling techniques have been developed that incorporate more variables and can forecast operations over longer periods of time.

The study of operations modelling is also a well-researched field. Different methods and applications have been discussed in literature. The discussed applications include sequential and network production environments, with either linear or non-linear system response. Solving these models most often employ mixed integer linear programming of mixed integer non-linear programming. All of the considered research proved effective, although the methods discussed are application-specific and need expert personnel to compile and solve. These modelling methods are also not applied in an automated control environment.

Various commercial packages have been released that can be used to simulate different processing environments. Most of the commercial modelling packages are focussed on specific problems, including batch processing, steady-state analysis and indices timing. These modelling packages are also mostly used for design of systems or reactors and are used for consultation. Commercial packages are in general not suited to real-time application and integrated control systems.

From literature, a modelling package that combines the accuracy of operations modelling and the mass implementation of real-world PLC integrated control systems was required. Such a modelling package will satisfy the problem statement and enable mass implementation and increased savings on multiple processing applications.

6.3 SOLUTION DEVELOPMENT

Following the literature review, a new modelling technique was proposed. The modelling technique was subdivided into two parts: modelling of systems and simulation of systems. The first part of the modelling technique focussed on new modelling components and the second on time simulation. The core building blocks of modelling and simulation, as depicted in considered literature, were re-evaluated and new techniques were developed.

The modelling of systems in literature comprised of three basic components, namely process components, buffer components and link components. Since the definitive components found in literature do not accurately describe the real-world process found in practical applications, the modelling components were redefined as *two* basic components. These new components are a process component that includes buffer capacity or residence time, and a link component that allows for process flow confluence and splitting.

Since most processes found in applications represent a process function with a designated residence time, a new component that combines the two concepts was developed. The new process component with residence time combines the process influence that the component has on the process fluid, with a time interval required to achieve this fluid alteration. The process component with residence time is shown in Figure 6-1.

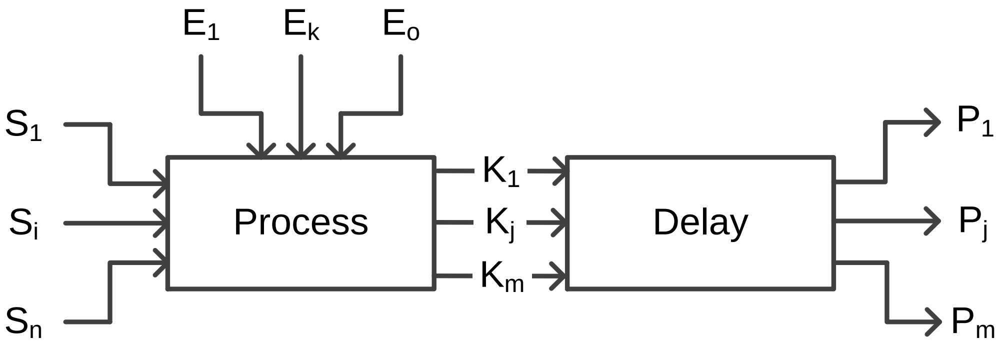


Figure 6-1: Schematic representation of the process component with residence time

The process component with residence time was simply described as a process- and a delay function. The process influence, with the assigned energy consumption, was described as either fixed, or as a function of the processing volume. The delay was also set in time with this associated process function as a constant, or function, of the process stream. Describing buffer- and process function in this way allows most components found in industry to be accurately modelled and simulated.

A process link component was also developed. The process link component links the outflows of the different process functions with the inputs of the following process functions. The link component was divided into two basic parts. The first part is a process summation function and the second part is a process distribution function. The different process streams are summed and then distributed according to a fixed or variable volume constant. Each of the addition or distribution entities was also assigned a fixed or variable energy consumption to account for logistics applications. The link component is shown in Figure 6-2.

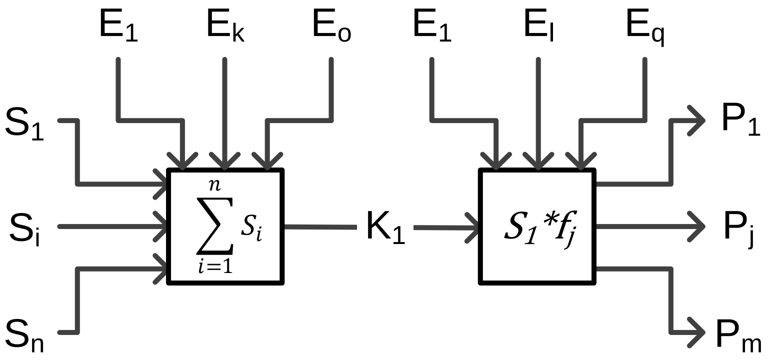


Figure 6-2: Schematic representation of the combined summation and distribution link component

The new modelling components were combined and used in a new simulation technique. The new simulation technique used the new modelling components to analyse the plant or system with time. To consider the different sources of energy and raw material consumption simultaneously, cost is used as global target variable. Energy consumption and raw material consumption was optimised by generating a universal cost of the system, which allowed contradicting variables to be optimised for a universally-optimal solution.

A new time analysis technique was developed by considering a natural water drop analogy. Similar to water settling on the lowest point of a considered surface, cost of operations during different periods of a set time interval is minimised. The new simulation technique was referred to as the Water Drop Formulation (WDF). Figure 6-3 depicts the natural optimisation occurrence of water settling on a surface.

Figure 6-3: Water settling on a surface

The cost of operation for the different energy sources was combined to generate an operational cost line. A maximum cost line ($C(t)$) was generated and iteratively increased to intersect the operational cost line ($E_c(t)$). Where the max cost line was less than the operational cost line, the component was seen as operational ($O(t)$). The total operational time was then used to calculate the operational utilisation and was compared to the target utilisation. The maximum cost line is iteratively increased until the target utilisation is equal to the operational utilisation. This process is depicted in Figure 6-4, showing the maximum cost line, the continuous cost of operation profile and the generated operational setting.

