Analysing electricity cost saving opportunities on South African gold processing plants

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Abstract

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Costs saving measures are important for South African gold producers due to increasing energy costs and decreasing production volumes. Demand Side Management (DSM) is an effective strategy to reduce electricity consumption and costs. DSM projects have been implemented widely on South African mining systems such as pumping, refrigeration, rock transport and compressed air. Implementations have, however, been limited on gold processing plants despite the significant amounts of energy that this section consumes.

The main objective of gold processing plants is production orientated and energy management is not a primary focus. This rationale is re-evaluated owing to high electricity price inflation and availability of DSM incentives. This study investigated the cost saving potential of DSM interventions on gold plants. Electrical load management was identified as a key opportunity that can deliver substantial cost savings. These savings were shown to be feasible in respect of the required capital expenditure, effort of implementation and maintenance of operational targets.

Investigation procedures were compiled to identify feasible load management opportunities. The most potential for electricity cost savings was identified on comminution equipment. Consequently, a methodology was developed to implement electrical load management on the identified sections. The methodology proposed simulation techniques that enabled load management and subsequent electricity cost optimisation through production planning.

Two electrical load management case studies were successfully implemented on comminution equipment at two gold processing plants. Peak period load shift of 3.6 MW and 0.6 MW, respectively, was achieved on average for a period of three months. The annual cost savings of these applications could amount to R1.4-million and R 660 000. This results in specific electricity cost reductions of 3% and 7% for the two respective case studies.

Results from the two case studies are an indication of potential for electrical load management on South African gold processing plants. If an average electricity cost saving of 5% is extrapolated across the South African gold processing industry, the potential cost savings amount to R 25-million per annum. Although the costs saving opportunities are feasible, it is influenced by the reliability of the equipment and the dynamics of ore supply. This insight plays a decisive role in determining the feasibility of DSM on gold processing plants.

Samevatting

Kostebesparings is belangrik vir die winsgewendheid van Suid-Afrikaanse goudprodusente weens die verhoging van energiekostes en die vermindering van produksie volumes. *Demand Side Management* (DSM) is 'n doeltreffende strategie om elektrisiteitverbruik en -kostes te verminder. DSM projekte is reeds wyd geïmplimenteer op groot mynboudienste soos pompe, verkoelingsisteme, ertsvervoer- en kompressorstelsels. Implementering daarvan is egter beperk op goudprosseringsaanlegte ten spyte van die aansienlike hoeveelheid energie wat dié aanlegte verbruik.

Goudaanlegte is hoofsaaklik produksie georiënteerd en energiebestuur is nie die primêre fokus nie. Hierdie denkwyse word tans geherevalueer weens hoë elektrisiteitskoste-inflasie en die beskikbaarheid van DSM geleenthede. In hierdie studie word die potensiaal van moontlike kostebesparingsgeleenthede ondersoek. Elektriese lasbestuur is geïdentifiseer as 'n uitvoerbare geleentheid wat aansienlike kostebesparings kan meebring. Hierdie besparings is haalbaar ten opsigte van die vereiste kapitaalbesteding en die instandhouding van operasionele doelwitte.

Ondersoekprosedures is saamgestel om haalbare lasbestuurgeleenthede te identifiseer. Die meeste potensiaal vir elektrisiteitkostebesparings was by komminusietoerusting geïdentifiseer. Gevolglik is 'n metode ontwikkel om die elektriese las op hierdie toerusting te bestuur. Die voorgestelde metode behels ook simulasietegnieke wat lasbestuur en die daaropvolgende optimalisering van elektrisiteitskostes kan bewerkstellig.

Twee gevallestudies toon die suksesvolle implementering van elektriese lasbestuur op komminusietoerusting. Die gemiddelde elektriese las wat vanuit piektye geskuif is, is 3.6 MW en 0.6 MW onderskeidelik by twee goudaanlegte. Die jaarlikse kostebesparings van hierdie toepassings beloop R1.4-miljoen en R 660 000 onderskeidelik. Dit lei tot 'n 3% en 7% verlaging in spesifieke elektrisiteitskostes vir die twee onderskeie gevallestudies.

Resultate uit die twee gevallestudies is 'n aanduiding van die potensiaal vir elektriese lasbestuur op Suid-Afrikaanse goudaanlegte. Indien 'n gemiddelde elektrisiteitskostebesparing van 5% geëkstrapoleer word oor die Suid-Afrikaanse goudindustrie, beloop die potensiële kostebesparing R 25-miljoen per jaar. Hoewel die kostebesparings haalbaar is, word dit beïnvloed deur die betroubaarheid van die toerusting en die dinamika van die ertstoevoer. Hierdie insig speel 'n bepalende rol om die sukses van DSM op goudaanlegte te bepaal.

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Abbreviations

AG	Autogenous
CDM	Clean Development Mechanism
CIL	Carbon-In-Leach process
CIP	Carbon-In-Pulp process
DR	Demand Response
DSM	Demand Side Management
ES	Electrode Steam boilers
IDM	Integrated Demand Management
ISO 50001	International Organisation for Standardisation: Energy management
MILP	Mixed Integer Linear Programming
OEM	Original Equipment Manufacturer
PI	Proportional Integral control
PSD	Particle Size Distribution
RD	Relative Density
ROM	Run-Of-Mine
SAG	Semi-Autogenous
SCADA	Supervisory Control and Database Acquisition
TOU	Time-Of-Use

Nomenclature

Symbol	***Description***	***Unit***
C	Overall cost savings	R
F_{OV}	Thickener overflow	tonnes
F_{THICK}	Flow to thickener	tonnes
F_{UN}	Thickener underflow	tonnes
i	Subscript indicator for time intervals	
I_{Av}	Equipment availability index	%
I_{Re}	Equipment reliability index	%
I_{SF}	Ore supply safety factor	%
j	Subscript indicator for ore supply sources	
k	Subscript indicator for mills	
$Level_{MAX}$	Maximum silo level	tonnes

$\mathrm{Level}_{\mathrm{MIN}}$	Minimum silo level	tonnes
m	Number of mills	
M	Overall milling capacity	tonnes
$\mathrm{M}_{\mathrm{TARGET}}$	Production target	tonnes
n	Number of time intervals	
P_{80}	80% Particle cut size	%
P_{OP}	Mill power operating point	kW
Q	Electrical energy consumption	kWh
Q_{BL}	Baseline period energy usage	kWh
Q_{OP}	Off-peak period electricity usage	kWh
Q_{P}	Peak period electricity usage	kWh
Q_{S}	Standard period electricity usage	kWh
$\mathrm{Q}_{\mathrm{Scaled\ BL}}$	Scaled baseline energy usage	kWh
RD	Relative Density	tonne/ m^3
$\mathrm{RD}_{\mathrm{LIQUID}}$	Relative Density of water	tonne/ m^3
$\mathrm{RD}_{\mathrm{MAX}}$	Maximum Relative Density	tonne/ m^3
$\mathrm{RD}_{\mathrm{MIN}}$	Minimum Relative Density	tonne/ m^3
$\mathrm{RD}_{\mathrm{SOLIDS}}$	Relative Density of rock	tonne/ m^3
$\mathrm{R}_{\mathrm{Eff}}$	Effective milling rate	tonnes/ hour
$\mathrm{R}_{\mathrm{Emp}}$	Empirical mill feed rate	tonnes/ hour
$\mathrm{R}_{\mathrm{MILL\text{-}FEED}}$	Total mill feed	tonnes
$\mathrm{R}_{\mathrm{SILO\text{-}IN}}$	Total silo inflow	tonnes
$\mathrm{R}_{\mathrm{SILO\text{-}OUT}}$	Total silo outflow	tonnes
$\mathrm{R}_{\mathrm{SUPPLY}}$	Ore supply schedule	tonnes
s	Number of ore supply sources	
S_{OP}	Off-peak period energy partition	%
S_{P}	Peak period energy partition	%
S_{S}	Standard period energy partition	%
T_{OP}	Milling operational schedule	time intervals
W	Weighted average cost function	R/kWh
W_{LM}	Weighted load management cost function	R/kWh
$\mathrm{W}_{\mathrm{Scaled\ BL}}$	Weighted baseline cost function	R/kWh
X	Solids fraction by weight percentage	wt%
X_{OV}	Solid fraction thickener overflow	wt%
$\mathrm{X}_{\mathrm{THICK}}$	Solid fraction thickener feed	wt%
X_{UN}	Solid fraction thickener underflow	wt%

Chapter 1.

Introduction

Chapter 1 provides a general background and sufficient relevance for the study. This includes the motivation, research objective and the scope boundaries of the study.

1.1. Background

Mining and mineral processing are some of the most energy intensive industries in South Africa. An estimated 15% of the national electricity power output is supplied to the mining industry. The largest electricity consumer in this sector is gold mining that consumes 47% of the total power supply [1]. Electricity cost management, through Demand Side Management (DSM), is therefore applied in the gold production industry.

1.1.1. Overview of gold mining and processing

The South African goldfields form an arc stretching roughly 500 km through the Free State, North-West and Gauteng provinces. This area is generally referred to as the Witwatersrand basin. Gold occurs mainly in sedimentary reefs up to several kilometres under the ground. The majority of gold produced in South Africa originates from deep-level mines across the Witwatersrand basin [2].

The term mining covers the activities that are dedicated to recover gold bearing material from its original source. These mining activities can be distinguished based on the location of the ore, i.e. underground mining or surface operations. Mined material is referred to as Run-Of-Mine (ROM) ore which is a mixture of variable size rocks with a gold content generally varying between 1 and 10 grams per tonne[1] [2]. Figure 1-1 illustrates a basic gold process line.

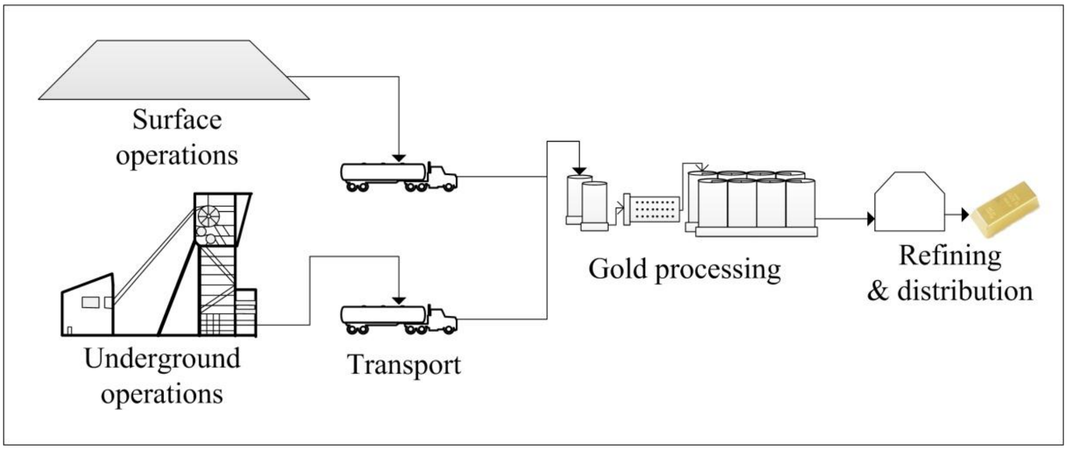

Figure 1-1: Basic layout of a gold process line

In underground mining, holes are drilled into ore bodies, filled with explosives and then blasted. The blasted rock is scraped to the main shaft and hoisted to surface. Underground mining commonly supplies two types of material, namely reef and waste rock. Reef has a much higher head grade than waste and is therefore the preferred material to retrieve due to its economic potential [3].

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[1] Goldfields Limited. 2012. "Resources and reserves statement". http://www.goldfields.co.za/ [Accessed 6 May 2013]
[2] Harmony Gold Mining Company Ltd. 2012. "Harmony integrated report". www.harmony.co.za/ [Accessed 6 May 2013]

Waste rock is hauled from underground and stored on surface dumps. In some instances these waste dumps bear a gold content that is economically feasible to recover due to either development in process technology or increased metal prices [4]. Activities that reclaim and process marginal grade ore dumps are referred to as surface operations. Other surface operations may also include open pit mines and tailings retreatment operations.

Once mined, ore has to be processed in order to increase the gold quality from mere parts per million up to a marketable purity. In order to reduce transport costs, processing takes place in the vicinity of the mining area at a gold processing plant. The Carbon-In-Pulp (CIP) or Carbon-In-Leach (CIL) processes are most commonly applied in the South African gold processing industry [5].

Gold processing plants

The first step on a gold processing plant is to reduce the particle size of ROM to the extent that the ore is susceptible to dissolution by cyanide leaching. This is done by pulverizing and grinding the ore in the comminution circuit which may consist of a number of crushers, classifiers and mills. The ore feed is stored in upstream silos or stockpiles which act as a buffer between mining and processing operations.

From the communition circuit, the fine ore particles are pumped into thickener dams where the slurry is dewatered. This is followed by sequential cyanide leaching, carbon adsorption, elution and precipitation. Smelting is the final step in the gold plant process that produces a final product with a gold content exceeding 80%. The final product is sent to refineries and gold distributers. Figure 1-2 illustrates the layout of a basic gold processing plant.

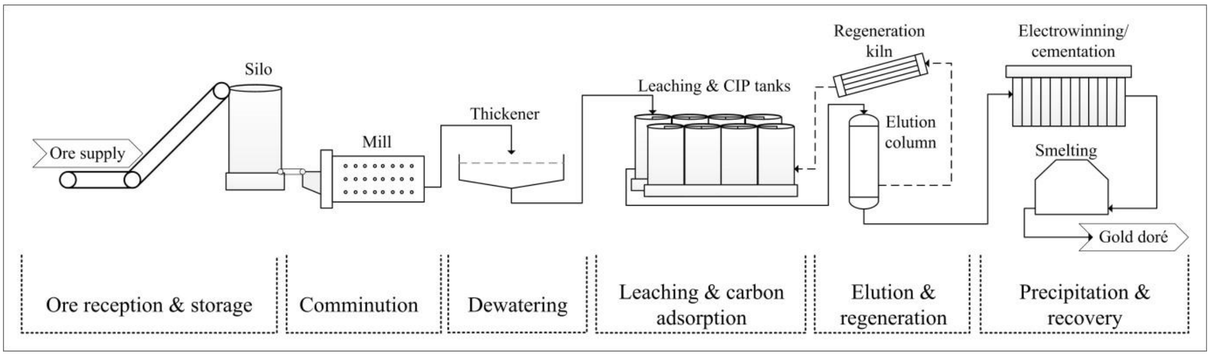

Figure 1-2: Simplified layout of a gold processing plant

Gold processing plants can vary significantly in energy requirements depending on the type of mine, geological composition of ore, type of energy sources and the extent to which to the final gold product is refined. Electricity is the most significant form of energy utilised in gold processing as comminution, compressed air and transport equipment are generally motorised. Electrical heating applications, such as electrode boilers or kilns, are also commonly used. Electricity consumption is therefore a major operational expense for gold processing plants. Figure 1-3 illustrates the energy flow diagram for gold processing.

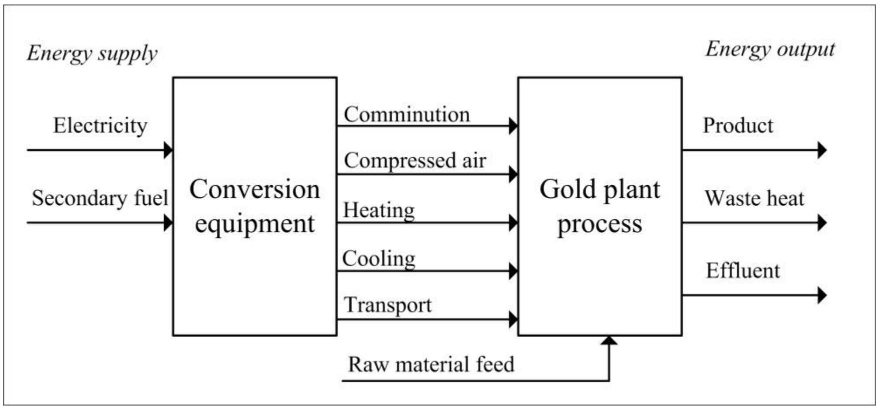

Figure 1-3: Gold processing energy flow diagram (adapted from [6], [7])

The main objective of a gold processing plant is to separate gold from gangue at an economically feasible rate. This separation requires vast amounts of physical energy inputs in the form of comminution, compressed air, heating, cooling and transport. These energy inputs are derived from electricity supply as well as secondary fuels, such as coal or liquid fuels. DSM applied on gold processing plants is aimed at increasing the efficient usage of the energy inputs for minimum costs.

1.1.2. DSM in the gold mining industry

Historically, South African electricity prices have been inexpensive relative to other countries. This has promoted passive habits with regards to optimal electricity usage. In lieu, this has presented numerous demand side saving opportunities, especially in the gold mining industry. A study done by Howells in 2006 ranked the gold industry as the industry with the most potential for energy savings and DSM initiatives [8].

Since the inception of DSM, several interventions have been implemented in the gold mining industry. Such applications have delivered substantial savings for gold mines. These include optimised water reticulation schemes [9]–[11], cooling auxiliaries[12]–[14], compressed air networks [15]–[19] and rock hoisting systems [20], [21]. DSM applications are generally divided into load management or energy efficiency projects. Figure 1-4 illustrates DSM categories by power profile depictions.

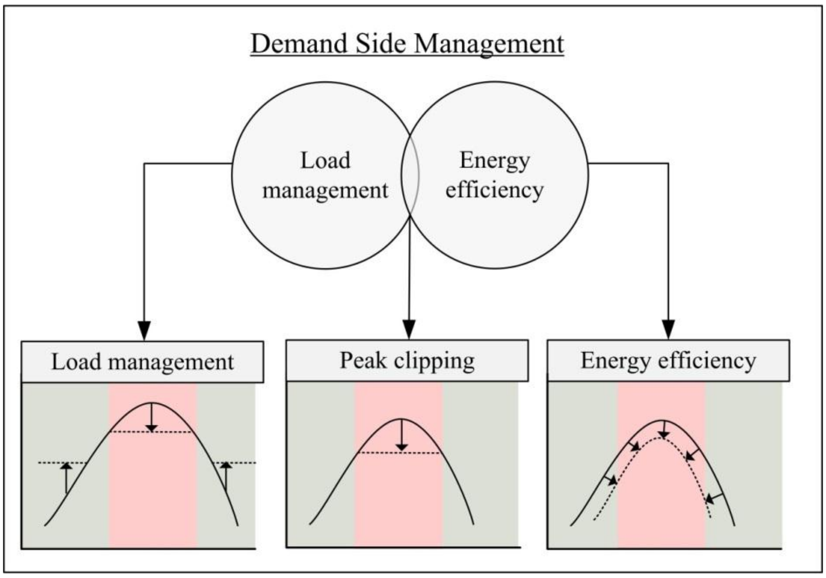

Figure 1-4: Power profile depictions of types of DSM interventions

Load management

Load management is based on minimising high demand or peak period electricity usage. It is beneficial for electricity utilities if a consumer curtails electricity consumption during high demand periods [22]. As a result, several systems have been established in order to promote peak period curtailment by electricity consumers. These include Time-Of-Use (TOU) tariff systems, Demand Response (DR) programs and other types of DSM incentives.

Typically, load management on a production line is based on the time sensitive electricity pricing structures. Cost savings can be achieved by scheduling electricity intensive operations in order to lower utilisation of more expensive TOU periods [23]. The benefit of load management on a production line can therefore be expressed in terms of specific electricity costs, i.e. electricity costs per tonne product (R/tonne). This is achieved by shifting electrical load to less expensive TOU periods.

Energy efficiency

Energy efficiency is based on the principle of doing more with less, i.e. increasing production capability within consistent or reduced energy consumption. It presents attractive benefits for electricity consumers in the form of cumulative cost savings which are linked to electricity price inflation [24], [25] (see Figure 1-5).

Energy efficiency initiatives are often also supplemented by environmental impact reduction [26] and the increase in operational efficiency [27]. Typically, energy efficiency on a production line is measured by specific energy consumption, i.e. kWh per tonne product (kWh/tonne). Peak clipping can also be applied by increasing energy efficiency in order to implement strategic load management. This can further reduce costs energy by lowering the utilisation of expensive TOU periods.

1.2. Problem statement

Electricity supply constraints in South Africa have been well documented since the national electricity shortfall became evident in 2008 [28]–[30]. The supply side can regain capacity margin by increasing generation capacity. This includes infrastructure investments that can be very capital intensive over an extensive implementation period [31]. In lieu, DSM can be utilised as a method to manage and lower electricity consumption within the short term.

DSM is an effective method from the supply side point of view since load conservation and management methods are generally less expensive than increasing base load and peak load generating capacity [22]. In South Africa DSM is utilised as a short term solution for the supply deficit caused by overdue maintenance[3] and construction[4] of generation facilities. These maintenance and construction efforts have promoted a substantial electricity tariff increase in recent years [24], [25], as illustrated in Figure 1-5.

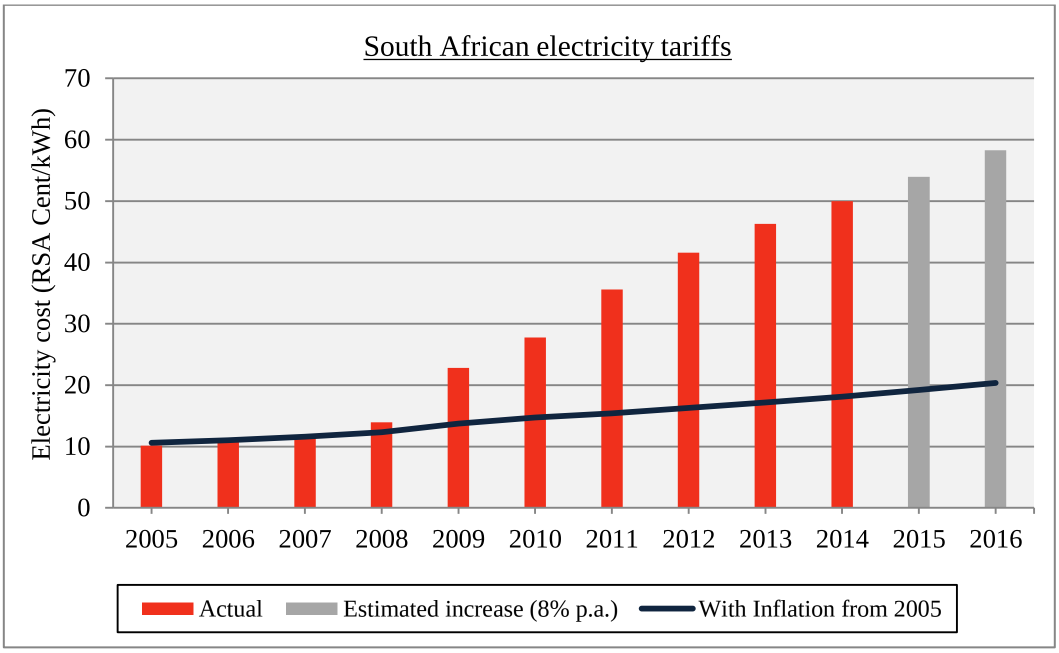

Figure 1-5: South African electricity tariffs [24], [25]

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[3] "Eskom faces more power supply risks" [Accessed 8 September 2014] http://www.iol.co.za/business/companies/eskom-faces-more-power-supply-risks

[4] "Eskom South Africa Power Plant Delayed to 2014 as Costs Rise" [Accessed 8 September 2014] http://www.bloomberg.com/news/2013-07-08/eskom-south-african-power-plant-delayed-to-2014-as-costs-climb

Over the same period as Figure 1-5, South African gold producers experienced increases in overall operating expenditure and decreasing ore grades [32], [33] (illustrated in Figure 1-6). Cost management thereby becomes a crucial element for gold producers, particularly electricity cost management owing to electricity price inflation.

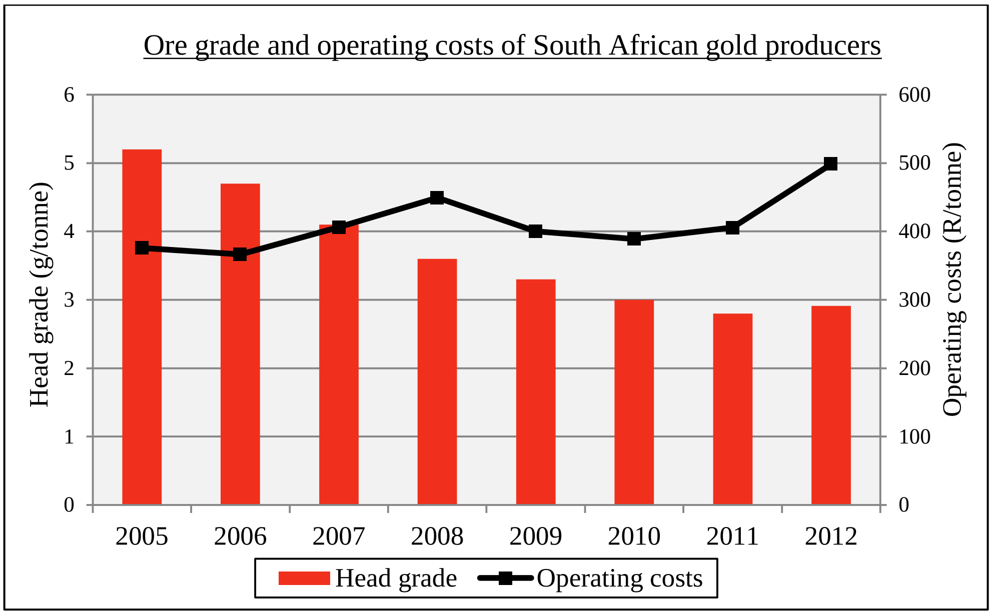

Figure 1-6: Ore grades and operating costs [32], [33]

In the South African mining industry DSM has gained significant merit as a measure to provide quick-win scenarios, i.e. implementing projects with acceptable payback periods within reasonable commission periods [34], [35]. Most of the known DSM interventions have been limited to mining operations while optimal energy management has been given less regard on the downstream mineral processing facilities. However, the increase of operational costs in the mineral processing industry, especially energy intensive processes, has prompted the re-evalution of existing operating procdures in order to identify cost saving opportunities [36].

DSM on gold processing plants

Research done by Jordaan in 2007 indicated that DSM can be viable on gold processing plants and that significant electricity cost savings are feasible [37]. However, in practice the application of DSM initiatives have been limited on gold processing plants. A possible reason for this is that production orientated activities are the key focus areas in industry. This may lower the priority of new energy saving initiatives.

The main operational target on gold processing plants is based on expenditure per gold unit produced, i.e. Rand per tonne. Intuitively, the best way to decrease the Rand per tonne ratio is to maximise production outputs. This is not always possible in the South African gold industry which has experienced significant decline in production. Figure 1-7 illustrates the consistent decline in production since 2003 in terms of ore treated.

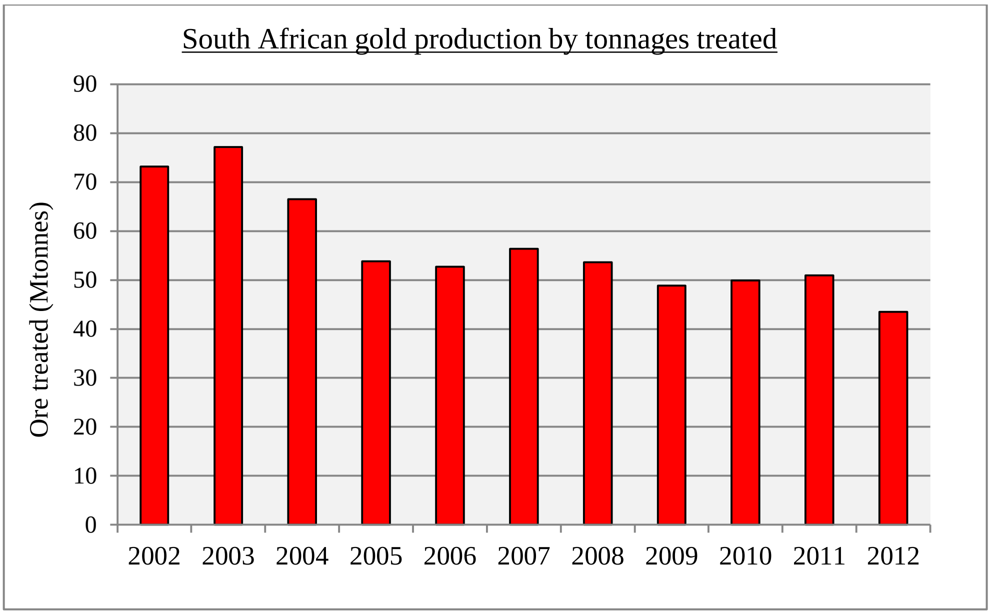

Figure 1-7: Ore treated by South African gold producers [32], [33]

A study done by Lidbetter in 2010 acknowledged that electricity cost savings can be beneficial during economic recessions or market declines [7]. In these cases electricity cost savings projects can be used to reduce production costs in the face of limited revenue owing to low production forecasts. The optimised management of no-demand periods is one such strategy that may present financial benefits.

It is expected that significant no-demand periods may be experienced on gold processing plants due to the overall decrease in South African gold production. This may present opportunities for gold producers to increase efficiency and reduce production costs through DSM projects. This study aims at investigating and verifying viable DSM projects on gold processing plants.

1.3. Research objective

The main objective of this study is to establish DSM opportunities against the background of the South African gold processing industry. The focus is on electrical energy efficiency and load management opportunities that are relevant to gold producers. The relevancy of the proposed electricity cost saving opportunities is based on the following considerations:

- Potential of cost savings;
- Capital expenditure required;
- Ease of implementation and operational feasibility within existing systems; and,
- Continuous upkeep of production, quality and other operational targets.

1.4. Scope of study

The research is based on electricity cost management in the South African gold processing industry. The scope is limited to electricity intensive processes within the ore reception, comminution, treatment and recovery sections of a typical Witwatersrand basin gold process line. Although there are numerous opportunities for electricity savings, the emphasis of the study is on load management of milling circuits.

1.5. Overview of dissertation

Chapter 1 provides general background and sufficient relevance for the study. This includes the motivation, research objective and the scope boundaries of the study.

Chapter 2 investigates the electrical energy consumption on gold processing plants. Several electricity saving opportunities in the form of energy efficiency and load management options are evaluated and summarised. This is used as project screening exercise by means of literature review. Based on the findings, a decision is made to further investigate electrical load management opportunities.

Chapter 3 describes the methods applied, including process investigations, techno-economic analyses and operational feasibility studies that are needed to implement electrical load management. Simulation techniques are developed as a tool to forecast operations and the potential of electricity cost savings.

Chapter 4 presents results of case studies that were measured during applications in the gold processing industry. These results are presented as verification of the research and methods applied. Additionally, the results are used to estimate the cost savings potential of the load management in the gold processing industry.

Chapter 5 compiles a conclusive discussion which reviews the key objectives, results and recommendations of the study.

Chapter 2.

Electricity cost saving measures in gold processing

Chapter 2 investigates the electrical energy consumption on gold processing plants in order to identify electricity saving opportunities. A project screening exercise is performed by means of literature review. The areas of investigation distinguish between energy efficient and load management applications.

2.1. Electricity consumption of gold processing plants

2.1.1. Preamble

Mineral processing consumes on average 17% of the total energy usage of mining operations [1]. Energy consumption on a gold processing plant can further be classified under the respective subsections of the process. The energy consumption partitions for typical South African mining and gold processing operations are illustrated in Figure 2-1.

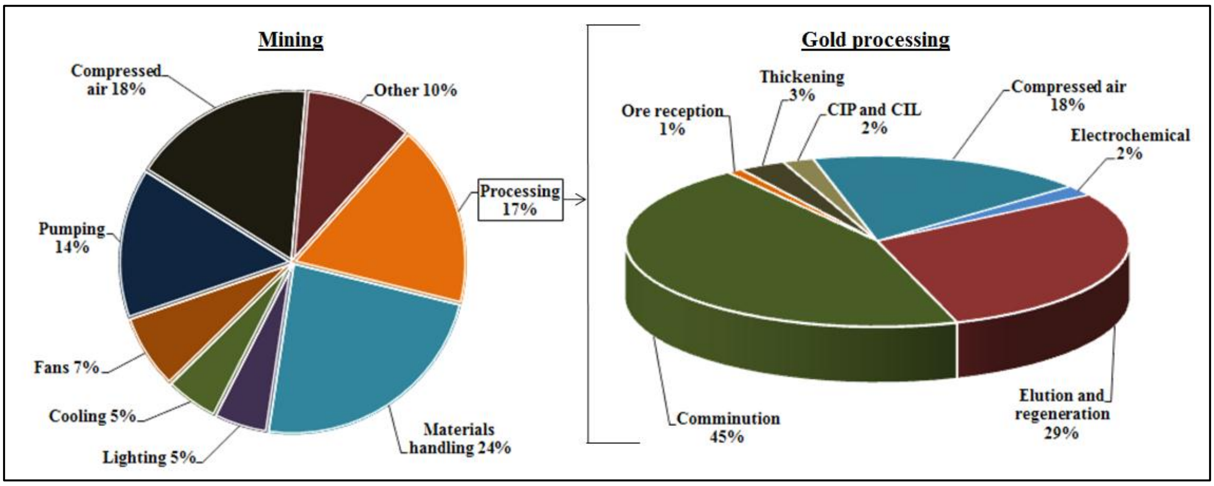

Figure 2-1: Energy consumption break-down of mining and processing [1], [37]

A gold processing plant consists of a number of interdependent sections which each comprise of electricity intensive equipment. Gold processing operations are divided into three types of equipment, namely (1) comminution, (2) transport, and (3) ore treatment equipment, for the purpose of quantifying its specific electricity consumption. This is done in order to identify areas where viable electricity cost savings interventions can be implemented.