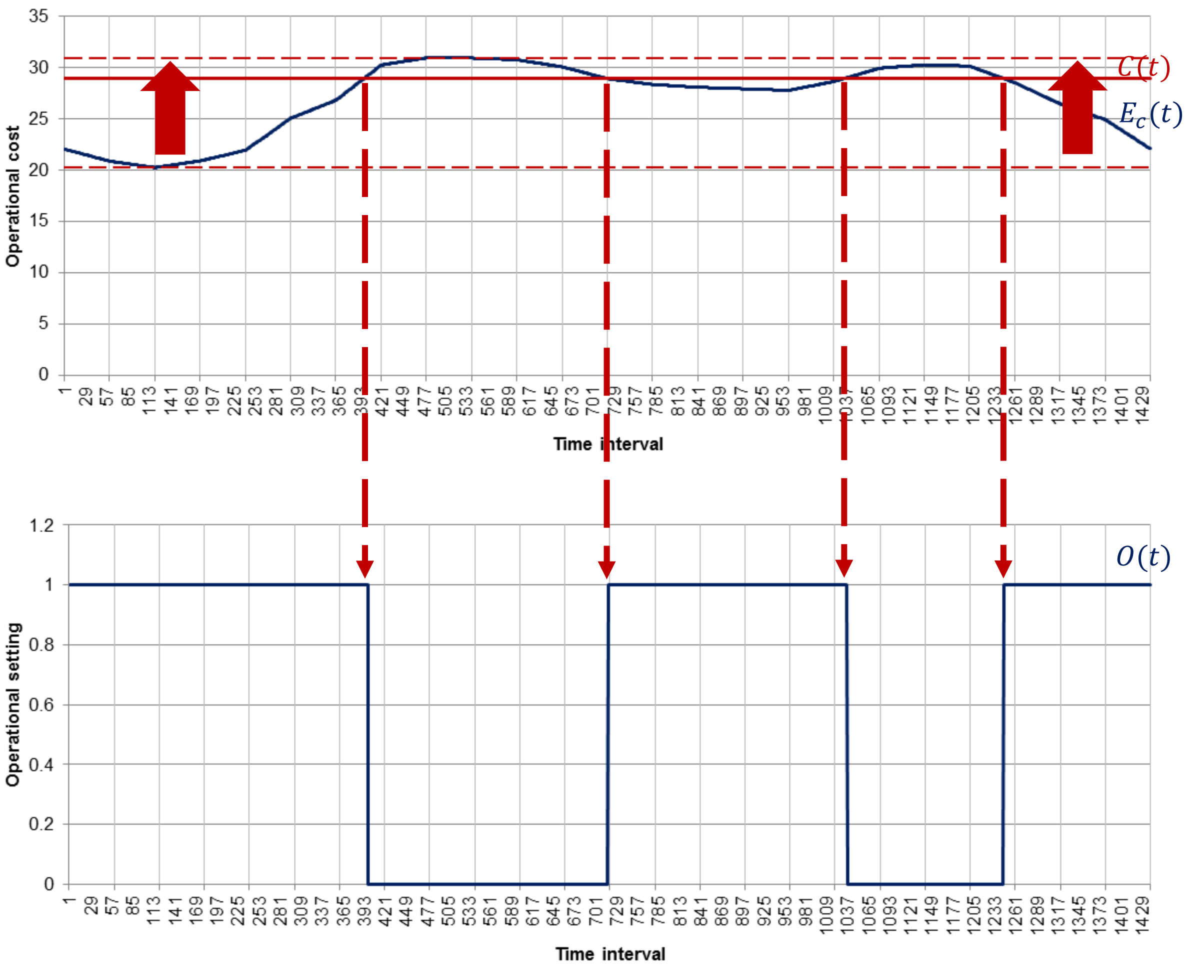


Figure 6-4: Example of continuous electricity cost profile and operational setting derived using the WDF

The same method was applied to multiple scenarios to develop a universal time analysis. A variable operational profile was developed to account for multiple modes of operation. This method was used to include buffer capacities, in turn combining multiple components into a single analysis method for multiple or continuous modes of operation. The method was extended to account for multiple products, widening the new modelling technique to multiple industries and real-world facilities.

6.4 IMPLEMENTATION RESULTS

The new modelling method was applied to three different industries. The industries that were tested were the South African cement industry, the South African platinum mining industry and the south African gold industry. The different plants and sites were investigated and the new modelling method was applied to reduce energy costs. Each of the three industries presented different challenges that clearly tested the different capabilities of the derived solution and would serve as validation and verification for the goal and methodology of the research.

The modelling and simulation technique was applied to three cement plants. The modelling components and plant layouts were compiled using the new components' descriptions. These components used electricity cost and buffer volumes to calculate optimal operational schedules. The operational schedules were generated in binary form to represent a simple on/off schedule for the large energy-consuming components. In addition to the electricity cost, raw material costs were incorporated to identify the most optimal component configurations when considering total production cost.

The new modelling technique was tested over an extended period of time and showed significant electrical cost savings. The costs savings were identified by rescheduling the production components to less expensive periods of the South African TOU tariff structures. The buffer volumes were also managed between the representative limits to ensure product quality and optimal operational management. The cost savings for the cement plant application amounted to R 5.75 million p.a., representing a 6.6% electricity cost reduction on the considered components.

The modelling technique was also used to analyse the logistics planning of a platinum group of mines. The platinum mines use trucks to transport ore from various plants to various concentrator plants. Originally these transport costs formed the only consideration during the logistics planning. The platinum logistics problem presented a link component challenge that took the plant operational costs and utilisation into account. The new modelling and simulation technique was used to optimise the solution by considering not only the fuel costs of ore transportation, but also the electricity costs associated with the plants, with different utilisation percentages.

The new modelling method proposed a redistribution of the ore between the shafts and the concentrator plants. The modelling and simulation method produced an optimal cost, with a utilisation figure for each of the concentrator plants. This was used in conjunction with the fuel costs to produce a saving of R 19 Million p.a.

The new modelling method was also applied on the gold ore processing industry. This industry presented a quality- and flow variance problem that was not present in the cement industry. The application of the new modelling method accurately simulated the response of the thickener components to the energy management interventions applied to the preceding milling circuits. Predicting and controlling the inflow to the thickeners and the underflow from the thickeners enabled the plant personnel to better plan the operations of the energy intensive components, such as the milling circuits.

The accurate modelling of the system response enabled the plant to operate the energy-intensive components to optimise the energy costs without influencing the quality or recovery figures of the gold plant. The energy management intervention showed a R 3.4 million p.a. improvement, amounting to a 6.8% reduction in energy costs on the considered components. Additional improvements included a better controlled underflow relative density, which in turn improved possible recovery of gold.

6.5 VERIFICATION AND VALIDATION USING RESULTS

Comparing the modelling results obtained from applying the new modelling components and the WDF to real-world systems served to validate and verify the approach. The forecasted system characteristics were compared to the actual response experienced on the industrial systems. The results accurately depicted what response was to be expected from the plants.

The cement plant application showed that the silo level response and the production target were accurately forecasted by using the new modelling components and the WDF. The gold plant application also showed that the modelling components accurately depict the multi-variable transient response of the thickener, also serving to verify the new modelling technique.

Additionally, the application of the modelling method to real-world systems generated electricity and operational savings, in turn validating the approach used. In every application the new modelling method generated operational schedules that reduced the operational cost of the considered industries. The peak electricity demand decreased on the cement plant, and the gold plant, in turn, used the buffer volumes to reduce total energy costs.

6.6 RECOMMENDATIONS

The new modelling method proved to be effective in optimising operations costs on three different systems. It also proved to be effective on binary or on/off scheduling and logistics optimisation. The application of the new modelling method is also applied to a fixed TOU tariff structure environment. The modelling method is capable of simulating a constantly-varying production cost. It is recommended that the new modelling technique is applied to constantly-varying operations costs environments to better explore the dynamic nature of the simulation approach.

It is recommended that the new modelling method be applied on batch scheduling problems as well. The residence time component will allow the new modelling method to be applied to batch systems. The three industries considered in the practical application of the modelling method mostly consisted of continuous processes. Applying the new modelling technique to batch problems will widen the scope for operational savings in different industries. Batch industries will include glass manufacturing and various types of smelters, which are also large energy consumers.

A further recommendation is made to develop a generic form of control system that applies the developed modelling technique to various industries by integrating data retrieval and so to automate the control of components. An automated control system that uses the new modelling method as core will further increase the effectiveness of the simulation approach. This will further simplify the application of the new modelling method and in so doing, open new opportunities for operational cost reduction.

6.7 CLOSE

Three different South African industries showed the need for operational cost reduction. A new methodology for operational management was proposed and a scope for the application was developed. A new operational modelling approach applied in real time to actual systems would reduce operational costs. Relevant literature was studied and the potential for a more comprehensive, generic operations modelling approach was identified.

A new modelling technique was developed in two parts. The first part of the methodology focussed on the virtual components that were used to create a computerised model of an existing plant. Two new modelling components were developed that simulated real-world components. The second part of the methodology focussed on the time analysis and operations simulation of this computerised model. An analogy of water settling on the lowest area of a given surface was used to develop an analysis and optimisation approach. The computerised model was optimised by using the new simulation technique.

The new modelling method was applied to three different South African industries and generated electrical cost savings. The application and savings were compared to the original goal statement and proved that the application of the new methodology was successful and that the new methodology solved the problem statement, in so-doing, validating and verifying the study. Applying an operations modelling technique in a more generic form in real-time proved to reduce operational costs and aided in keeping the considered industries competitive in an international market.

7 APPENDIX A

Eskom MegaFlex tariff structure charges (2014/2015).

Megaflex tariff

Non-local authority

Transmission zone	Voltage	Active energy charge [c/kWh]												Transmission network charges [R/kVA/m]	
		High demand season [Jun - Aug]						**Low demand season** [Sep - May]							
		Peak		**Standard**		**Off Peak**		**Peak**		**Standard**		**Off Peak**			
			VAT incl		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*		*VAT incl*
≤ 300km	< 500V	**248.94**	*283.79*	**75.74**	*86.34*	**41.35**	*47.14*	**81.52**	*92.93*	**56.25**	*64.13*	**35.86**	*40.88*	**R 7.12**	*R 8.12*
	≥ 500V & < 66kV	**245.03**	*279.33*	**74.23**	*84.62*	**40.31**	*45.95*	**79.93**	*91.12*	**55.02**	*62.72*	**34.90**	*39.79*	**R 6.51**	*R 7.42*
	≥ 66kV & ≤ 132kV	**237.28**	*270.50*	**71.87**	*81.93*	**39.04**	*44.51*	**77.41**	*88.25*	**53.27**	*60.73*	**33.80**	*38.53*	**R 6.34**	*R 7.23*
	> 132kV*	**223.63**	*254.94*	**67.74**	*77.22*	**36.79**	*41.94*	**72.96**	*83.17*	**50.20**	*57.23*	**31.86**	*36.32*	**R 8.01**	*R 9.13*
> 300km and ≤ 600km	< 500V	**250.97**	*286.11*	**76.04**	*86.69*	**41.29**	*47.07*	**81.87**	*93.33*	**56.36**	*64.25*	**35.76**	*40.77*	**R 7.18**	*R 8.19*
	≥ 500V & < 66kV	**247.48**	*282.13*	**74.97**	*85.47*	**40.71**	*46.41*	**80.74**	*92.04*	**55.56**	*63.34*	**35.25**	*40.19*	**R 6.57**	*R 7.49*
	≥ 66kV & ≤ 132kV	**239.61**	*273.16*	**72.58**	*82.74*	**39.41**	*44.93*	**78.16**	*89.10*	**53.79**	*61.32*	**34.12**	*38.90*	**R 6.39**	*R 7.28*
	> 132kV*	**225.86**	*257.48*	**68.43**	*78.01*	**37.14**	*42.34*	**73.67**	*83.98*	**50.70**	*57.80*	**32.16**	*36.66*	**R 8.09**	*R 9.22*
> 600km and ≤ 900km	< 500V	**253.47**	*288.96*	**76.78**	*87.53*	**41.68**	*47.52*	**82.69**	*94.27*	**56.91**	*64.88*	**36.09**	*41.14*	**R 7.27**	*R 8.29*
	≥ 500V & < 66kV	**249.96**	*284.95*	**75.73**	*86.33*	**41.12**	*46.88*	**81.54**	*92.96*	**56.12**	*63.98*	**35.60**	*40.58*	**R 6.63**	*R 7.56*
	≥ 66kV & ≤ 132kV	**242.05**	*275.94*	**73.33**	*83.60*	**39.81**	*45.38*	**78.95**	*90.00*	**54.34**	*61.95*	**34.47**	*39.30*	**R 6.43**	*R 7.33*
	> 132kV*	**228.14**	*260.08*	**69.10**	*78.77*	**37.54**	*42.80*	**74.42**	*84.84*	**51.22**	*58.39*	**32.50**	*37.05*	**R 8.20**	*R 9.35*
> 900km	< 500V	**256.02**	*291.86*	**77.58**	*88.44*	**42.12**	*48.02*	**83.53**	*95.22*	**57.48**	*65.53*	**36.48**	*41.59*	**R 7.29**	*R 8.31*
	≥ 500V & < 66kV	**252.45**	*287.79*	**76.47**	*87.18*	**41.51**	*47.32*	**82.34**	*93.87*	**56.66**	*64.59*	**35.95**	*40.98*	**R 6.71**	*R 7.65*
	≥ 66kV & ≤ 132kV	**244.48**	*278.71*	**74.06**	*84.43*	**40.21**	*45.84*	**79.74**	*90.90*	**54.89**	*62.57*	**34.82**	*39.69*	**R 6.48**	*R 7.39*
	> 132kV*	**230.37**	*262.62*	**69.82**	*79.59*	**37.93**	*43.24*	**75.19**	*85.72*	**51.76**	*59.01*	**32.86**	*37.46*	**R 8.26**	*R 9.42*

* 132 kV or Transmission connected

Distribution network charges						
Voltage	**Network capacity charge [R/kVA/m]**		**Network demand charge** [R/kVA/m]		**Urban low voltage subsidy charge** [R/kVA/m]	
		VAT incl		*VAT incl*		*VAT incl*
< 500V	**R 14.15**	*R 16.13*	**R 26.83**	*R 30.59*	**R 0.00**	*R 0.00*
≥ 500V & < 66kV	**R 12.98**	*R 14.80*	**R 24.62**	*R 28.07*	**R 0.00**	*R 0.00*
≥ 66kV & ≤ 132kV	**R 4.63**	*R 5.28*	**R 8.58**	*R 9.78*	**R 11.43**	*R 13.03*
> 132kV / Transmission connected	**R 0.00**	*R 0.00*	**R 0.00**	*R 0.00*	**R 11.43**	*R 13.03*

Voltage	**Ancillary service charge [c/kWh]**	
		VAT incl
< 500V	**0.33**	*0.38*
≥ 500V & < 66kV	**0.32**	*0.36*
≥ 66kV & ≤ 132kV	**0.30**	*0.34*
> 132kV / Transmission	**0.28**	*0.32*

Customer categories	**Service charge** [R/account/day]		**Administration charge** [R/POD/day]	
		VAT incl		*VAT incl*
> 1 MVA	**R 162.48**	*R 185.23*	**R 73.23**	*R 83.48*
Key customers	**R 3 183.88**	*R 3 629.62*	**R 101.68**	*R 115.92*

Reactive energy charge [c/kVArh]			
High season		**Low season**	
	VAT incl		*VAT incl*
11.44	*13.04*	**0.00**	*0.00*

Electrification and rural network subsidy charge [c/kWh]		**Affordability subsidy charge** [c/kWh] Only payable by non-local authority tariffs	
All seasons		**All seasons**	
	VAT incl		*VAT incl*
6.33	*7.22*	**2.44**	*2.78*

8 APPENDIX B

Journal article:

Swanepoel J.A., Mathews E.H., Volsoo J.C., Liebenberg L., "Integrated energy optimisation for the cement industry: A case study perspective", Energy Conversion and Management, 2014 (78), pp. 765-775.

Energy Conversion and Management 78 (2014) 765–775

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Integrated energy optimisation for the cement industry: A case study perspective

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ARTICLE INFO

Article history:
Received 18 June 2013
Accepted 22 November 2013

Keywords:
Integrated energy model
Cement plant
Energy management system

ABSTRACT

Energy costs play a major role in the cement production process. As much as 60% of total cost is allocated to energy and 18% to the consumption of electrical energy. Historically, energy cost savings were achieved by large infrastructure upgrades. These upgrades are often costly and lead to interruptions in production. In this paper the operation of all the energy intensive components of the cement production process are identified, modelled, integrated and optimised for minimum operational costs while meeting production targets. This integrated approach allows for simulation of the collective effect of individual production components. The system incorporates constraints such as maintenance, production and dynamic energy costs. No published research could be found where these constraints are incorporated into a single operational solution. The system was implemented on four cement plants and a total energy cost saving of 7% was achieved. This highlights the practical significance of an integrated approach to energy cost savings.

1. Introduction

A large portion of the total financial expenditure in the production of cement is allocated to cost of energy [1,2] which is increasing in some instances at a more rapid rate than inflation [3–8]. Resultingly, the proportion of cost allocated to energy in cement production is increasing. This highlights the importance of decreasing cost in a competitive market that is under pressure due to increasing energy costs [9,10].

The layout of a typical cement plant is shown in Fig. 1, whilst the major energy consuming components in the production of cement are shown in Fig. 2.

Fig. 2 shows that approximately 60% of the energy is consumed by the grinding circuits. These circuits consume both thermal energy, provided by coal fired kilns, and electrical energy to power the drive motors, conveyor transport systems and fans. Modern cement plants consume an average of 100–120 kW h per ton in the grinding circuits [12,13].

Electrical auxiliary systems of the grinding circuits include air compressors, conveyor transport, water- and oil pumps, and various large fans. The combined electrical energy consumption of grinding systems can constitute up to 75% of all energy used in the cement industry [2,12]. This corresponds to a total production cost component of 50–60% for energy of which 17.8–42.6% is allocated to electricity alone [2]. The fairly large variation is attributed to different pricing structures and electricity costs in different areas in the world.

In addition to energy costs, environmental conservation in terms of reducing carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions is a global concern [14]. 33% of global emissions are directly linked to the use of energy of which the cement industry contributes up to 7% of global CO_2 emissions [15,16].