2.1.2. Comminution equipment

The comminution circuit is the most energy intensive section on a mineral processing plant [4]. Comminution entails pulverising and grinding ore to a size that enables the liberation of the constituent metals. The most commonly applied comminution equipment includes crushers and tumbling mills.

Typically, Run-Of-Mine ore (ROM) feed has wide Particle Size Distribution (PSD) with a typical top size of 300 mm [38]. The PSD, among other ROM feed characteristics, determines the layout and type of equipment in the comminution circuit. In South Africa ROM milling is the most commonly applied comminution approach [2].

ROM milling comprises of single stage closed circuit tumbling mills in parallel. This is opposed to the multistage crushing, sorting, washing and milling circuits found on older gold processing plants [2]. Variations of comminution circuits with primary and secondary mills are also in common use [39]. This study focusses on single stage ROM milling circuits for further discussion.

Electricity consumption of milling circuits

ROM mills are fed ore as it is hoisted and hauled to the gold processing plant. Together with the ore, a mill is fed dilution water and grinding media. Dilution water is added to improve the rheological characteristics within the wet milling process [4]. Grinding media is used for breakage and may consist of steel balls (Semi-Autogenous or SAG milling) and/or abrasive rocks (Autogenous or AG milling). The electrical installed capacity of these mills typically range between 2000 kW to 3300 kW [37].

A mill discharges to a sump which acts as a buffer for the downstream classifier. Classification is executed through a hydrocyclone that discharges a specified particle size overflow and an oversize underflow. The oversize particles from the underflow are recycled to the mill feed stream. The overflow is treated in a thickener in order to produce a consistent density flow to the leaching section. Flocculent is added to the thickener to enhance solid-liquid separation.

A typical closed circuit ROM mill is illustrated in Figure 2-2.

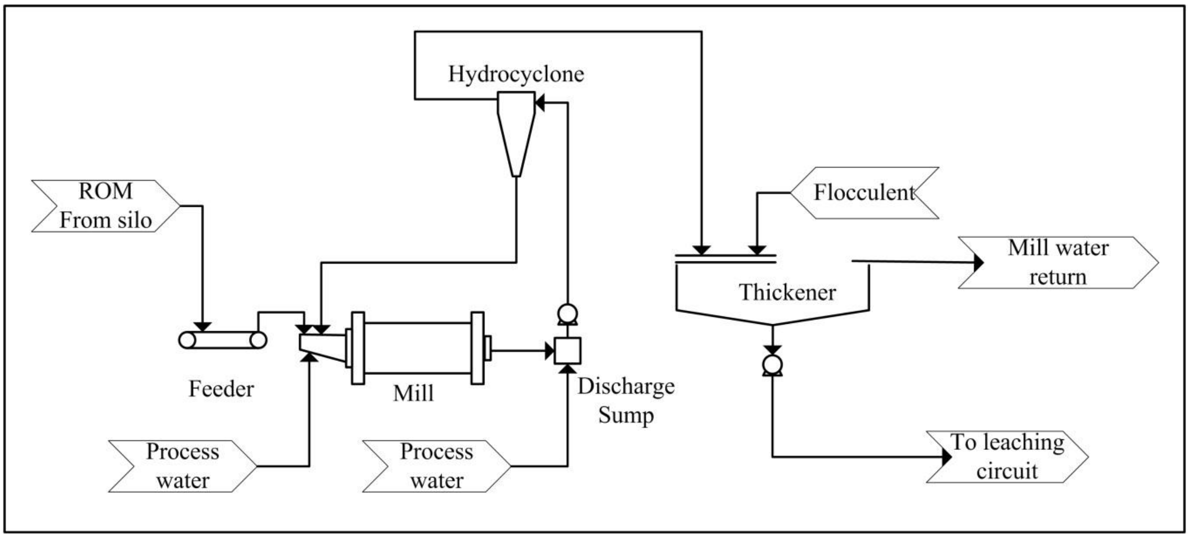

Figure 2-2: Typical closed circuit ROM milling layout

ROM mills are commonly operated at maximum electrical power draw in order to maximise the fines throughput to downstream treatment processes [2]. The loaded fraction of a mill has a strong correlation with the mass of the mill and consequently also the power draw needed for the tumbling motion. The loaded content of a mill is generally controlled at a set-point in order to keep power consumption consistently at its peak [2], [4].

2.1.3. Transport equipment

Transport equipment is essential to link the various components in a gold production line. The specific transport equipment varies as the conditions of the process streams change along the production line. Mined material in the form of rock or sand is typically transported by trams, chutes, rock winders or conveyors. Pumps, launders and pipelines are used more as the rheological characteristics increase through the addition of dilution water. Table 2-1 summarises operating ranges of the most commonly used electrical transport equipment.

Table 2-1: Summary of electrical equipment for ore transportation

Equipment	Typical range motor (kW)	Material stream
Rock winders [40]	2600 - 4400	Run-of-mine rock
Conveyor belts [41]	15 - 160	Rock
Pumps [37], [42]	8 - 175	Slurry intermediates

The transport processes in a gold process line can consist of electricity intensive equipment. Rock winders are used to hoist mined material from vertical deep level mines to the surface. Once on the surface, a combination of transfer equipment, including motorised conveyors and pumps, is used to transport the rock and slurry intermediates to and within the gold processing plant. The electricity usage of transport equipment may vary for different applications depending on the designed capacities.

2.1.4. Ore treatment and recovery processes

The specific mineralogy of gold ore presents numerous processing routes which can be followed to separate and recover gold from the constituent ore body. In South-Africa the typical Witwatersrand ore types are classified as free-milling which means that cyanide leaching can achieve recoveries exceeding 90%. This has made cyanide leaching combined with carbon adsorption the most commonly applied processing route [39]. The equipment used in the ore treatment processes are discussed under the following subsections:

A: Leaching and adsorption
B: Elution and regeneration
C: Electrochemical precipitation
D: Calcining
E: Smelting

A: Leaching and adsorption

Cyanide leaching entails dissolving gold to solution by forming an aurocyanide anion complex. This takes place in a series of agitated tanks, known as leach reactors or pachucas. Agitation is performed mechanically and/or by supply of compressed air. The residence time of material in the leaching section is typically between 20 to 40 hours across a leaching module of 6 to 12 tanks-in-series [39].

Once in solution, the gold is recovered by adsorption to activated carbon. This takes place in a series of well-mixed reactor tanks. Gold is adsorbed to activated carbon which is pumped counter currently to the flow of the slurry. The loaded carbon is then recovered from the first tank by fine aperture screens and sent to the elution section [39]. The slurry from the last adsorption tank is considered as tailings.

Leaching and adsorption is chemical processes that are moderately electricity intensive. Electrical energy is used for agitation and transportation of process streams. The typical motor capacities of pumps and agitators in this section range from 10 kW to 90 kW. Compressors are the largest electricity consumers in this section when compressed air is used for agitation. A typical plant compressor has an installed capacity ranging between 160 kW to 1000 kW, depending on the layout of the compressed air network [19], [37].

B: Elution and carbon regeneration

Elution entails the recovery of gold from loaded carbon. Firstly, the carbon is treated by a diluted acid wash in order to remove impurities that adsorbed to the carbon. Washed carbon is then eluted by treatment with a caustic cyanide and hydroxide solution at elevated temperatures ranging between 90°C and 120°C [39]. This results in gold desorbing back into solution at high concentrate. The gold in the high concentrate solution can then be recovered by a precipitation process, such as electrowinning or cementation.

Eluted carbon from the elution column can be reused if it is regenerated by thermal processing. This is performed in rotary kilns operating at temperature ranges from 650°C to 750°C [39]. Regeneration is carried out in a steam environment in order to prevent oxidation and degradation of the carbon. Table 2-2 lists the equipment summary of an elution and regeneration section on a gold processing plant [37].

Table 2-2: Summary of electrical equipment within elution and regeneration section [37]

Equipment	Qty.	Unit Power (kW)	Total Power (kW)
Loaded carbon screen	2	4	8
Eluted carbon screen	2	4	8
Rotary kiln	2	530	1 060
Diluted acid mixing tank agitation	1	1.5	1.5
Diluted acid transfer pump	2	4	8
Potable water pump	2	5.5	11
Caustic/ cyanide tank agitation	1	1.5	1.5
Caustic/ cyanide transfer pump	2	4	8
Kiln drive motors	2	5.5	11
Kiln screw feeder	2	1.1	2.2
Boilers	6	1 566	9 396

The rotary kilns and boilers are the largest of the electrical equipment presented in Table 2-2. These heating applications within the elution and carbon regeneration section account for significant energy usage. The electricity usage may vary significantly across different plants due to the availability of alternative energy sources. These include coal, liquid fuels and gas.

C: Electrochemical precipitation

The concentrated gold bearing solution from the elution section needs to be precipitated in order to further recover the gold. The most common method to do this is by either one of two electrochemical processes, namely cementation or electrowinning. These processes exploit the difference in electrochemical potentials in order to precipitate elemental gold.

In the case of cementation, zinc powder is added to precipitate gold by the dissolution of zinc. This reaction is thermodynamically self-driven since the electrochemical potential has a difference exceeding +0.5V [43]. Electrowinning entails the precipitation of gold by inducing a potential difference through the eluate. This is a low voltage application (< 5 V). The electricity usage associated with electrochemical processes is therefore negligible when excluding the heating applications such as the electrode boilers noted in the elution section.

D: Calcining

Calcining is a roasting process that oxidises sundry metals and impurities in order to remove it as slag in the subsequent smelting process. This is performed by dewatering the gold precipitate and prolonged heat treatment in ovens operating at temperatures reaching 700°C. Calcining ovens are relatively small electrical appliances. The installed capacities typically range between 42 kW batch multiple tray furnaces or 180 kW continuous steel belt furnaces [2].

E: Smelting

Smelting is the final stage on a gold processing plant. The smelting process separates gold from the slag phase which contains oxidised metals and other impurities. This is done by roasting the calcined product with a mixture of slag-forming fluxes at temperatures sufficient to melt the mixture. This enables the separation of the gold from the slag. The final product is referred to as doré bullion with a gold content exceeding 80% purity. Smelting is done in furnaces that can induce extreme temperatures (1200°C to 1400°C). Electric arc furnaces are in common use for this purpose. The typical installed capacity of an arc furnace is 242 kVA [2].

2.1.5. Summary of electricity consumption on gold plants

In this section the typical electrical components within gold processing are reviewed. Significant electricity intensive applications include comminution, transportation and process heating equipment. The comminution equipment is identified as the most energy intensive section. This section consists of tumbling mills that are driven by large electrical motors.

The next step in this study is to identity opportunities in respect of the identified equipment that can provide electricity cost savings. This study distinguishes between energy efficiency and load management as measures that can present electricity cost saving opportunities. Energy efficiency opportunities that are relevant to gold processing plants are reviewed firstly.

2.2. Energy efficiency DSM opportunities

2.2.1. Preamble

Energy efficiency opportunities are broadly aimed at reducing or optimising energy usage. This matter draws considerable attention since energy scarcity and cost inflation have been identified as significant risks for production orientated industries. Energy efficiency may include a wide variety of activities that can be classified into four major categories [7], [44], namely:

1. Retrofits: Replacement or modification of existing processes or equipment with high efficiency retrofits.
2. Controls: The improvement of operational performance by optimal equipment and process control systems.
3. Observation and maintenance: Consistent monitoring of equipment may present opportunities to repair or recalibrate existing equipment.
4. Benchmarking and standards: Best practice can be benchmarked and monitored by adhering to standardisation codes, such as ISO50001 (International standard for energy management).

The main areas for investigating energy efficiency opportunities are divided per section, i.e. the comminution circuit (2.2.2), transfer equipment (2.2.3), and process heating applications (2.2.4).

2.2.2. Comminution circuit

The comminution process is energy inefficient as only 1% of the total energy input is used for actual breakage and size reduction. The rest of the input energy is lost mainly as heat, as well as noise and mechanical losses [45]. Comminution equipment is therefore a popular research topic when investigating energy efficiency opportunities.

The majority of energy efficiency initiatives are related to retrofitting or replacing comminution circuits with new technologies. These include initiatives such as improving flow sheet design [46], improving control and test procedures [47] and utilising new grinding [48] and screening technology [46], [49]. Substantial capital expenditure requirements are generally the main deterrent against implementing these new technologies.

Operational improvements can also be considered as measures of energy efficiency. This can be achieved by maximising ore throughput or by selecting the coarsest possible grind size. Such operational changes that improve energy efficiency can be counterproductive since gold recovery is optimal at finer grind size [39]. Hence, control and operational set-points should be carefully investigated when opting for energy efficiency improvements. This can be done by accurate modelling and performance optimisation of comminution circuits [50].

Mill optimisation

Mills are the most commonly applied comminution devices in gold processing. Although mills have been designed to have a high degree of mechanical efficiency and reliability, they are inefficient in terms of energy utilised for actual breakage. Scope for optimisation exists since breakage occurs due to repeated random events of impact and attrition [4]. Process control has been a key area of investigation when attempting to improve the efficiency of milling circuits [51].

The control of a milling circuit is a cumbersome activity due to its multivariable and interactive nature. Additionally, the long response time between measurement and control points make the use of conventional controllers challenging [52]. For this reason expert or advanced control systems have gained merit to stabilise and optimise milling operations. The traditional control objectives for milling circuits in order of importance are given as follows [38]:

1) Improving the quality by increasing fineness and decreasing variations of the grind product.
2) Maximising mill throughput.
3) Minimising grinding media consumption.

4) Minimising power consumption.

These control objectives are not all complementary which necessitates trade-offs between contradicting objectives. A commonly acknowledged trade-off is between maximising throughput and maximising fineness of grind [4], [38]. For gold processing, fineness of grind is preferred over maximum throughput due to improved gold recovery at finer grinds. However, it is possible to improve throughput while adhering to a grind quality set-point by improving mill control.

Mills are commonly operated at maximum power in order to maximise the fines throughput to downstream recovery processes. The throughput of a milling circuit can be increased by improving the mill power or mill load set-point control. Deviation from load and power set-points by over- and under tuning feed rate reduces the overall tonnage throughput. In lieu, by improving feed rate control, the overall specific energy consumption can be improved [51]. Figure 2-3 illustrates the faster response time of optimised feed rate control when compared with conventional Proportional Integral (PI) control.

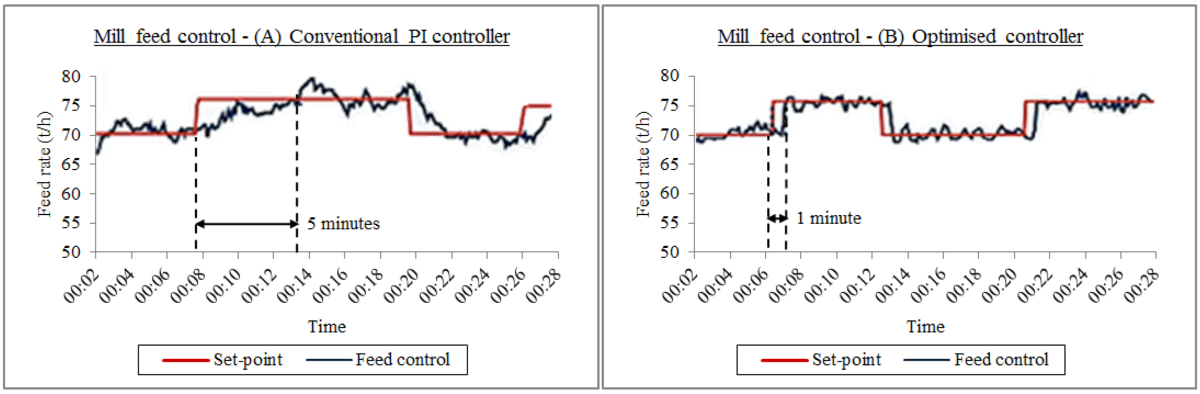

Figure 2-3: Conventional (A) and expert mill (B) feed control comparison (adapted from [51])

An average throughput increase of between 4% and 10% has been proven possible by expert mill feed control [51]. This in effect reduces the specific energy consumption ratio. However, the optimisation of milling circuits has to take into account several variables, including ROM feed conditions, equipment specifications, ore characteristics, waste characteristics and rheology. This makes advanced process monitoring and control systems essential for optimisation. The holistic approach to achieve this can be executed via the mine-to-mill concept.