South Africa's primary electricity utility, Eskom, produces 95% of the electricity consumed in the country. 93% of this electricity is generated in coal-fired power plants and the remaining 7% produced by hydro-, nuclear- and gas turbine power generation [17-19]. Reducing electricity demand of cement plants in South Africa will therefore serve to reduce CO_2 emissions. Managing the demand of the cement industry will also assist in creating a more uniform daily demand distribution and eliminating peaks and valleys in the electricity demand profile.

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 [2,21]. Most of these technologies require the installation of new equipment and offer average electrical energy savings of between 1 kW h and 5 kW h per ton [22–24]. In a life-cycle assessment, Valderrama et al. [20] reported that the implementation of best available technologies (BAT) reduced the electricity consumption of clinker production from 76 kW h to 69 kW h per ton. These installations are however costly

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http://dx.doi.org/10.1016/j.enconman.2013.11.033

Nomenclature

Abbreviations

APC	All Purpose Cement
BAT	best available technologies
DMP	Demand Market Participation
ENMS	energy management system
FEMP	Federal Energy Management Projects
FM	Finishing Mill
GHG	greenhouse gas
HSC	High-Strength Cement
IPMVP	International Performance Measurement and Verification Protocol
M&V	Measurement and Verification
OPC	OLE process control for object linking and embedding process control
PDCA	Plan, Do, Check, Act
PLC	Programmable Logic Controller
PTB	Process Toolbox
RHC	Rapid Hardening Cement
RM	Raw Mill
RTN	Resource Task Network
SCADA	Supervisory, Control and Data Acquisition
TOU	time-of-use
VRM	vertical roller mill

Symbols

EL	electricity supply
M_k	processing machine or component
P_{ij}	process flow/product outflow from component
S_{ij}	process flow/product inflow to component

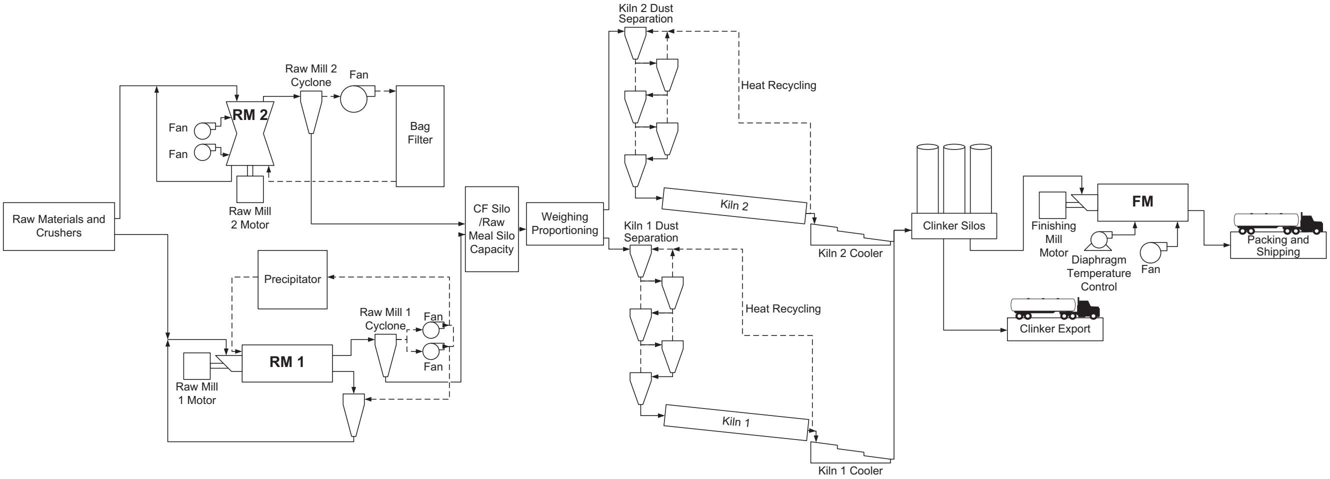


Fig. 1. Physical layout of a typical cement plant: Adapted from site audit and plant layouts drawings RM – Raw Mill; FM – Finishing Mill. (Adapted from [11]).

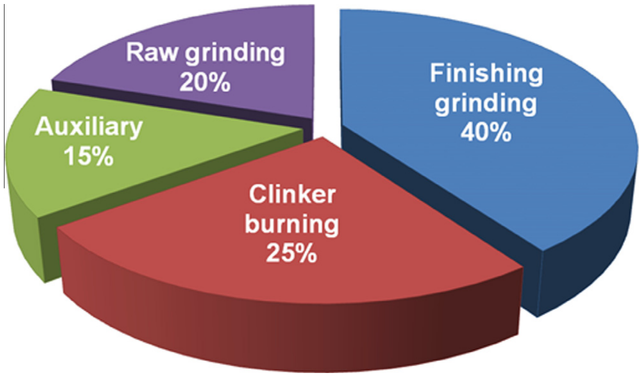


Fig. 2. Energy distribution of cement manufacturing equipment [12].

and require extended production down time [12,13]. The payback period for these installations is often longer than 10 years [23]. Considering emissions, Valderrama et al. [20] reported a 4% reduction in CO_2 emissions by implementing BAT. Reduction in NO_x, SO_2 and dust emissions of 20.5%, 54% and 84% respectively are also possible.

Another technique for achieving energy savings is improved control systems. These systems optimise specific component operation, thus ensuring stable, optimal operation [25]. Savings of between 1.4 kW h and 6 kW h per ton can be realised [22–25]. Even larger energy savings can be obtained when considering more than one component. While the individual components function optimally, the combined analysis of the system will provide interlinked savings. An example is presented by Chae et al. [26]. Doing a plant wide analysis identifies the possibilities for these savings [27].

No published literature could be found on the application of management and computerised modelling systems that simultaneously integrate the numerous production components. A new energy management system was therefore developed and implemented that provides a solution for reducing energy consumption and emissions. The new energy management system not only integrates, optimises and controls specific subsystems according to energy cost saving strategies, but can also predict future electricity costs. Results from *in situ* experiments at four existing South African cement plants are reported, including financial savings.

2. System architecture

On a cement plant, most modern control system utilise PLC networks to capture data from instrumentation devices and also to control the machines. The PLC's are connected to the *Supervisory Control and Data Acquisition* (SCADA) system via either an Ethernet or a Profibus network. The SCADA accesses the relevant PLC to control and record data from the process control network. The SCADA system is thus ideal for accessing relevant data sets regarding plant operation. This is achieved by setting up an *OLE Process Control* or *Object Linking and Embedding Process Control* (OPC) connection. The database component of the *energy management system* (ENMS) communicates with the SCADA to record and store relevant data from the plant process control network. The layout of the ENMS is shown in Fig. 3.

The database compiles a data file and stores it on the on-site server (as depicted in Fig. 3). For flexibility and ease of operation, email is used to send this data file to the centralised, local server and the web-based reporting suite, by implementing a simple, automated mail applet. The data file is integrated into the simulation package and optimised using a third party linear optimiser. The simulation package generates an optimised data file which in turn is sent back to the on-site server.

Two different applets extract information from the data file. First, the optimised operations schedule is displayed to the plant operators to start and stop the plant components. Second, the forecasting applet accesses other information including silo levels, predicted production and raw material requirements. This is displayed to plant operational personnel with an intuitive user interface (shown in Fig. 4).

During the implementation of the first projects, full control of the plant was not assumed. A simple and user-friendly interface was created for plant operating personnel to view (further described in the section regarding integrated modelling). These plant operators control different plant components in accordance with the generated operating schedule, effectively implementing a manual control mode. The capability of the ENMS to automatically control plant components via OPC and the PLC networks is possible; though not accepted during the first implementations of the energy management system.

3. Integrated modelling

The new system conforms to the "Planning", "Doing", "Checking" and "Acting", or PDCA structure as set out in ISO 50001 [28]. The energy management system (ENMS), referred to as the *Process Tool Box* (PTB), includes an integrated modelling system. Fig. 5 is a simplified 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.