Mine-to-mill concept

The comminution process is not limited to the gold processing plant. It starts at the front end of mining activities, i.e. drilling, excavating, blasting, scraping, crushing and storage which plays a role in the Particle Size Distribution (PSD) of the Run-Of-Mine (ROM) ore. For this reason the mine-to-mill concept is well known in comminution practice [47], [48], [53], [54].

Mine-to-mill is an optimisation strategy that integrates blasting, crushing, comminution and classification operations [48]. This allows an optimal PSD control across the mine-to-mill process. A study done by Morrell & Valery in 2001 has shown that ROM ore feed size plays a substantial role in the performance of a mill. The feed size can be controlled by controlling stockpile segregation, increasing crushing capacity or altering blasting patterns [53].

The feed size is, however, not the most important factor as the competence of ROM ore is the most influential factor for breakage [53]. Ore competence refers to the ability of the ore to act as a grinding medium. This is especially important for AG mills where steel balls are not used as grinding media. Ore competence can be controlled by blending reef and waste rock during stockpiling [47]. This suggests that improved blending of the harder and softer rock can significantly improve milling performance.

Mine-to-mill optimisation can increase throughput and stability of comminution equipment which in turn improves specific energy consumption. Although it can be effective in optimisation the overall comminution process [54], no notable publications have been made for South African case studies. The reason for this may be attributed to practical limitations in controlling inherently fluctuating ore characteristics. Additionally, stockpile blending is rare due to the use of conventional silos which limit blending capabilities.

2.2.3. Transfer equipment

Motorised transfer equipment includes conveyors, pumps, compressors and agitators that are used for transferring or transporting process streams. These pieces of equipment can account for significant electrical energy usage which makes it a necessary area of investigation when probing energy efficiency opportunities [55]. The following opportunities are generally considered as energy efficiency applications [56]:

- Motor management plan
- Effective maintenance and monitoring
- High efficiency motor retrofits
- Correct motor sizing
- Rewinding of motors
- Variable speed or frequency drives
- Guide vanes and surge control for compressors
- Minimise throttling and looping streams

- Correct pipe sizing and distribution network
- Reduction of leaks and wastage

The majority of energy efficiency opportunities are considered as standard industry practice. Hence, in most cases these opportunities would have been considered by plant personnel. Some energy efficiency opportunities that are more relevant to gold processing plants may include retrofits of oversized equipment, such as conveyor belts, as well as agitation and pumping alternatives.

Conveyor belts

Conveyor belts are commonly used in the ore reception, storage and comminution sections of gold plants. It is considered industry practice to overdesign conveyor drive motors in order to allow for surge conditions [57]. This is especially relevant in the South African mining industry where "Langlaagte" chutes are commonly used to feed belts. The feed conditions can vary significantly resulting in spillages and belt damage. This necessitates a standard overdesign of 67% [41].

The safety factors used to overdesign belts often present spare operational capacity, especially if operational conditions vary from the original design conditions. Spare operational capacity can be optimised in order to use energy more efficiently. This is can be done by improved energy efficient operation [58], [59] and optimal load management [60], [61].

Compressed air

Compressed air is used for standard pneumatic instrumentation and the transfer of air to the leaching process. The generation of compressed air is inefficient since it is typically 6.5% efficient overall [6]. Compressors are therefore large energy users on gold processing plants.

The leaching process must be maintained continuously with compressed air which renders energy efficiency by peak clipping unfeasible. Alternatively, mechanical agitation in place of compressed air can be considered. This may negatively influence the leaching performance which will decrease gold recovery. Hence, energy efficiency opportunities on gold plant compressors are limited, assuming that standard compressor maintenance and management is sufficient.

If a gold processing plant is part of a larger mine compressed air network, the option of isolating the gold plant compressed air ring can deliver energy savings for the overall mining operations. A study done by Joubert *et al.* [19] reported that such a strategy is not only feasible but also effective since the distribution efficiency and load management potential is increased. Isolating a gold plant compressed air ring is done by installing a stand-alone high pressure compressor at the plant [19].

Slurry transportation

The transportation of slurry streams is common practice on gold processing plants. The majority of process intermediates are transported by centrifugal pumps which are energy intensive. An energy efficient consideration is to use gravitational flow via feed launders as much as possible. Slurry pumping becomes increasingly energy and operationally intensive as the density and coarseness of slurry streams increase over longer distances. This necessitates the use of larger pump stations.

Positive displacement slurry pumps are reported to have a substantially higher efficiency rating than conventional centrifugal slurry pumps. The Phoenix™ Slurry Pump is a positive displacement pump that uses a clear water pumping cycle as a piston for pumping slurry streams. This system has reportedly high overall system and energy efficiency with lower maintenance requirements [42]. The main deterrent to such an installation is the high capital expenditure required.

2.2.4. Process heating

Second to comminution, process heating is the largest energy intensive section on gold processing plants. Heating is an area with substantial energy efficiency opportunities due to energy losses during heat generation and transfer applications. If heat energy can be contained and subsequently recovered then the overall energy input of heating processes can be decreased.

Process heating on gold processing plants is required for the elution, regeneration, precipitation, calcining and smelting sections. The general equipment used for heating includes boilers, kilns, ovens and furnaces. As in the case of comminution equipment, the majority of large energy efficiency opportunities require significant infrastructure upgrades. These include the retrofit or replacement of heat generation equipment. Typical payback periods for these types of projects can range between 15 and 20 years[5].

Regeneration alternative

Carbon regeneration is executed at high temperatures which necessitate a substantial heat energy input. Rotary kilns or vertical tube furnaces are used conventionally to indirectly heat the carbon feed stream by electricity or gas-firing [62]. Alternative equipment for carbon regeneration is available to gold producers in the form of microwave based regeneration or by Mintek’s Minfurn™ application [62], [63].

Operational improvements and cost savings are possible with alternative regeneration applications as opposed to conventional equipment. The energy efficiency improvement can be measured by the

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[5] Vosloo, J. 2014. Personal communication with Engineering Manager at HVAC International (Pty) Ltd. Tijger Vallei Office Park, 13 Pony Street, Pretoria, South Africa.

decrease in specific energy usage (kWh/ kg dry carbon). Technological alternatives to conventional rotary kilns can present a decrease in specific energy usage ranging between 20% and 48% [62].

Heat recovery

A study by Vatanakul *et al.* [64] investigated several waste heat recovery opportunities in the metals processing industry. In this study the gold calcining process was identified as a significant source of waste heat. A case study showed that 100 MW of thermal energy was lost due a 370 tonne/h off-gas stream at 550 °C being quenched after discharge. The study estimated that an electrical output of 19 MW can be supplied by a cogeneration application [64].

Substantial electricity cost savings can be benefited from heat recovery and subsequent cogeneration. It is also considered as a Clean Development Mechanism (CDM) that induces significant environmental impact reduction. The feasibility of a heat recovery applications are however subject to the availability of equipment, a consistent heat source and capital resources. It is therefore recommended that waste heat recovery be implemented during the greenfields design phase rather than a retrofit [64].

Alternative fuels

The study done by Jordaan [37] investigated the possible use of coal fired boilers as opposed to conventional Electrode Steam (ES) boilers. The motivation for this study was founded on the excessive electricity price inflation experienced in South Africa [37]. This opened up a variety of opportunities for alternative fuels, such as gas, coal and renewables, which were historically not feasible compared to inexpensive electrical heating applications. Alternative fuels, especially renewables, are gaining substantial merit as feasible solutions for energy shortages and cost inflation. Although the options for alternative fuels are considered as feasible new developments for energy efficiency, they are excluded from the scope of this study.

Numerous energy efficiency opportunities have been reviewed at this point of the study. The next section covers electricity cost saving opportunities through load management applications.

2.3. Load management DSM opportunities

2.3.1. Preamble

Electricity suppliers often undertake electrical load management when (1) electricity demand tends to exceed supply or (2) electricity suppliers have a lack of resources resulting in delays in the construction of new power generation plants [65]. Both of these criteria are relevant to electrical supply in South Africa. Therefore, demand side load management is promoted by the national utility provider, Eskom.

Electricity cost savings for consumers through load management is based on variable price structures. These include Time-Of-Use (TOU) energy tariffs. Two main reasons are highlighted for the application of TOU tariff systems. Firstly, it is more cost reflective which allows consumers to be billed relevant to their unique load profiles. Secondly, TOU tariffs empower the consumer to manage loads accordingly in order to regulate electricity costs [66].

In South Africa the majority of large electricity consumers, including mines, are billed according to the Eskom Megaflex tariff structure that incorporates TOU active energy charges. Peak TOU active energy charges are between 200% (during the low demand summer season) and 600% (during the high demand winter season) more expensive than off-peak charges [24]. Hence, load shifting and curtailment measures through strategic load management can deliver significant cost savings for consumers.

2.3.2. Load management on processing plants

Several authors have presented load management applications on electrical energy intensive processing plants. These processes include cement [67]–[70], steel [71], fertilizer [72], coal [60], [61], [73], crusher [74], [75], milling [36], air separation [70] and precious metal processing plants [37]. Electrical load management has been proven especially relevant to processing plants where energy costs contribute significantly to overall operational expenses.

Electricity costs account for up to 15% of the total cement manufacturing costs [68]. Research by Groenewald *et al.* [68] proposed the simulation and management of silo levels on a cement plant in order to schedule milling operations according to TOU periods. This allowed effective electrical load management that delivered subsequent cost savings associated with load shifted from peak periods. It is however subject to the implementation of a real-time energy management system [68].

Research by Swanepoel *et al.* [69] presented further energy optimisation for cement processing by integrated modelling techniques. This included TOU optimisation for parallel process components, utilising storage capacity for extended periods and accounting for multiple energy sources as well as raw material costs. The implementation of the integrated modelling techniques improved operational planning capacity on cement plants. This in effect improved electrical load management cost savings [69].

Mitra *et al.* [70] presented a model for computing optimal production planning scenarios for continuous power intensive processes. A Mixed Integer Linear Programing (MILP) model was proposed to represent transitions between operating modes for discrete time intervals. This was proven accurate and efficient for load management scheduling on cryogenic air separation and cement processing plants [70].

Since electrical load management on cement plants was proven successful it has likewise been proposed on precious metal processing lines [37]. The study done by Jordaan [37] investigated load management of mills on platinum ore concentrators. The study proposed load shifting by switching mills off to stationary positions. It was shown to be unfeasible due to unwanted ore surface oxidation and flow reduction. This would negatively influence recovery of the flotation based process [37].

Matthews & Craig [36] resolved this deterrent by controlling mill rotational speed in order to investigate electrical load shifting on a ROM ore milling circuit. Cost savings of $ 9.90 (or R108 [6]) per kg of unrefined platinum product was shown to be feasible. The load shifting intervention could also be implemented without negatively influencing the grind quality constraints at a platinum ore concentrator plant. This is however subject to availability of a VSD on the mill motor and real time particle size measurement [36].

Jordaan's [37] research analogously investigated load management of mills on CIP gold processing plants. Due to the different process requirements in gold ore processing, it was shown to be a feasible option to implement load shifting on these mills [37]. Although load management on precious metal processing plants indicated potential for cost savings, it has not been implemented in practice [37]. The criteria for the feasibility of load management on gold processing plants are consequently reviewed in more detail.

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[6] Exchange rate as on 2014/10/28: 1$ = 10.85 ZAR

2.3.3. Load management on gold processing plants

Research done by Jordaan [37] identified the milling section on gold processing plants as the area with the most potential for electrical load management. Generally, mills are operated continuously with electricity cost management only implemented in some cases by aligning scheduled maintenance with morning peak TOU periods. The following criteria are applicable in order to review this load management opportunity [37]:

1. ***Upstream and downstream buffer capacity*:** Storage buffers must be present in order to absorb disturbances caused by load management interventions. This ensures that processes adjacent to the managed load system can function normally.
2. ***Uncompromised production throughput*:** Overall production volumes must be maintained in order to avoid revenue loss.
3. ***Overtake operational capacity*:** The system must adhere to an operational capacity threshold during less expensive periods in order to compensate for lost production due to peak load curtailment.
4. ***Energy neutral*:** If production volumes are not compromised, the post-implementation energy consumption needs to be equal to the pre-implementation energy consumption when assuming consistent efficiency.

The criteria as applied on gold plant milling sections are discussed further:

1. Storage buffer capacity:

Ore is transported from mining operations to gold plants where it is stored in large capacity silos. The silos provide an upstream buffer for the milling circuit. Thickeners are present downstream to mills for dewatering purposes. The capacity and residence time over the thickening process can act as a suitable buffer in order to prevent disturbances in the downstream leaching section.

The typical milling circuit is accompanied by the necessary buffer capacity in order to implement load management on mills. However, excessive mill stoppages will create a shaft back log in the event that the plant is the bottleneck of the system. Therefore it is necessary to keep silo levels below a maximum threshold level to prevent the risk of a plant bottlenecking.

The leaching process, downstream from thickening section, is much dependent on the Relative Density (RD) of the thickened underflow. If milling operations are interrupted then the thickener feed rate and underflow RD decreases. However, the automated control of thickener underflow and the mills-to-thickeners setup can provide a sufficient downstream buffer for load management on mills.

2. ***Production volumes:***

   The cost savings of electrical load management will not amount to the value of precious metal produced at a gold plant. It is therefore imperative to maintain production volumes for the feasible implementation of load management. The milling circuit must adhere to a certain tonnage throughput in order to prevent a bottleneck situation. However, in several cases the plant's milling capacity is overdesigned for the amount of ore that is supplied from mining operations. Thus the mining side creates the production bottleneck and provides potential for the implementation of load management.

3. ***Overtake capacity:***

   Mills are generally operated continuously at maximum operational capacity as discussed under the previous criterion. The operational capacity of a mill is generally stipulated by the mill load and rotational speed characteristic to the mill design. Deviation from these parameters will cause less efficient comminution. Therefore overtake capacity is limited since the mass throughput of a mill is relatively consistent as that the plant personnel operate the mill at its design parameters. The overtake capacity is therefore dependent on upstream ore supply.

4. ***Energy neutral:***

   This criterion is analogous to the overtake capacity if the efficiency of the system is consistent. Mills are generally operated at a set-point load and specific rotational speed. This means that the energy usage of a mill stays relatively consistent under optimal operating conditions. Therefore, the electricity consumption during off-peak and standard periods cannot be increased in order to compensate for the load reduction during peak hours.

It is important to simulate and control silo levels owing to the small overtake capacity of a milling circuit. If the milling throughput is less than the ore supply tonnages for an extended period a shaft back log and production loss will occur. This should be avoided at all costs. It is therefore recommended to simulate ore supply and silo level trends in order to determine the feasibility of load management [37].

The study done by Jordaan [37] presented a simulation method in order to determine the feasibility of load shifting on gold plant mills. The simulation required several input parameters that were gathered by means of a questionnaire. The simulation then determined the feasibility of load management schedule based on the forecasted silo storage levels. It also forecasted energy usage and subsequent energy costs. Figure 2-4 illustrates the layout of the simulation procedure.

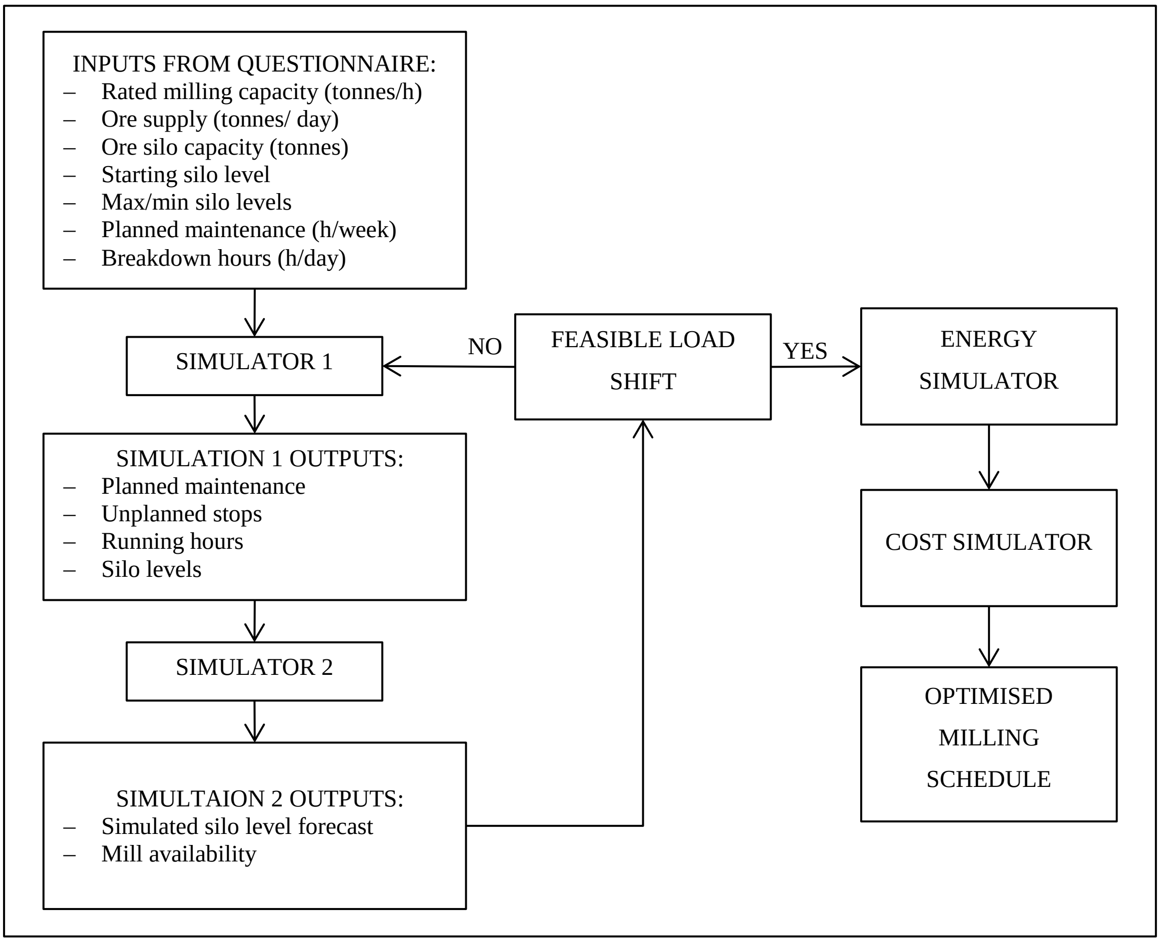

Figure 2-4: Flow sheet representation of Jordaan [37] simulation model

The simulation procedure presented in Figure 2-4 has proven useful to determine load management potential across a horizon period of a month. Although Jordaan [37] validated and verified the simulation procedure for gold processing plants, effective load management has not been adopted in this industry. It is expected that if the limiting factors can be addressed, then load management can become a practical solution to optimise energy usage on gold processing plants. The successful implementation in other processing industries, such as cement processing, suggests this.

2.4. Evaluating the validity of DSM opportunities

Although significant opportunities for energy efficiency and energy cost savings are available, it is important to consider why gold producers would implement DSM opportunities. Therefore, the priority of DSM needs to be determined by identifying and rating the relevant factors. This will allow for the elimination of inapplicable projects on a preliminary basis.

2.4.1. Factors influencing DSM opportunities

Generally, DSM initiatives attract noteworthy attention in South Africa since they are regarded as measures of energy conservation and environmental impact regulation [76] in addition to energy cost management. These issues form an integral part of a company's sustainability policy. However, upon consideration of all business factors, it is shown in Table 2-3 that *identifying and implementing cost saving measures* are low on the overall priority list [7].

Table 2-3: Rated business factors [7]

Business factor	**Ranking** **(0 = unimportant; 5 = very important)**
Meeting regulatory requirements	5
Meeting production schedule	4.5
Maintaining product quality and consistency	4.3
Keeping up with the new or shifting market demands	3.3
Having reliable, high quality supply of electricity	3.3
Maintaining market niche	2.5
Keeping up technologically with competitors	2.3
Maintaining a happy and productive staff	2.3
Identifying and implementing cost saving measures	1.3

The low ranking of *identifying and implementing cost saving measures* can be attributed to the following deterrents generally encountered in industry practice [7]:

- Limited capital – Energy efficiency improvements often necessitate large capital expenditure. This is a key factor that limits the applicability of energy efficiency projects.
- Production concerns – Production is the main concern on processing plants. This includes maintaining production volumes and quality. A DSM initiative would experience significant opposition if it compromises any production orientated activity.
- Limited staff time – Implementing and maintaining DSM projects may require additional staff and resources. The time dedicated to DSM projects will not have priority over production orientated work.

- Information – Although information on energy usage and possible improvements is readily available, it is time consuming to process all the relevant information and make informed decisions.
- Reliability – Maintenance of processing equipment is essential to maintain production targets. Therefore, compromising the reliability of equipment needs to be mitigated when implementing DSM interventions.
- Inconvenience – The reward rate of a DSM initiative is important. If the reward rate is too low, then it will be considered an inconvenience to implement and maintain. Thereby compromising the savings and sustainability of the initiative.

Several inhibitive factors are encountered when determining the validity of DSM opportunities. It is therefore important to determine the feasibility of these opportunities when compared with inhibitive factors. The first step in doing so is to prioritise the non-negotiable factors, i.e. the production and quality factors that cannot be compromised by the implementation of a DSM initiative.

Priorities for gold processing plants

Assuming safety and regulatory requirements are in place, the most important priority for gold processing plants is to meet production volumes and quality. Gold recovery by means of leaching and the CIP process is improved by the finer grind of ore particles [4], [39]. Figure 2-5 illustrates the correlation between gold recovery and particle size.

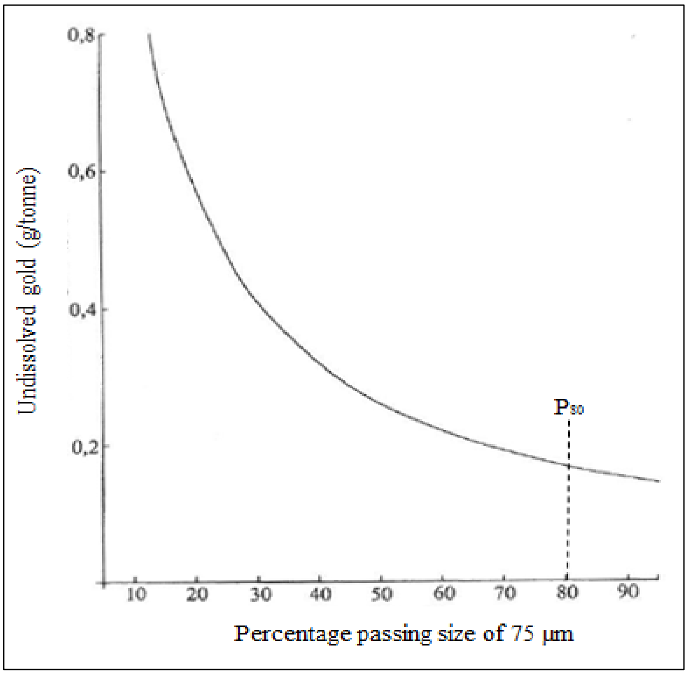

Figure 2-5: Recovery curve for leaching based on particle size (adapted from [2])

Undissolved gold is an indication of the gold not recovered per tonne ore processed. A particle cut size of 80% (P_{80}) below 75µm is a heuristic product set-point commonly applied for optimal recovery [2], [39]. Increased recovery due to finer grinding is not considered economical since comminution is one of the most cost intensive processes in gold processing [4]. It is subsequently a key priority to maintain a stable comminution circuit that produces a consistent grind size product to downstream recovery processes.

Once a stable comminution circuit is attained the next priority is to maintain the required production volume throughput. This is achieved by upkeep and maintenance to maximise the availability of process equipment for the purpose of operating at the required set-points and for the required periods. Assuming that optimal recovery and throughput is achieved, the next significant priority is to minimise operating costs. The breakdown of typical operating costs is illustrated in Figure 2-6.

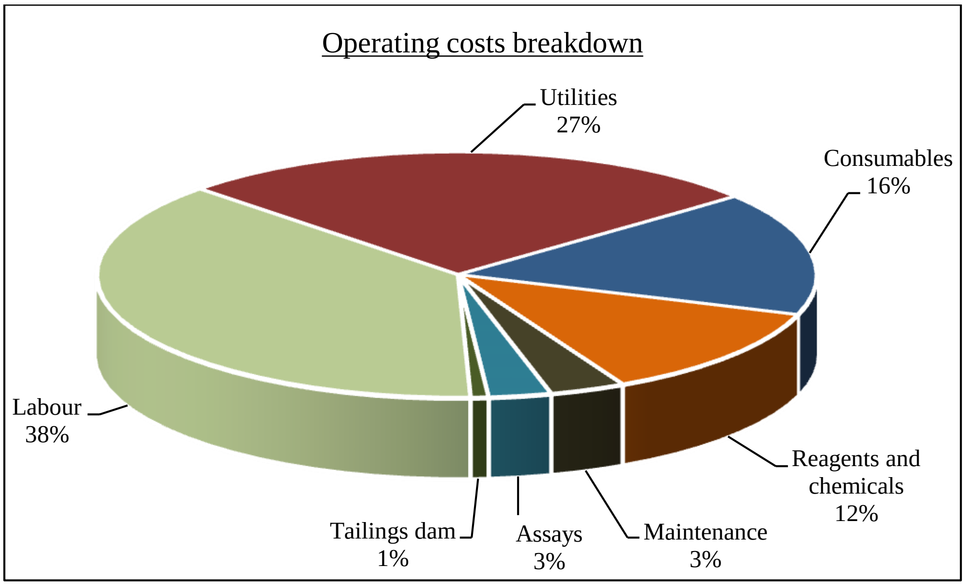

Figure 2-6: Typical operating cost breakdown of a gold processing plant [39]

Labour costs are the most important operating cost to manage according to the breakdown presented in Figure 2-11. Electricity costs are included in the utilities, i.e. electricity and water, partition that accounts for the second largest operational expense [39]. This indicates that electricity cost management has priority compared to other operating costs of lower magnitude.

Although maintenance is not a major operational expense, it is imperative for the upkeep of equipment. This is significant due to large capital expenditure required to construct a gold processing plant. Milling equipment is the largest capital expense required during the design of a plant [39]. The replacement of mistreated or neglected equipment can be costly. Maintenance is therefore also a substantial priority for plant management.

The implementation of electricity cost saving measures can influence other operational factors. It is therefore important to consider the negative effects of possible cost saving interventions. Jordaan [37] cites several practical reasons why electrical load management on gold processing plants are generally considered counterproductive. These include the following:

- Increased machine wear due to increased stop and start cycles.
- Increased maintenance on various pieces of equipment.
- Machines malfunctioning due to reduced levels and flow in various sections.
- Clogging of pipes or chutes due to slurry hardening in the wet processes.
- Reduction in recovery efficiency due to changes in the carefully controlled relative density of the thickener underflows.

Gold processing plants are generally designed to have a high degree of reliability and stability. The commonly applied leaching and CIP process is also considered mechanically robust and tolerant to process disturbances [5]. Hence, several of the above mentioned concerns can be addressed and mitigated by the control systems implemented on processing plants. That being said, it is important to evaluate the possible benefits and drawbacks of potential DSM opportunities.

2.4.2. Evaluation of identified DSM opportunities

The research objective is reviewed in order to evaluate the relevancy of the identified electricity cost saving opportunities. According to the research objective the following is considered to evaluate this:

- Potential of cost savings;
- Capital expenditure required;
- Ease of implementation and operational feasibility within existing systems; and,
- Continuous upkeep of production, quality and other operational targets.

Based on the research objective the following criteria are formulated as indicators to evaluate identified DSM opportunities:

[1] Suitable electricity cost payback period (less than 12 months).
[2] Conventional installation and/or commissioning period without excessive down time.
[3] Brownfields implementation.
[4] Operational ease and feasibility.
[5] Maintain production and quality targets.

Table 2-4 summarises all the electricity cost saving opportunities that were identified as part of this study. The relevance of these opportunities is rated according to the formulated criteria.

Table 2-4: Summary of DSM opportunities

Transport and transfer equipment					
Ref.	**Description of study**	**Energy saving potential**	**Requirements**	**Criteria check**	**Viable**
[42]	Energy efficient slurry transport by specialised positive displacement pump.	Energy efficient retrofit results: Case study 1 -709 kW Case study 2 - 1645 kW	Procurement and installation of positive displacement pump. New technology.	[1], [3], [4], [5]	No
[19]	Isolation of gold plant compressed air ring.	Energy efficiency of 840 kW for larger compressed air network. Payback period of 3 months.	Procurement and installation of stand-alone high pressure compressor.	[1], [2], [3], [4], [5]	Yes
[61]	Load management on conveyors systems of a colliery	49% reduction in electricity costs.	Implementation of optimal control model.	[1], [2], [3], [4], [5]	Yes
[60]	Load management on mine conveyors systems.	Peak period demand shift of 1.7 MW to 3.6 MW.	Implementation of load management control strategy.	[1], [2], [3], [4], [5]	Yes
Comminution					
Ref.	**Description of study**	**Energy saving potential**	**Requirements**	**Criteria check**	**Viable**
[47]	Expert mill control	Improved grinding and circuit stability. Increased recovery.	Expert mill control system.	[1], [3], [4], [5]	No
[49]	HPGR primary crushing	10% – 25% reduction on specific energy for secondary mills.	New technology. Specified comminution flow sheet.	[4], [5]	No
[54]	Mine to mill optimisation on conventional grinding circuits	4% - 5% throughput increase. Improved specific energy usage.	Change in blasting practice. PSD control.	[1], [3], [5]	No
[51]	Mill feed control optimisation	4% - 10% throughput increase.	Expert mill control system.	[1], [3], [4], [5]	No
[74]	Load management on deep level mine crushers	45% energy cost saving.	Implementation of optimal control model. Soft starter for switch control.	[1], [2], [3], [4], [5]	Yes
[68]	Load management on cement plants	3.6 MW peak load shift.	Implementation of real time energy management system.	[1], [2], [3], [4], [5]	Yes
[77]	Load management on processing plants	2.5 MW peak load shift. 9.8% annual electricity cost savings.	Switch to optimal tariff structure. Implementation of real time energy management system.	[1], [2], [3], [4], [5]	Yes

Table 2-4 (continued): Summary of DSM opportunities

[36]	Load management of ROM milling circuit by variable speed drive	Specific cost reduction per quantity of unrefined product.	Real time optimiser and predictive control. VSD mill drive installation (if not already fitted).	[3], [4], [5]	No
[71]	Load management of electric arc furnaces on steel plants.	5.7% electricity cost reduction.	Optimised scheduling tool	[1], [2], [3], [4], [5]	Yes
[23]	Optimal operational production planning for continuous power-intensive processes.	5% to 10% savings on operational expenditure.	Implementation of model for optimal production planning.	[1], [2], [3], [4], [5]	Yes
[69]	Integrated energy optimisation by operations modelling.	5% to 14% savings on operational expenditure.	Implementation of integrated operations models.	[1], [2], [3], [4], [5]	Yes
Process heating					
Ref.	**Description of study**	**Energy saving potential**	**Requirements**	**Criteria check**	**Viable**
[37]	Alternative fuel boiler.	Electricity cost savings by peak clipping of existing electrode boiler.	New boiler installation. Payback period of 3.77 years.	[3], [5]	No
[64]	Waste heat recovery from calcining ovens.	19 MW electrical output from recovered heat energy. 60 kt CO_2 emission reduction per annum	Capital expenditure. Greenfields design required.	[5]	No
[62]	Microwave based carbon regeneration.	Lower operating costs. Improved operational efficiency.	New equipment installation.	[3], [4], [5]	No
[63]	Minfurn™ furnace for carbon regeneration.	Lower energy usage and operating costs. Improved operational efficiency.	New equipment installation.	[3], [4], [5]	No

The majority of energy efficiency opportunities are associated with performance efficiency, equipment efficiency and technology efficiency. The main deterrent to these applications is the capital expenditure required. Large capital investments require substantial returns in order to maintain a feasible payback period. The performance of new technologies and installations is not always guaranteed which increases the risk of not meeting the payback period.

Load management applications focus on operational improvements. These opportunities generally require low capital inputs that make it more relevant to processing plants in order to achieve electricity cost savings within short payback periods. Literature indicates that load management can strongly influence production targets and constraints. This necessitates the capability to implement accurate production planning and subsequent load management.

Given the criteria from the research objective, it is observed that load management opportunities are preferred over energy efficient measures. The decisive factor is based on the low capital expenditure input and the ease of implementation. This presents a quick win scenario where moderate operational interventions can deliver substantial cost savings.

2.5. Conclusion

Gold plants consist of energy intensive processes, of which several are amendable to energy saving interventions. Studies have shown that there are numerous opportunities that can be effective in reducing energy demand and costs. In some studies these opportunities have been implemented, while other opportunities have been limited by several deterrents which prevent practical applications.

Several energy efficiency measures require substantial capital input and operational effort upon implementation. In lieu, electrical load management is identified as a quick win measure where moderate operational changes can deliver large scale interventions. However, the practical applications on gold processing plants have been limited due to several process constraints.