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 [28]. The core of the ENMS is the PTB modelling system that operates within the larger system (refer to section IV for "Acting"). Various production components have an influence on the cost of the final product and on electricity consumption. In most cases these are either directly or indirectly linked to the operation of the plant. The modelling system therefore considers various constraints that were not previously integrated in similar operations models.

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

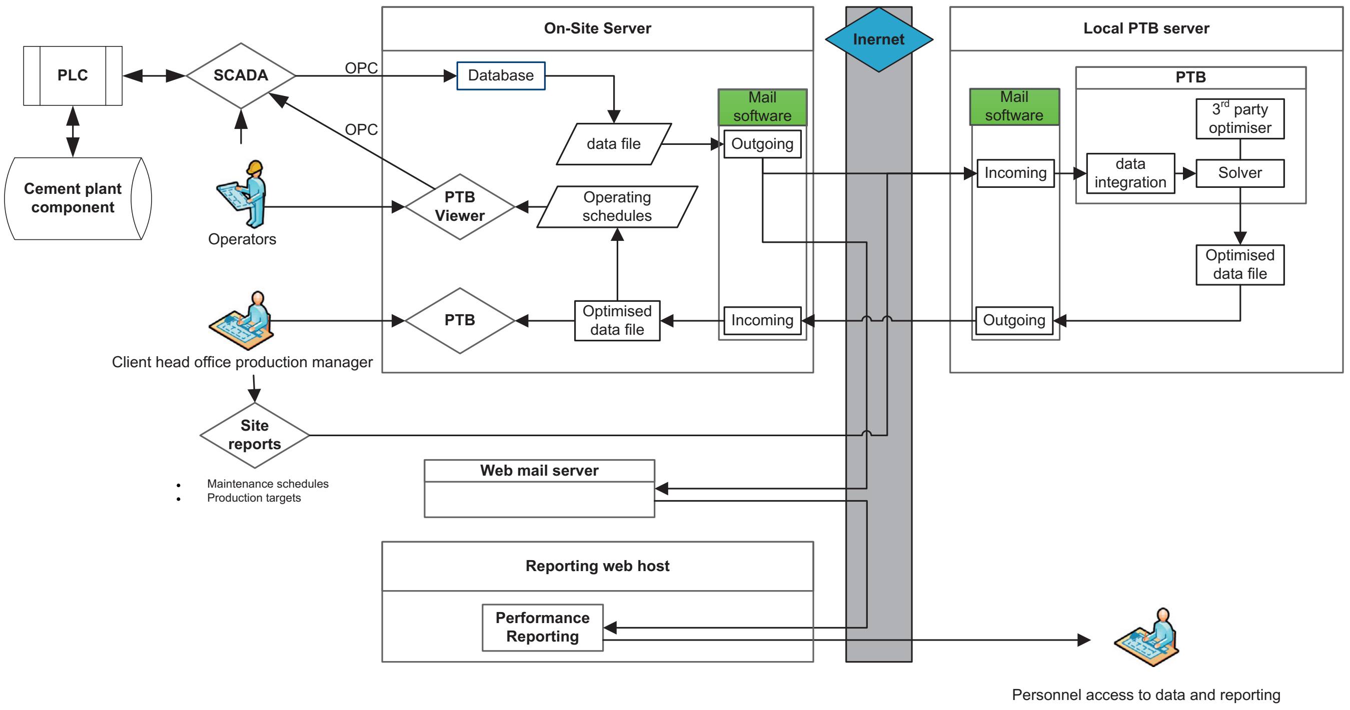


Fig. 3. Systems layout of the ENMS.

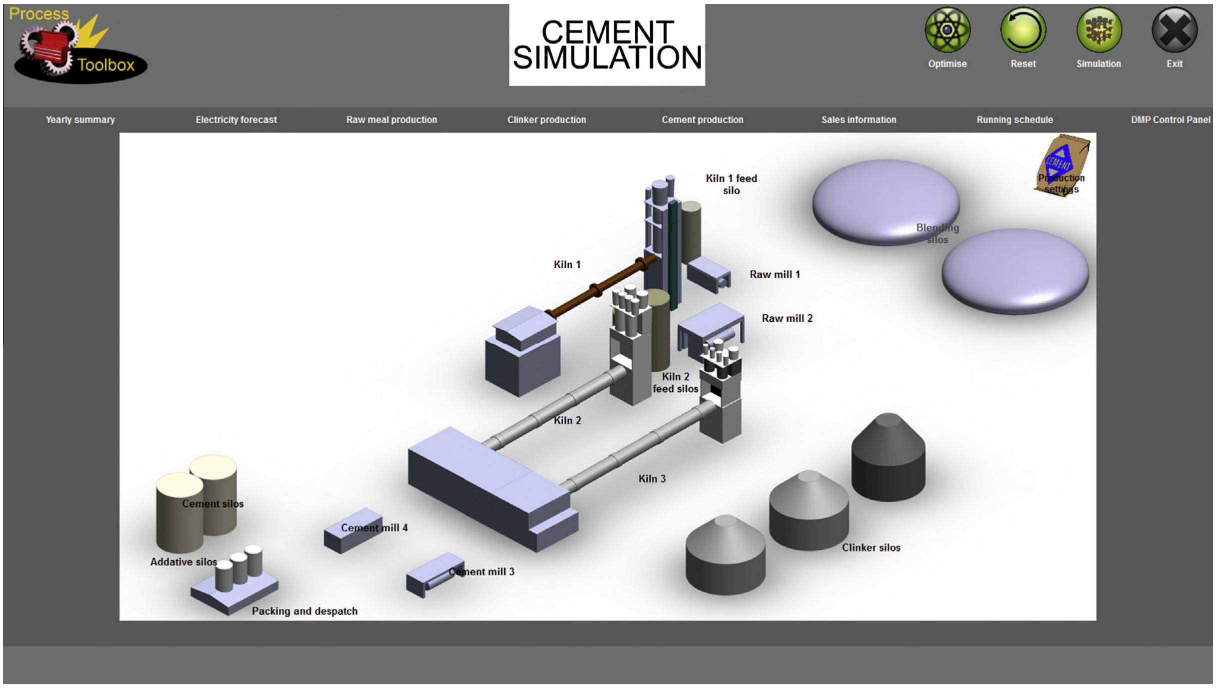


Fig. 4. Example of a main user interface in the new energy management system.

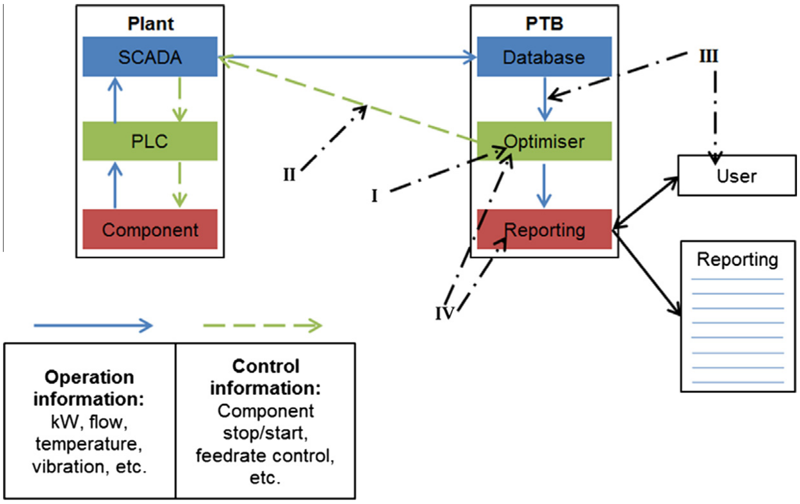


Fig. 5. Schematic of PTB system integration and functionality.

To facilitate construction of an integrated model, the constraints of the different production 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.

Each of the components was modelled in steady state. Simple operational mathematics was used to estimate the different operational values. The cement production process is divided into its main components for modelling purposes. These components are the raw mill, finishing mill, coal mill, kiln, and the buffers or silos. Fig. 6 shows the Resource-Task Network (RTN) diagram for the main cement components. The RTN diagram represents the structure in which the mathematical model is compiled. The different components in Fig. 6 are listed in Table 1.

An RTN description elucidates the different tasks that are used to produce the final product. In Fig. 6 these tasks are laid out with the different components that are used to complete these tasks. Fig. 7 displays the layout of the elements of the diagram shown in Fig. 6.