The next chapter of this study entails a detailed investigation into the feasibility of load management on South African gold plants. The main process and production objectives, as well as limiting factors are addressed during the investigation. For this purpose a methodology has been developed that serves as a guideline for the implementation of electrical load management on gold processing plants.

Chapter 3.

Implementation of electrical load management

In the preceding chapter a project screening exercise was executed in order to identify feasible DSM opportunities on gold processing plants. Findings indicated that load management is an effective electricity cost saving measure given the criteria of cost and ease of implementation. This chapter provides a methodological approach to implement load management on gold processing plants.

3.1. Overview of methodology

Although literature indicates that electrical load management is feasible on gold processing plants, the implementation thereof has not been reported. As such, the methods required for implementation could not be found in literature. This chapter provides the methodology to identify, analyse and implement load management on gold processing plants. Figure 3-1 illustrates the sequence of stages applied in the methodology.

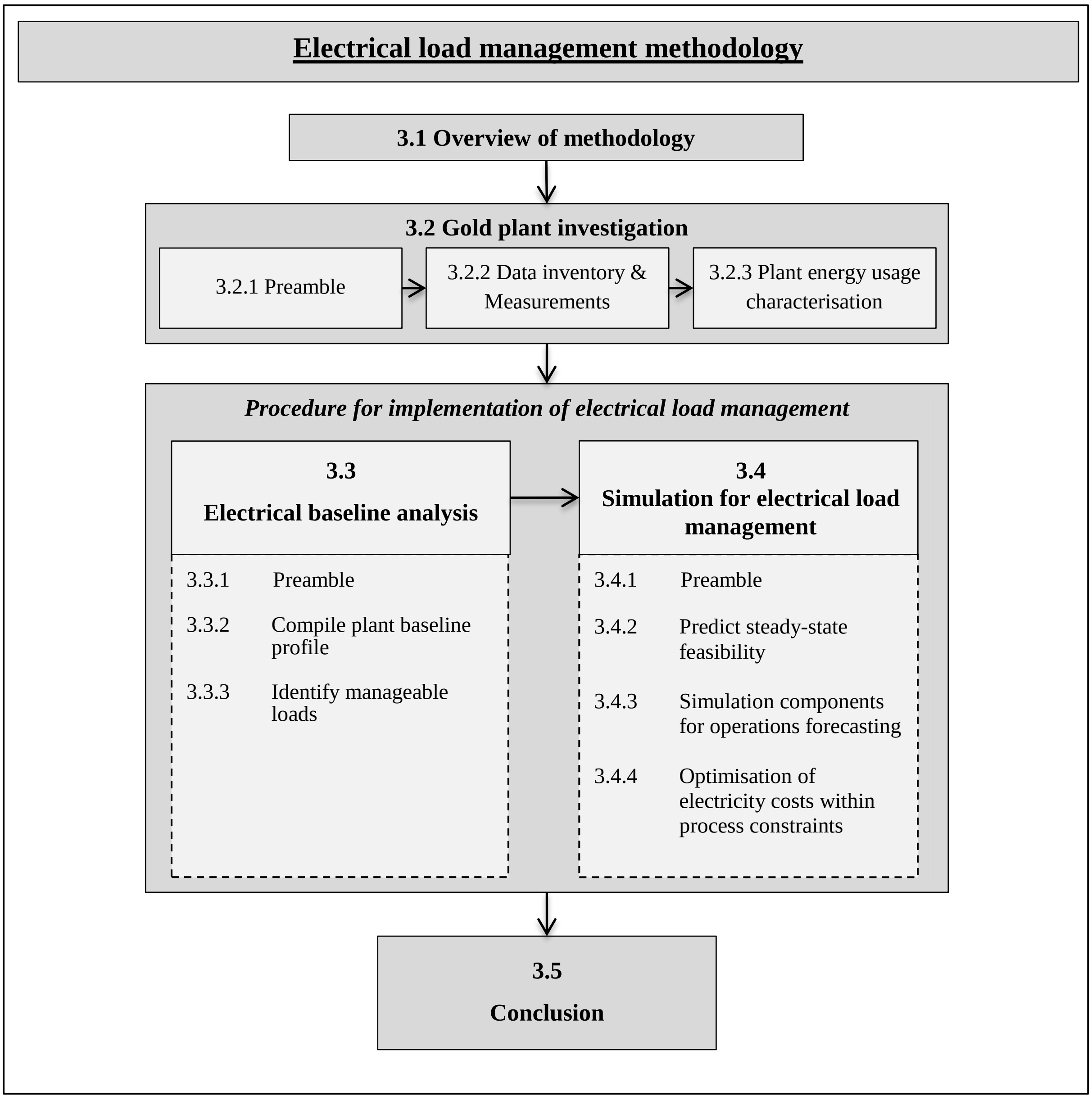

Figure 3-1: Layout of methodology

Preliminary investigations consist of general data capturing and plant characterisation exercises. Once the overall operation of a gold processing plant is well defined, the electricity usage is analysed by means of electrical baseline analysis. The baseline is used to identify potential load management opportunities.

The second stage of the load management procedure is to investigate the operational feasibility of load management applications. This is done by identifying and forecasting key production and process constraints. The final stage is to employ production planning with optimal TOU electricity usage and to calculate the subsequent cost savings. The assumptions made during the development of the methodology are also reviewed in this chapter.

3.2. Gold plant investigations

3.2.1. Preamble

Several gold plants were investigated during this study. The load factors of these gold plants were calculated as a preliminary indication of load management potential. Low load factor values usually indicate the capacity for load management and cost reduction. Equation 3-1 illustrates the formula used to calculate the load factor of a plant [6].

(Eq. 3-1) $$Load\ factor = \frac{Energy\ used\ during\ investagation\ period\ (kWh)}{Maximum\ demand\ (kW) \times Investigation\ period\ duration\ (hr)} \times 100$$

Table 3-1 summarises the measured load factors of eight South African gold plants. The cited gold plants are referred to by a number in order to keep the names and associated information of the gold producers confidential.

Table 3-1: Summary of electricity usage on selected South African gold plants

Reference	Monthly electricity usage (kWh)	Maximum demand (kW)	Load factor
Gold Plant 1	12 986 100	22 040	72%
Gold Plant 2	1 670 200	4 050	57%
Gold Plant 3	4 429 800	10 720	57%
Gold Plant 4	4 250 800	8 000	74%
Gold Plant 5	3 297 200	6 990	66%
Gold Plant 6	2 771 900	4 770	81%
Gold Plant 7	5 144 300	8 850	81%
Gold Plant 8	3 879 400	7 000	77%

A number of the plants investigated shows relatively low load factors. This indicates potential for strategic load management. It is however not a conclusive indicator and further investigation is required. The required investigation procedure is discussed in the remainder of this methodology. Figure 3-2 illustrates a layout of the procedure required during the preliminary investigation phase.

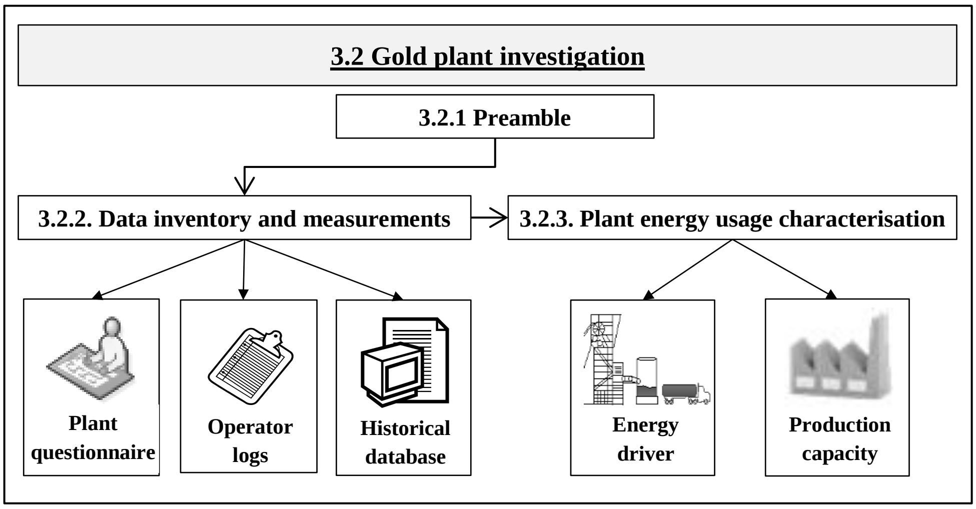

Figure 3-2: Layout of gold plant investigation procedure

Although the methodology is developed to be generic to gold processing plants, a specified plant is used to represent a typical South African gold plant. This gold plant is used as reference throughout the chapter in order to describe key steps in the methodology. Firstly, this section describes the preliminary data capturing and plant characterising procedures.

3.2.2. Data inventory and measurements

The first step of an energy audit is to compile an inventory of electrical loads on a gold plant. The magnitude and type of load is also determined to prioritise possible electricity cost saving opportunities. The characteristics of electrical loads may vary as applicable to different gold processing plants. It is therefore important to get a good understanding of the plant under investigation.

General and plant specific information can be acquired by conducting interviews and walk-throughs with plant personnel. These include plant layouts and data capturing points which will provide a foundation for further investigation. Appendix A presents a generic questionnaire which is used as a guideline to gather preliminary information. Figure 3-3 illustrates the layout of a typical gold processing plant.

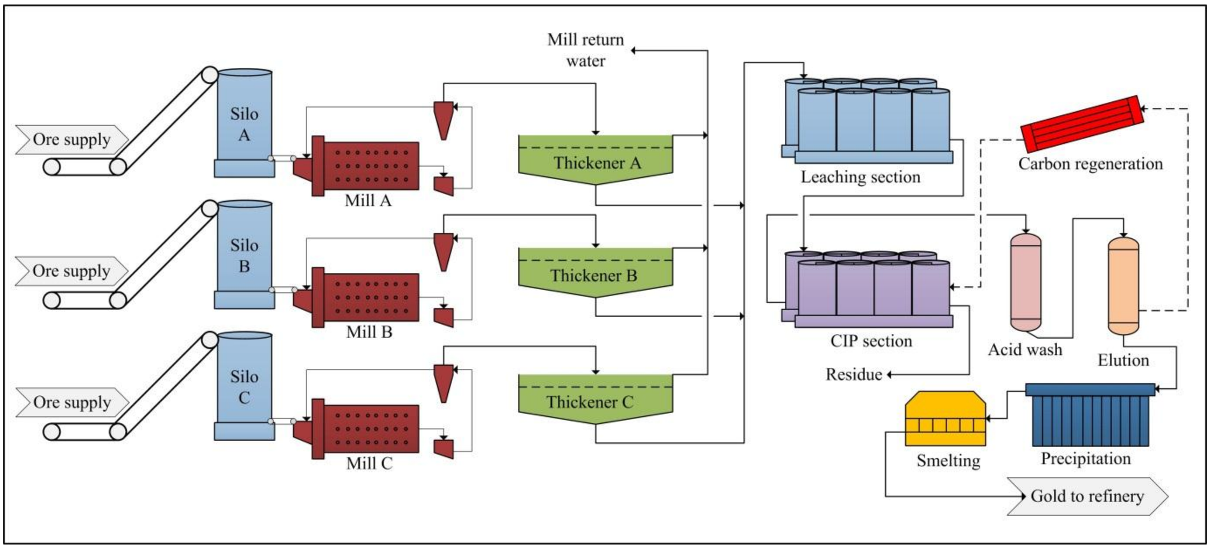

Figure 3-3: Operational layout of typical South African gold plant

The plant illustrated in Figure 3-3 consists of three parallel milling circuits that are fed ore supply from upstream storage silos. Each mill is operated in closed circuit with a hydro-cyclone classifier. A classifier ensures that oversize particles are recycled for reprocessing in the mill. The milled product is dewatered in thickener tanks before being pumped to sequential leaching, CIP adsorption and elution treatment. The eluate stream is precipitated and smelted in order to produce the final gold product.

Collecting adequate and accurate data is one of the fundamental phases in an energy audit. The typical gold processing plant is well instrumented for process control purposes. The Supervisory Control and Database Acquisition (SCADA) system displays and logs a multitude of process parameters and set-points in a historical database. These include power metering, storage levels and material stream characteristics, such as flow rates and Relative Densities (RD).

Several parameters can also be logged manually depending on the level of instrumentation on a plant. These include labour shift based log sheets that also provide keen insight into the operational trends of a plant. Once data capturing has been enabled, it is necessary to determine the link between the plant operations and the electricity usage of the plant. This is done by identifying and characterising the plant’s main energy driver.

3.2.3. Determine plant energy usage characteristics

In mineral processing the main energy driver is determined by the ore supply from downstream mining operations. If downstream ore supply can be forecasted then energy usage can also be forecasted to a certain degree. The utilisation of plant equipment is therefore dependent on the amount of ore supplied.

It is essential that a gold plant maintains the required production throughput in order to prevent a back log at mining operations. The throughput of the comminution section is generally the bottleneck on a gold processing plant. Hence, it is necessary to determine the production capacity of the plant's comminution equipment in order to characterise the plant's overall production capacity. Typically, this is done by determining the plant's milling capacity.

The feed rate of a mill is an indication of the tonnage throughput that is achieved. It is therefore an essential parameter that indicates the time value of production. It can also be used as an indicator of energy efficiency (kWh/tonne) since the set-point power consumption of a mill is relatively consistent. This is especially relevant for milling circuits where energy usage is strongly correlated to tonnages.

The average throughput of mills needs to be determined in order to characterise the plant's operational capacity. Additionally, the power consumption of the mills needs to be determined in order to calculate specific energy consumption. This is done by compiling historic milling data and observing operational trends, as illustrated in Figures 3-4 (A) and 3-4 (B), respectively. These figures show the frequency of power readings and feed rates measured on three mills on a typical gold plant. The data is measured only during periods when the mills are running. Hence, the reliability of equipment is not yet accounted for at this stage of the methodology.

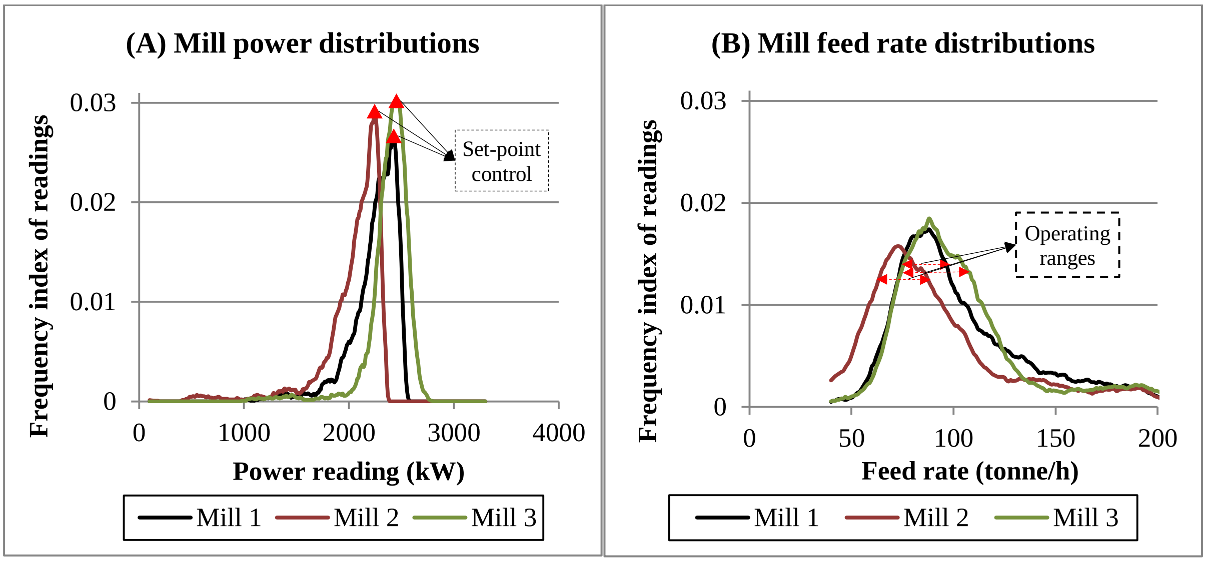

Figure 3-4: Mill power (A) and mill feed (B) rate frequency distributions

The power consumption of a mill is relatively consistent since mills are commonly controlled at a set-point mill mass or loading fraction. This results in a peak power reading that is also considered to be the average operating point of a mill, as indicated in Figure 3-4 (A). In order to keep the mill power usage at its peak, the mill feed rate is varied. This is the most common control philosophy used for South African style ROM mills [78]. Table 3-2 summarises the range of typical operating averages of gold plant mills.

Table 3-2: Energy usage summary of gold plant mills

Parameters	Range	Peak value	Standard deviation
Average running capacity (kW)	2000 - 2400	2200	200
Average feed rate (tonne/h)	70 - 130	100	30
Specific energy usage (kWh/tonne)	16 - 28	22	6

The values used for operations forecasting (section 3.4.3) are the peak values as indicated in Figure 3-4. This leads to a consistent specific electricity consumption value for the milling section. The consistency of this value is however an assumption since the mill feed characteristics may vary significantly. Disturbances such as variations in feed size, abrasiveness and rheology influences the specific energy consumption [3]. It is recommended that the standard deviation is used as a measure to estimate the accuracy of the operational parameters.

Table 3-2 presents the average operating parameters based on empirical data. The use of empirical data also accounts for operating variations. The resultant values are used to characterise the production capacity and energy driver of the plant under investigation. The next step is to determine the electricity usage trends of the plant. This is done through electrical baseline analysis.

3.3. Electrical baseline analysis

3.3.1. Preamble

The procedure developed for electrical baseline analysis is analogous to the execution of industrial energy audits as described by authors such as [56] and [6]. The known methodology is applied more specifically to gold processing plants with the emphasis placed on the use of electrical energy. Figure 3-5 redisplays the layout of the methodology in order to show the stage at which electrical baseline analysis is performed.

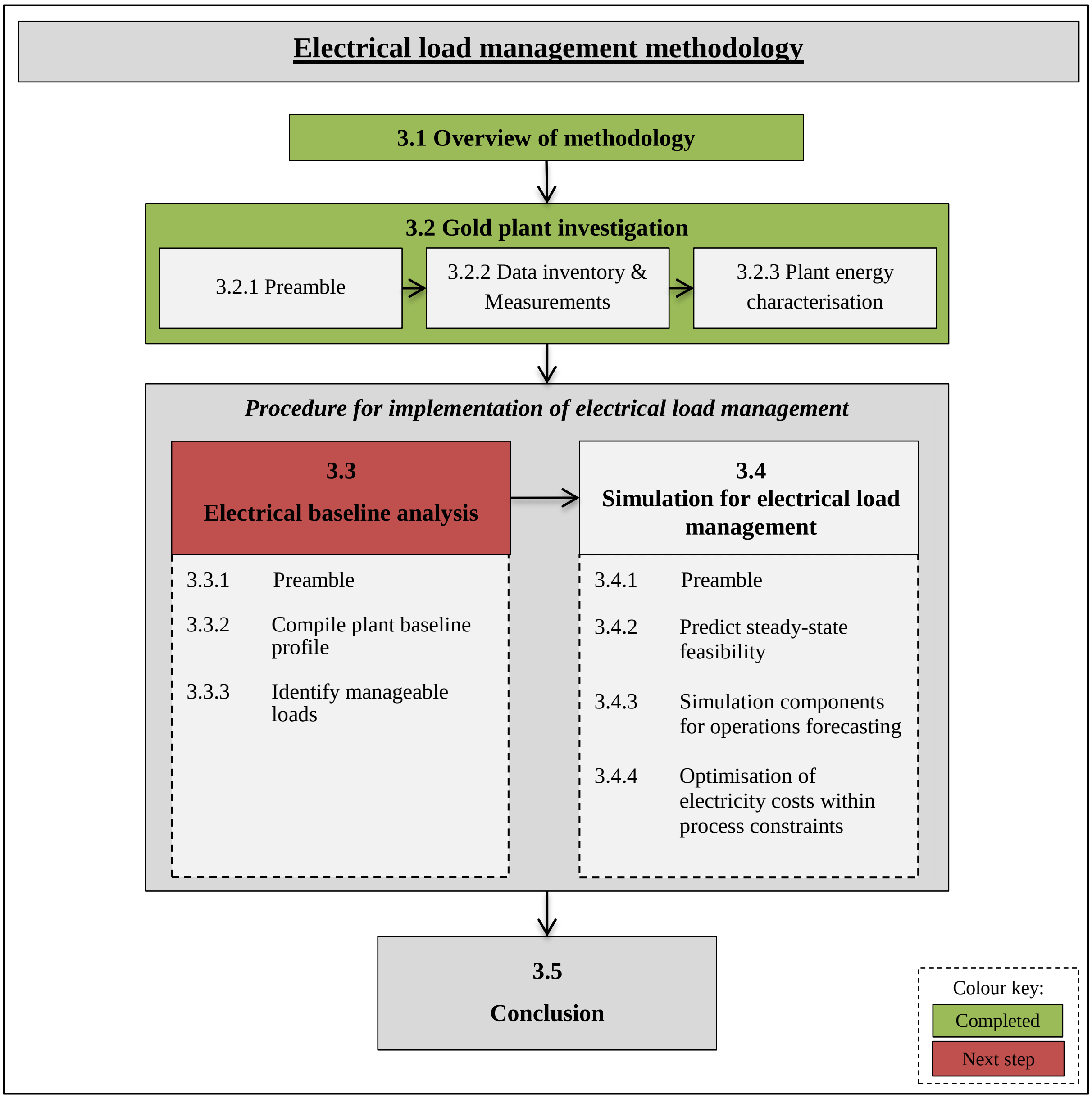

Figure 3-5: Electrical baseline analyses stage of methodology

Once the preliminary gold plant investigation has been completed, it is possible to compile electricity usage profiles of the plant under investigation. This allows the interpretation of electricity usage trends to subsequently identify manageable electrical loads. These profiles are also used as baselines to measure the impact of DSM interventions.

3.3.2. Baseline electricity usage profile

Baseline profiles are compiled from electricity usage data over a period of at least three months. It is essential that "normal" operation, without extreme or infrequent disturbances, is experienced during this baseline period. This presents a pre-implementation scenario against which load management opportunities can be identified and analysed. Figure 3-6 illustrates the different sections of a gold plant that are considered for electrical baseline analysis.

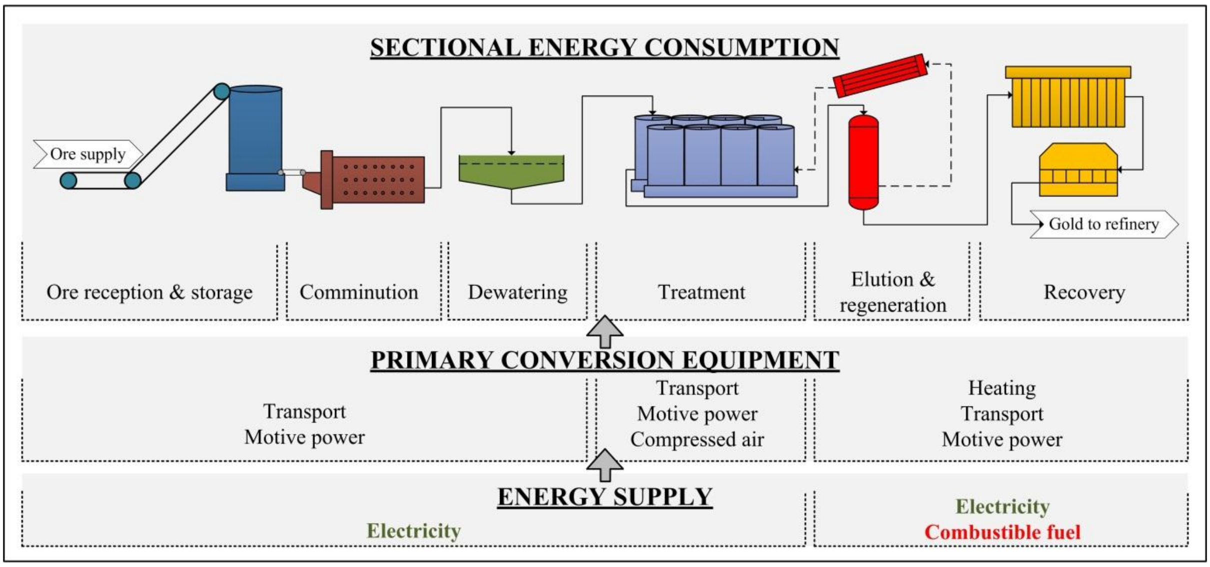

Figure 3-6: Sectional energy consumption layout

The scope of the study is limited to electrical energy usage. Therefore the use of combustible fuels for heating purposes is excluded from the scope of investigation. Figure 3-7 illustrates the electricity usage of a typical plant in terms of electrical (A) energy and (B) demand.

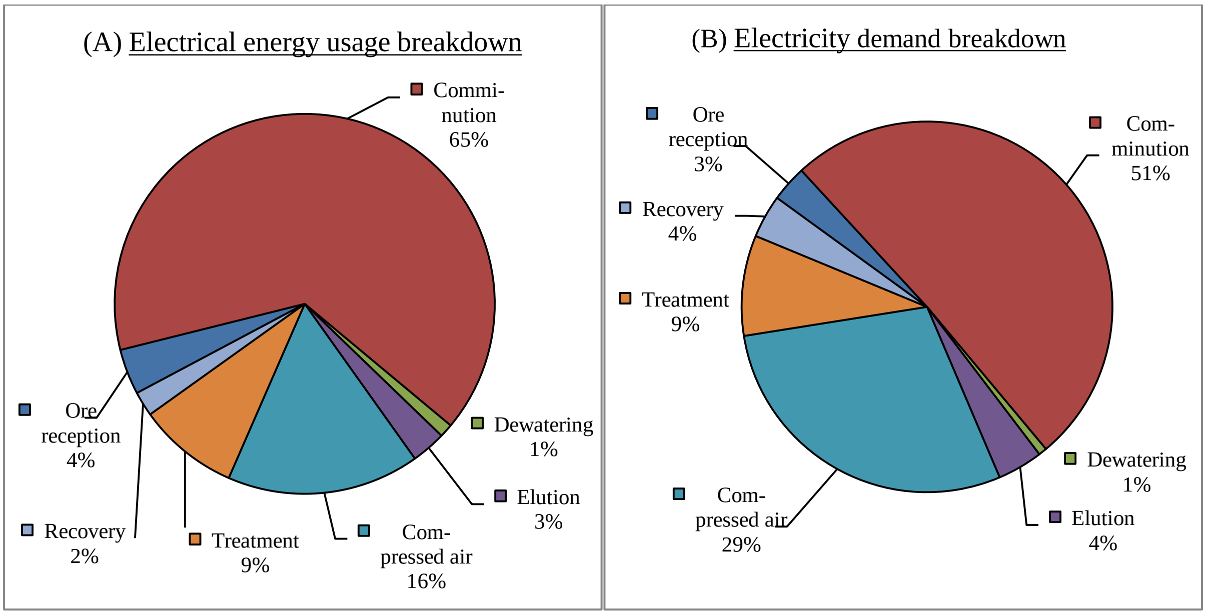

Figure 3-7: Typical (A) electrical energy usage and (B) demand of a typical gold plant

The comminution section is the most significant electricity intensive section on a typical gold plant. In this case it accounts for 65% of the total plant electricity usage and 51% of the plant's maximum power demand.

Once electricity usage is quantified, it is necessary to further analyse electricity usage qualitatively. Time-of-use energy consumption is the principal qualitative parameter under consideration for load management. Figure 3-8 illustrates the baseline electricity usage profiles of a typical gold plant for the relevant TOU days of the week. These baseline profiles illustrate the electricity usage trends across 24-hour periods averaged for a baseline period.

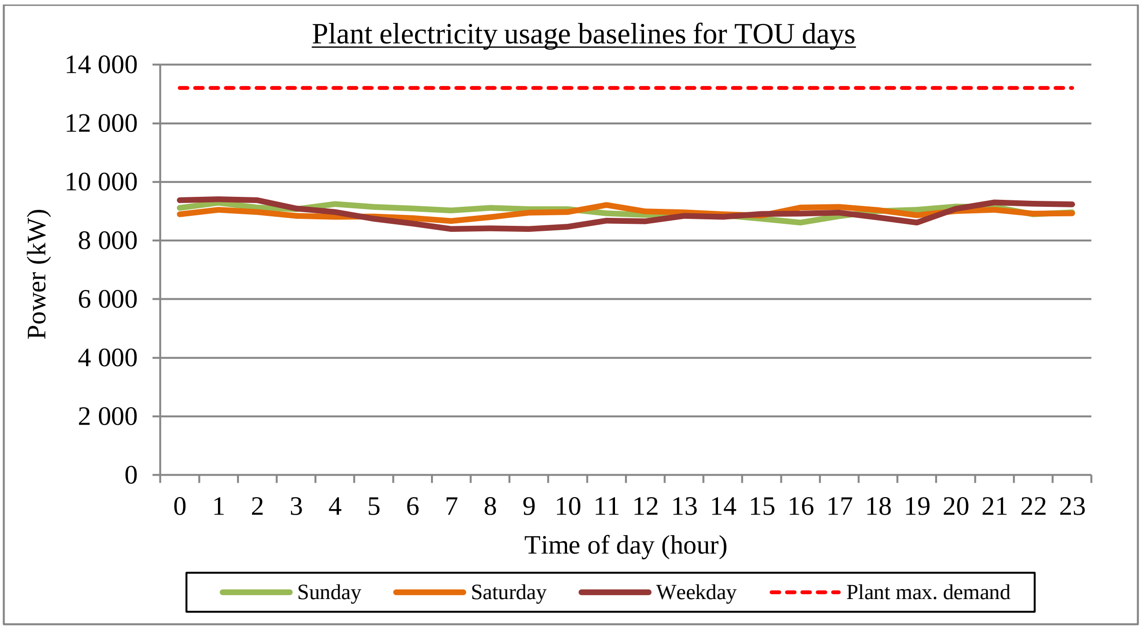

Figure 3-8: Plant electricity usage baselines for TOU days

It is observed that electricity consumption is relatively flat when averaged over the baseline period. However, the plant’s average operational usage is roughly 70% of the maximum demand measured during the same period. A clear load reduction is also observed on weekday mornings due to routine maintenance during which motorised equipment is stopped. A more detailed view of the weekday electricity usage per process section is illustrated in Figure 3-9.

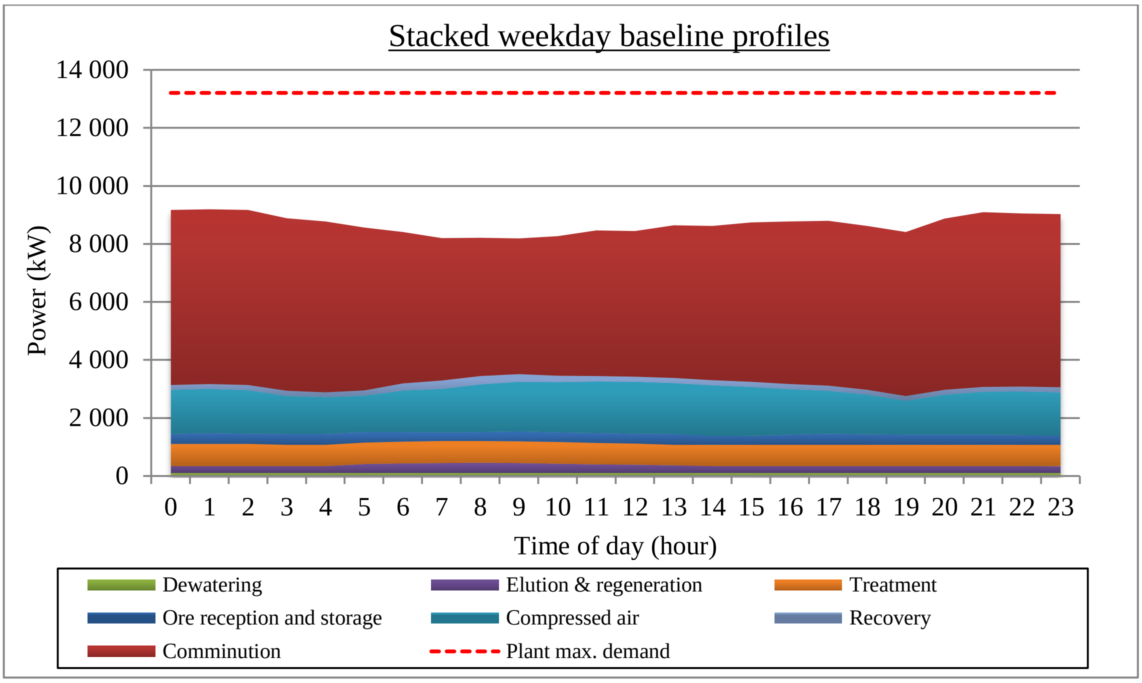

Figure 3-9: Stacked weekday baseline profiles of process sections

The stacked weekday profiles reaffirm the magnitude of the comminution electrical load when compared with other sections of the plant. It can also be observed that certain sections show a consistent flat load profile, while other sections show more variable profiles. In order to describe this trend of certain loads it is required to classify these loads.

Classifying electrical loads

If electricity usage can be controlled according to TOU it is possible to implement cost saving measures through strategic load management. However, it is important to consider which electrical loads are amendable to the criteria set for load management. For this reason electrical loads need to be classified. In broad terms, this methodology distinguishes between variable and fixed loads.