The RTN diagram depicted in Fig. 6 serves to display the different characteristics of the simulated system. In Fig. 7, S_{ij} and P_{ij} represent the process flows that are considered inflows and outflows, respectively. The centre block represents the process that is followed to transform the process flow from S_{ij} to P_{ij} at a specific rate. M_k represents the machine or component used to execute

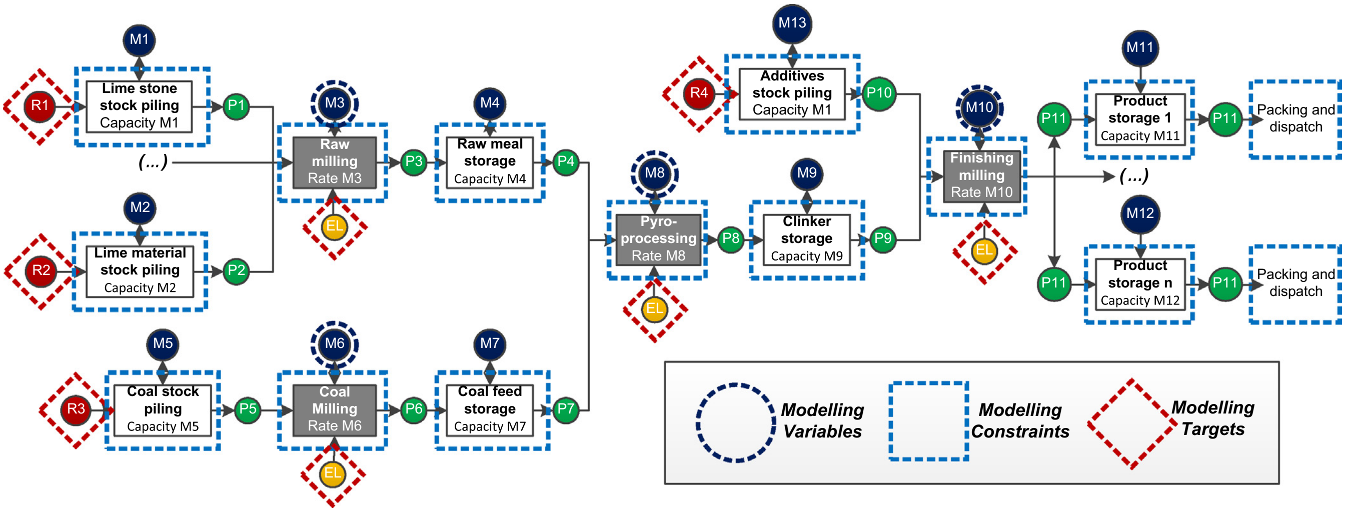


Fig. 6. Simplified Resource-Task Network (RTN) diagram for a single-line cement plant.

Table 1
Components description of a simplified Resource-Task Network (RTN) representation of the integrated modelling approach.

Products	Description	Component	Description
P1	Raw material 1 (example lime stone) [t]	M1	Raw material stockpile
P2	Raw material 2 (example production shale) [t]	M2	Raw material store
P3	Raw meal [t]	M3	Raw mill
P4	Raw meal [t]	M4	Homogenisation/kiln feed silo
P5	Raw fossil fuel (example coal and fuel oil) [t]	M5	Coal stockpile
P6	Supplied fossil fuel (i.e., crushed or pumped) [t]	M6	Coal mill
P7	Supplied fossil fuel (i.e., crushed or pumped) [t]	M7	Coal storage bin
P8	Clinker [t]	M8	Pre-calciner, kiln and cooler
P9	Clinker [t]	M9	Clinker silo
P10	Cement additives [t]	M10	Finishing mill
P11	Cement (*n* products) [t]	M11	Cement silo for product *i*
		M12	Cement silo for product *n*
Raw materials	Description	M13	Additives stockpile
R1	Raw material 1 (example lime stone) [t]		
R2	Raw material 2 (e.g., production shale) [t]		
R3	Raw fossil fuel (e.g., coal & fuel oil) [t]		
R4	Cement (*n* products) [t]		

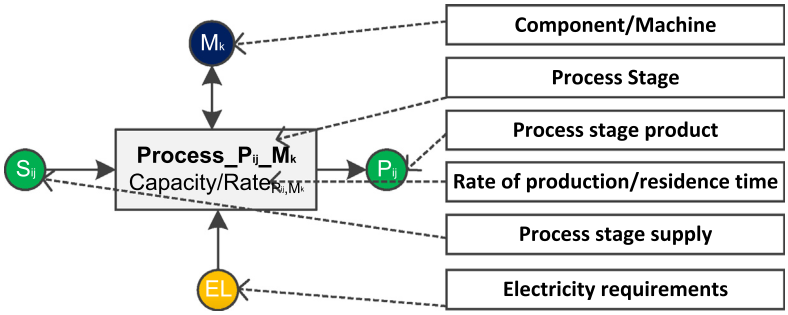
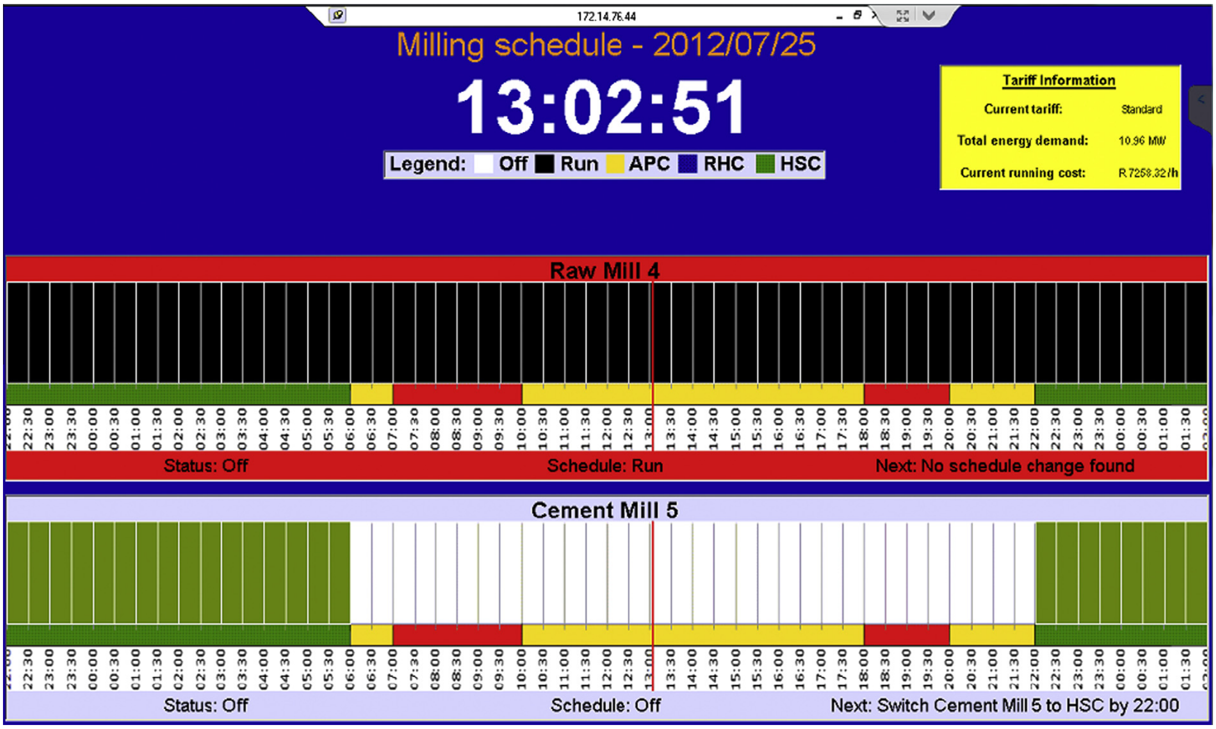


Fig. 7. RTN description for process lines.

the process (i.e., a mill, storage silo or kiln in the case of cement production). The processing rate or storage capacity is denoted by the machine or component used. EL represents the electricity supply required to execute the process stage by component M_k.

The constraints of the component M_k include silo minimum and maximum allowable limits. Another constraint is the total allowable operating time available for the different process stages. The allowable operating time is a function of the preventative- and breakdown maintenance of the machines completing process tasks (availability and reliability). The modelling variables that are used to optimise the operation of the plant are the running times of the components used to complete the process tasks (on/off schedules). The variables are either binary or fractions depending on the time analysis being used. As part of Fig. 6, the modelling constraints, variables and targets are also shown. The primary focus of the process is to reach sales/production targets. Resultantly, fixed constraints in the form of lower bounds are allocated to the sales targets.



Milling schedule - 2012/07/25

13:02:51

Tariff Information

Current tariff: Standard

Total energy demand: 10.96 MW

Current running cost: R7258.32/h

Raw Mill 4

Status: Off Schedule: Run Next: No schedule change found

Cement Mill 5

Status: Off Schedule: Off Next: Switch Cement Mill 5 to HSC by 22:00

Fig. 8. Daily operations schedule plan (APC = All-Purpose Cement, RHC = Rapid Hardening Cement, HSC = High-Strength Cement).

The optimisation target is minimum cost. This includes the cost of electricity and all raw materials used. A third-party optimiser was used to optimise the generated model for optimal cost. This model was compiled using a discrete time formulation as described by Mendez et al. [29]. This includes the energy used in the production process and the raw materials used. Minimising the total cost of production enables the plant personnel to compare the effect of using different process components in a TOU tariff structure and the cost of the raw materials used.

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

II. Doing:

The "do" clause describes the implementation of the action plan by establishing management structures for maintaining the strategies developed in step I. Implementation also encompasses the actual undertaking of the improvement measures [28]. 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 Fig. 8. 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).

On this display, as shown in Fig. 8, the thin red line represents the prevailing moment. The highlighted blocks represent proposed operating times, [1]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 Fig. 8.

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 [28]. Sustainability is a major aspect to consider in the implementation of an optimised solution. For sustainable optimal operation and energy efficiency improvement, a reporting component is added to the PTB system.

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

IV. Acting:

Using an iterative process, these new savings strategies and targets are implemented. These savings strategies are continuously monitored to maintain and improve the implemented energy-savings measures [28]. 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.

PTB is limited by to the client's database and instrumentation and updated in real-time. Statistical predictions of the operating

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[1] For interpretation of color in Fig. 8, the reader is referred to the web version of this article.

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

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

4. 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 Fig. 9.

Loads shifted out of these two peak periods will assist in reducing the maximum supply of the utility so doing implementing a demand side intervention [31]. To encourage industries to reduce peak time loads, a TOU billing structure was adopted whereby Eskom applies different tariffs for peak, standard and off-peak periods [8], as shown in Fig. 10.

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

Second, if two components operate in parallel but with different specific electricity consumptions (kW h per ton), as indicated by Fig. 11, 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).

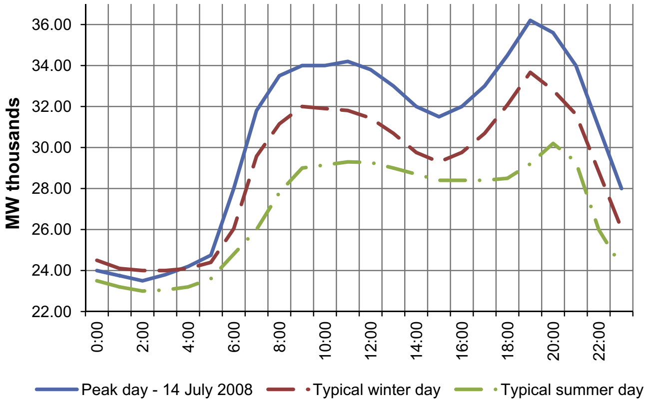

Fig. 9. South African average daily electricity demand profile in 2008 [30].

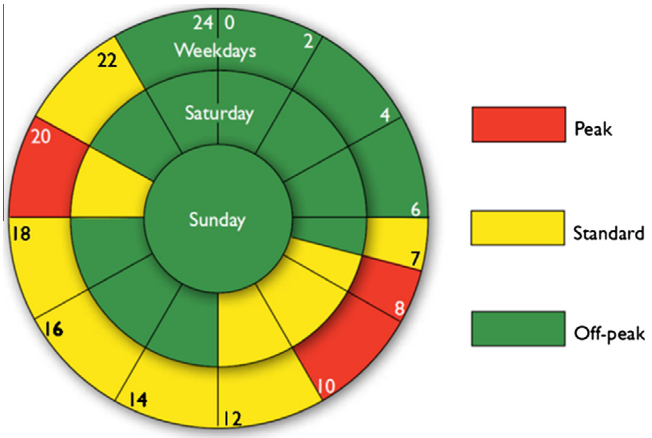

Fig. 10. Time of use (TOU) tariff structure implemented by electricity utility, Eskom [8].

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 Fig. 4 realised an average 0.97 kW h 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 Fig. 12.

The trends in Fig. 12 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. 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

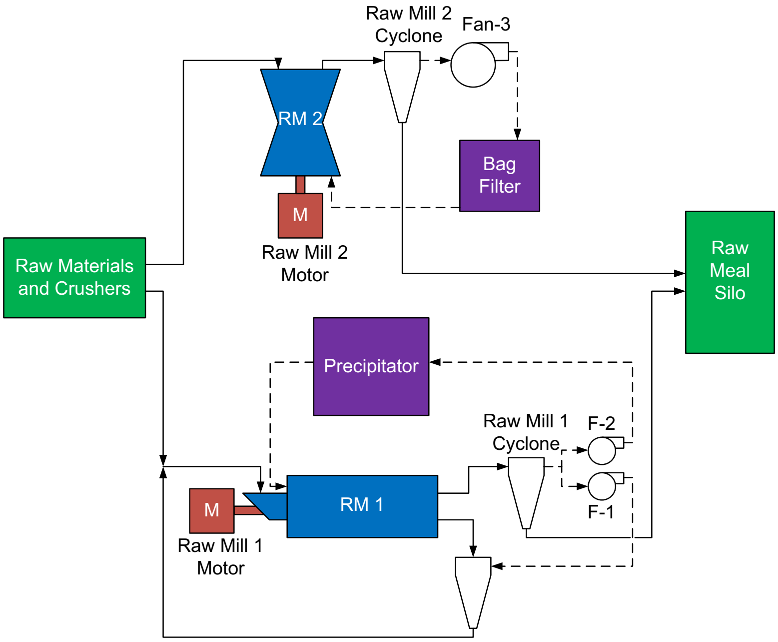

Fig. 11. Schematic representation of Case Study 1 with two different raw mills operating in parallel. ("RM" = Raw Mill; "F" = fan).

Fig. 12. Power consumption with load-shift and energy efficiency trend during the implementation of PTB in Case 1.

weekdays to weekends. The operation during an average week of implementation of the ENMS PTB is indicated in Fig. 13.

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 Fig. 13, 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.

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 Fig. 14.

PTB indicates that it is in most cases more effective to undertake large annual maintenance events, such as kiln relining, during the

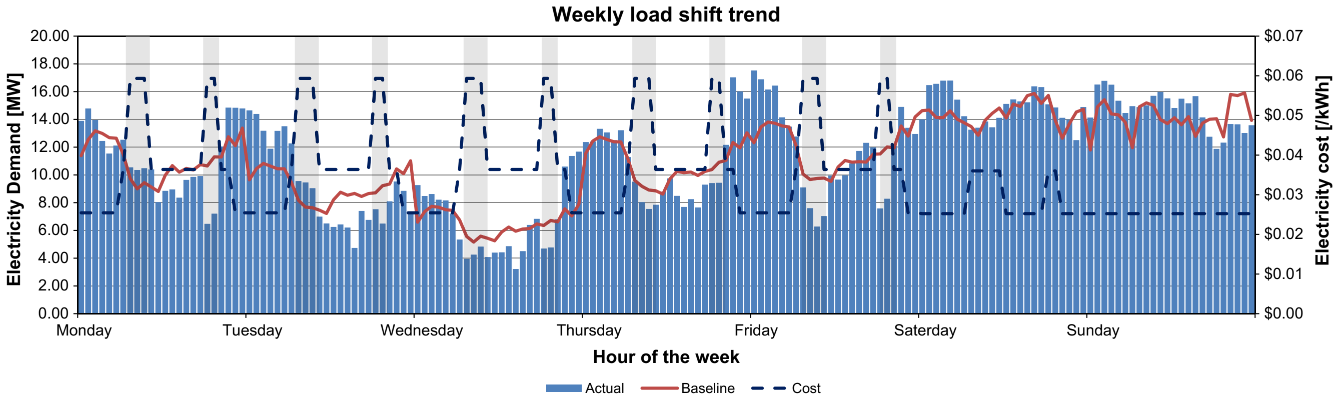

Fig. 13. Power consumption trend for weekly load shift of Case 2.

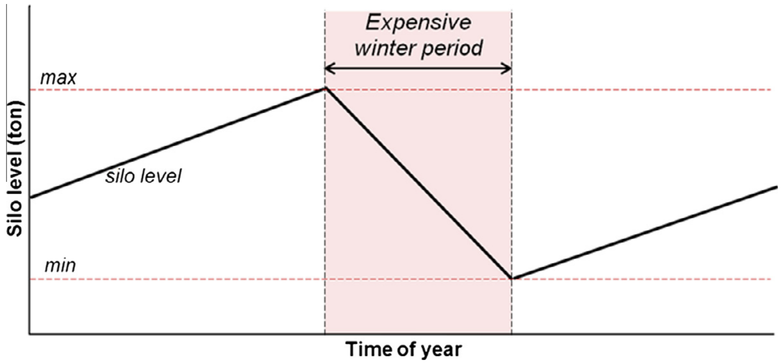

Fig. 14. Storage utilisation (i.e., silo usage) to reduce annual electricity cost.

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. 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.

6. Case 3: accounting for multiple energy cost influences

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.

Combining the DMP program with the TOU tariff structures imposed by the national utility poses a difficult problem to solve during implementation. However, frequent data acquisition and iteration to an optimal solution allows the simulation to account 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.

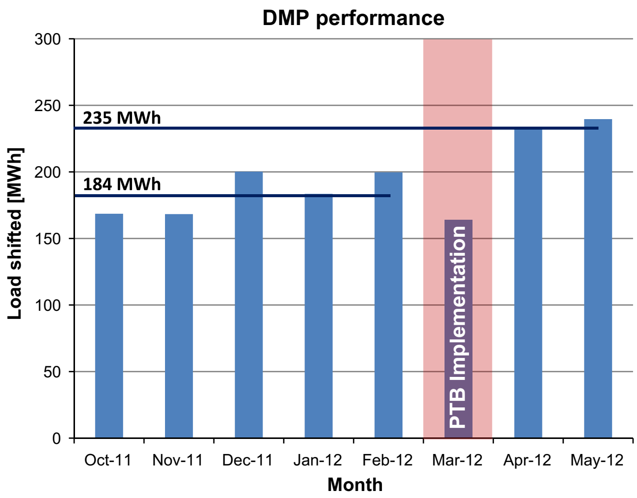

Fig. 15. Demand Market Participation (DMP) performance before and after implementation of the Process Toolbox (PTB) system (Case 3).

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. Fig. 15 indicates the DMP performance of Case 3 with a monthly average before and after PTB was implemented.

Fig. 15 shows a lower DMP performance due to the setup of the control and communication systems during the month of implementation. Once the implementation was completed, an instantaneous increase in DMP performance can be observed.

7. 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 Fig. 16.

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

Once again, as with parallel mills of differing efficiency, it is clear that the production of the more efficient mill (with regards to raw materials cost) should be maximised during normal operation. However, combining TOU tariffs, raw material cost and dynamic electricity cost influences, this problem also becomes too complex to analyse manually. Fig. 17 shows an example of combining the costs of both electricity usage and raw materials cost.

The discontinuity in the specific cost of production shown in Fig. 17 is attributed to the mills needing to operate in different TOU tariff periods. This dramatically increases the specific cost when compared to operating during less expensive time periods alone.

Fig. 17 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

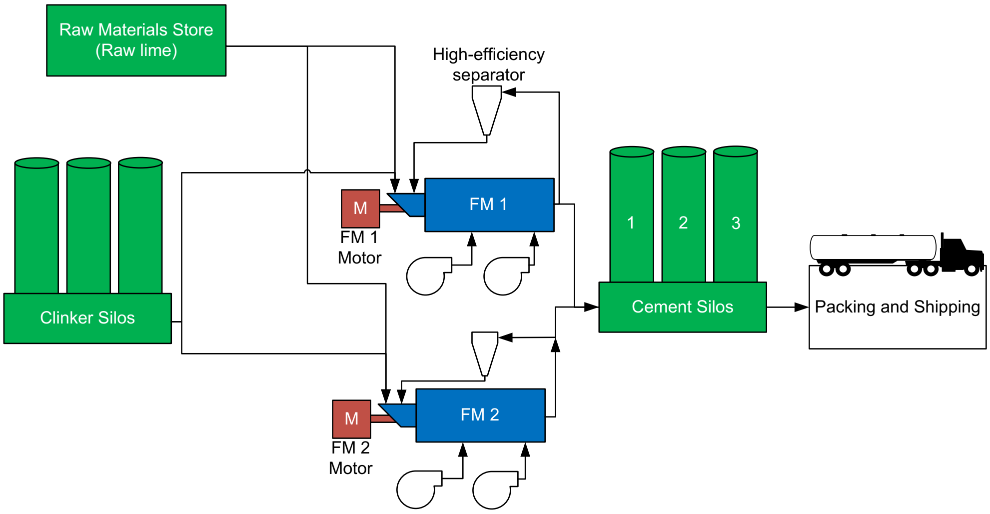

Fig. 16. Production component schematic indicating two finishing mills in parallel, with different separators.

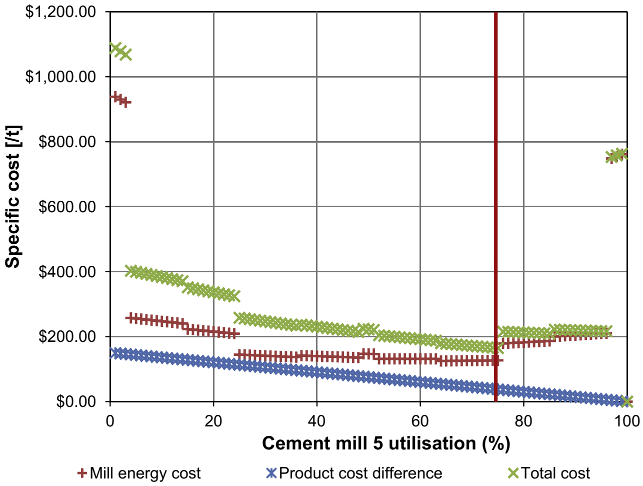

Fig. 17. Cost comparison of raw materials cost to electricity cost of operation.

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%.

8. 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. The results are recorded by an independent *Measurement and Verification* (M&V) team according to the *International Performance Measurement and Verification Protocol* (IPMVP) and *M&V Guidelines for Federal Energy Management Projects* (FEMP) as prescribed by Eskom Integrated Demand Management [32].

9. 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 system 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 system was implemented by creating an ENMS that conforms to the ISO 50001.

During the investigation, the study found that electricity is the major form in which energy is consumed by the cement industry. The energy analysis was extended to a national electricity demand level. Energy and emission reductions were shown to be possible by changing the load profile of the cement production plants.

Table 2
Summary of savings achieved during the implementation of the ENMS [33–42].

	Actual operations cost per month	Baseline cost per month	Savings	
			Cost	%
Case 1	$737980.00	$752694.04	$14714.04	14.76
Case 2	$655595.80	$765793.26	$96322.54	14.39
Case 3	$1677552.41	$1765264.13	$87711.72	5.23
Case 4	$2037433.41	$1872051.94	$165381.47	8.12
Total	$5122436.53	$5155803.37	$364129.78	10.63

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 approach, combined with TOU electricity cost saving and system characteristics resulted in an overall energy cost saving. In addition to these savings, frequently updating the modelling constants in real time, these savings can be obtained with dynamically fluctuating energy cost as well.

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

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

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