Variable loads refer to electrical equipment that is used as part of schedulable or interruptible processes. Whereas fixed loads is mandatory equipment that needs to be functioning 24 hours for 7 days-a-week under normal operating conditions and are considered uninterruptible. Figure 3-10 illustrates this concept.

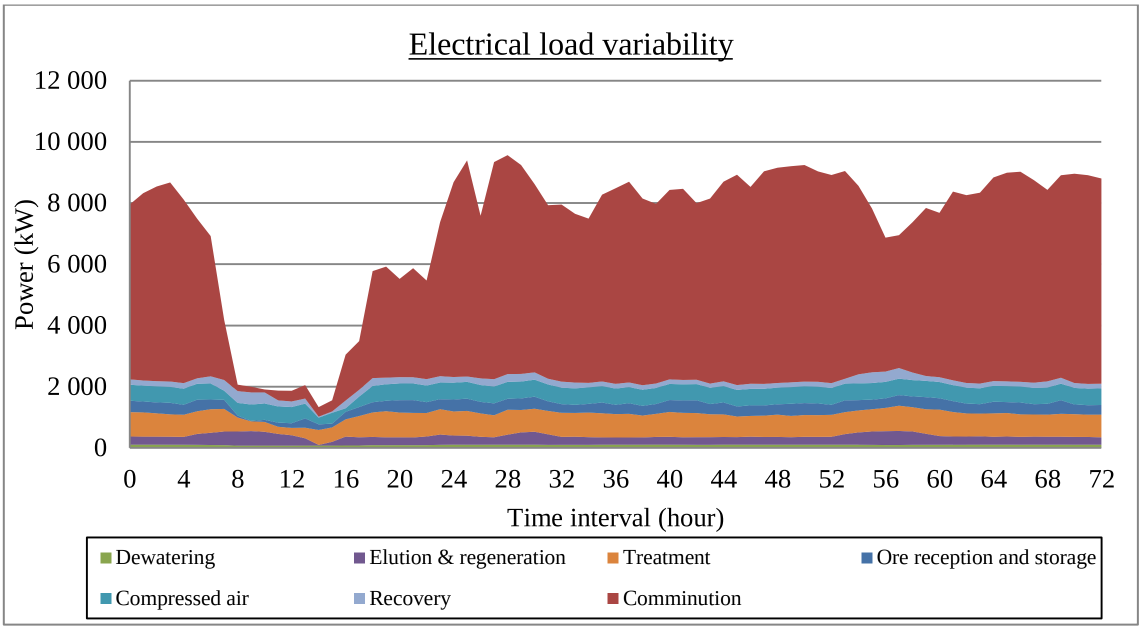

Figure 3-10: Representation of variable electrical load profiles across a 72 hour interval

Figure 3-10 illustrates the power readings captured during a 72 hour interval for the different plant sections. In real time it is observed that some of the sections can show significant variance in electrical load. For instance, during the hours from 7 to 16 a clear load reduction is observed due to a maintenance stop. However, not all of the sectional loads are reduced during this stop. It is therefore possible to classify the sectional electrical loads according to measured load factor. Table 3-3 summarises the electrical load classification of different sections of a typical plant under investigation.

Table 3-3: Electrical load classification of a typical plant under investigation

Process sections	Load factor	Type of load
Ore reception and storage	70%	Interruptible
Comminution	73%	Interruptible
Dewatering	91%	Fixed
Elution and regeneration	43%	Batch
Compressed air	92%	Fixed
Treatment	93%	Fixed
Recovery	32%	Batch

The largest variable load is ore reception, storage and comminution section which consists of parallel running milling equipment. Additional variable loads are batch processes within the elution, regeneration and recovery sections of the gold plant. Since significant variable electrical loads exist on gold plants it is possible to further investigate load management opportunities by identifying manageable loads.

3.3.3. Identify manageable electrical loads

Manageable loads refer to electrical intensive components in a process line that can be controlled or scheduled according to TOU periods. These electrical loads are amendable to strategic load management that aims to optimise TOU energy costs. The criteria set to identify manageable loads are as follows:

1. **Storage capacity:** Upstream and downstream buffer capacity.
2. **Availability:** Uncompromised production throughput.
3. **Utilisation:** Overtake operational capacity.

It is also important to understand the electricity tariff structure of the gold plant since the key cost drivers of electricity tariffs may vary for different structures [77]. In South Africa most mining companies are charged according to the Megaflex tariff structure. This is the preferred tariff structure since it is more cost reflective of specific electricity usage profiles and it enables strategic load management [66]. Figure 3-11 illustrates TOU tariff periods of the Megaflex tariff structure.

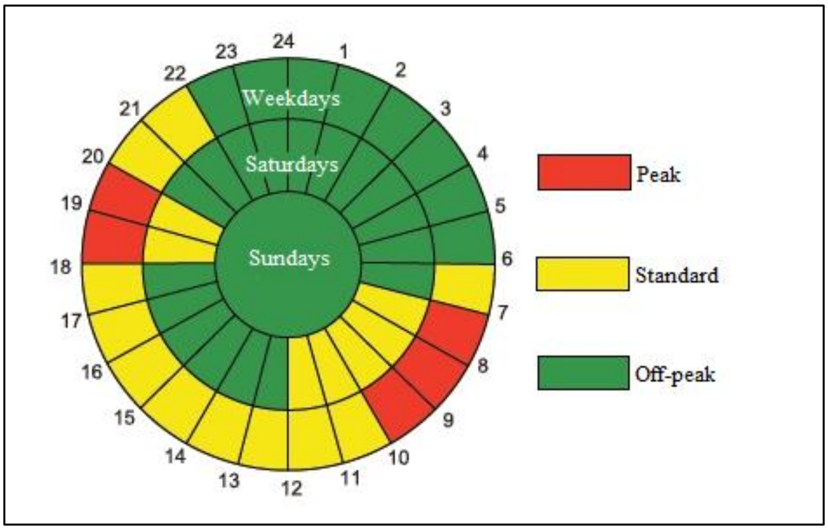

Figure 3-11: TOU tariff for time sensitive electrical energy usage[7]

The Megaflex TOU tariffs are summarised in Appendix B. The key concept of strategic load management is to allocate operating hours to less expensive TOU periods before it is allocated to more expensive TOU periods. Peak periods are between 230% and 600% more expensive than off-peak periods. Compared to standard periods, peak periods are between 145% and 330% more expensive [24].

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[7] Adapted from Eskom Enterprises. "Schedule of standard prices 2014/15." [Online]. Available: http://www.eskom.co.za. [Accessed 03 Apr. 2014].

The following load scheduling options can present cost savings on the Megaflex tariff structure:

A. **Weekend load filling:** Weekend periods consist of off-peak and standard TOU periods.
B. **Weekday night-time load filling:** Weekday night time periods consist of off-peak and standard TOU periods.
C. **Weekday mid-day load filling:** Midday periods during weekdays consist of standard TOU periods.

Mills are operated continuously for extended periods of time at the gold plant. Scheduled stoppages are regularly implemented during short and extended maintenance stoppages. Batch sequence processes in the elution and recovery sections are generally fixed according to labour shifts. These labour shifts are not amendable without disrupting normal operating procedures.

In order to classify a manageable load it must adhere to the load management criteria (1,2,3) and possible scheduling options (A,B,C). Table 3-4 summarises these requirements for the identified sections of a typical gold processing plant. In some cases strategic load management is prevented by certain constraints, such as storage capacity and labour shifts.

Table 3-4: Identifying manageable loads on a typical gold processing plant

Plant section	Manageable load criteria	Load management options	Prevention of load management
Ore reception and storage	2,3	-	Upstream storage capacity
Comminution	1,2,3	A,B,C	-
Elution and regeneration	1,3	-	Labour shifts
Recovery	1,3	-	Labour shifts

Based on the standard criteria and scheduling options it is feasible to implement load management on comminution equipment. However, plant process constraints have not been included at this stage of the methodology. In order to do so, it is necessary to simulate all significant parameters that can be influenced by implementing load management interventions.

3.4. Simulation for electrical load management

3.4.1. Preamble

Up to this point the methodology has covered the principles of identifying electrical load management opportunities. It has been shown that due to the variable nature of some electrical loads on a gold plant that strategic load management is possible. The comminution circuit is however the section with most potential considering magnitude and manageability of the electrical load. Figure 3-12 redisplays the layout of the methodology in order to show the stage at which the simulation techniques are developed.

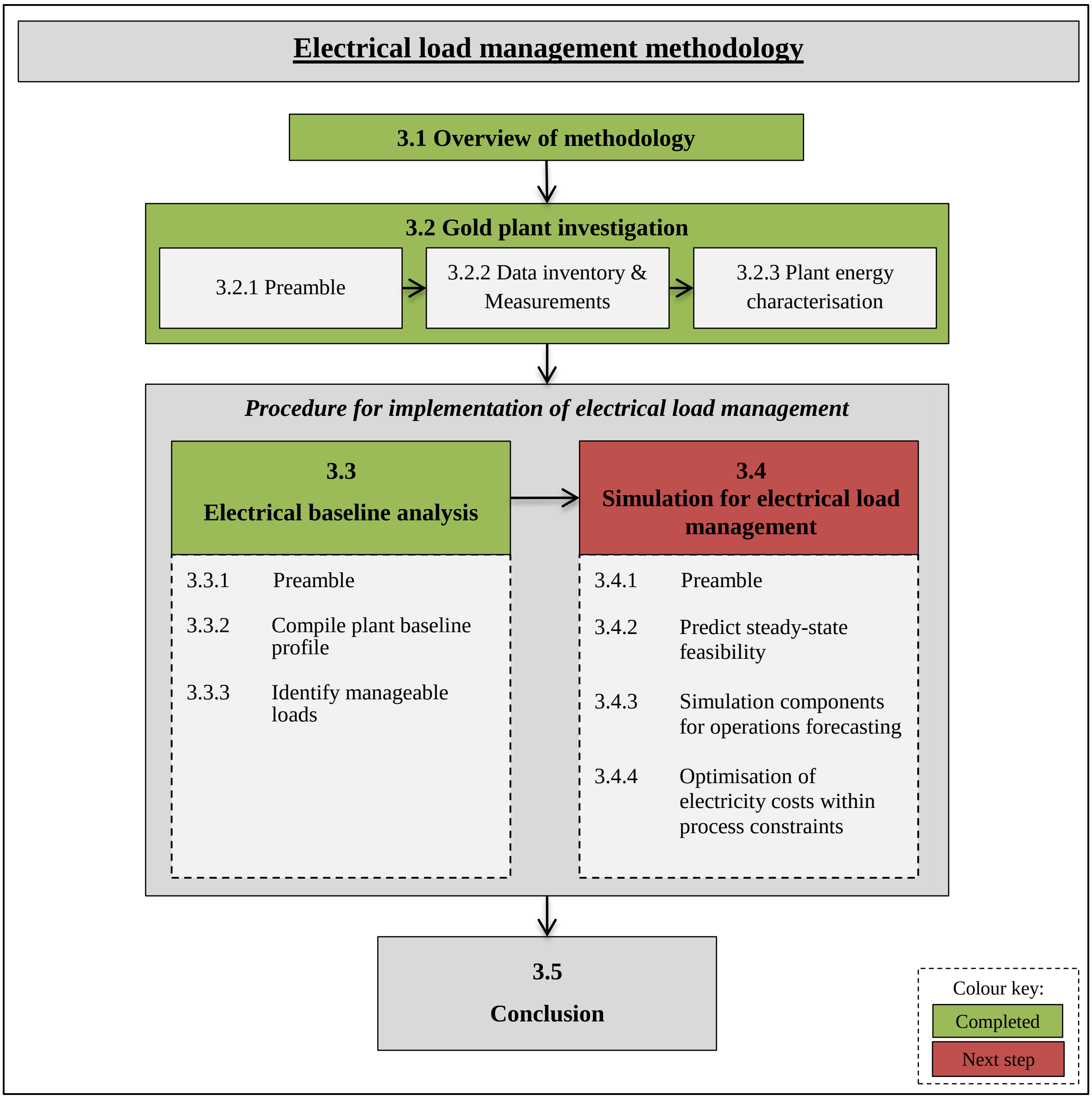

Figure 3-12: Stage of methodology for development of simulation techniques

Electricity cost savings are feasible if low demand periods can be aligned with more expensive TOU periods. This is dependent on whether the electrical load can be scheduled within operational boundaries. Multiple factors need to be taken in account since most process components are interdependent. The main factors that are considered include the following:

- Production forecasts
- Maintenance schedules
- Equipment reliability
- Operational capacity of equipment
- Energy intensity of equipment
- Upstream and downstream storage levels

In order to consider all operational constraints it is required to model and simulate the effects of load management. This requires steady state forecasting in order to determine the load shift potential as well as determining optimal production schedules within set operational constraints. Figure 3-13 illustrates a layout of the simulation procedure that is discussed further.

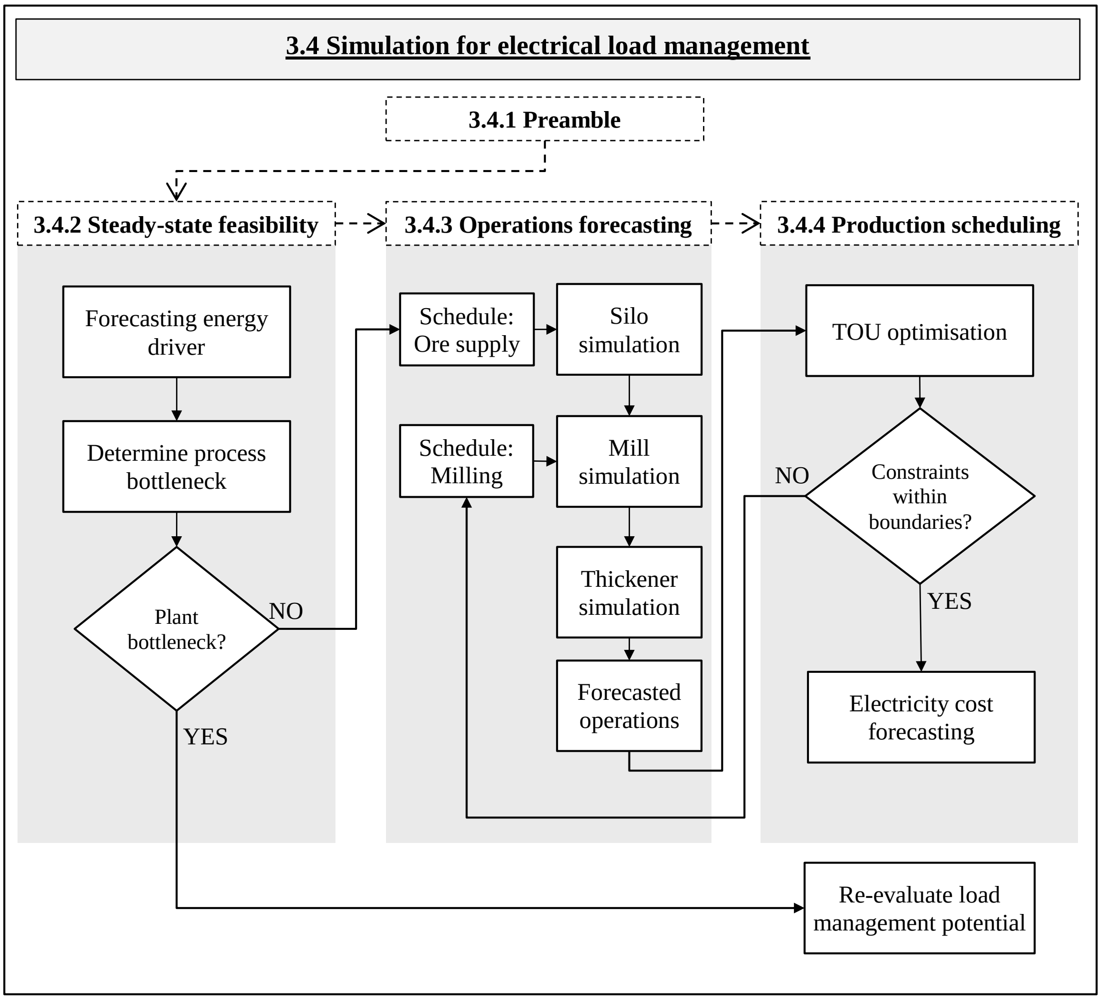

Figure 3-13: Layout of simulation procedure

3.4.2. Steady-state feasibility

The steady-state feasibility of load management is dependent on a gold plant's overall production demand compared to its overall production capacity. Production demand is determined by downstream ore supply from mining operations. In turn, a plant's production capacity is usually reliant on its milling capacity.

If ore supply is below the plant's milling capacity for an extended period without the prospect of additional ore supply resources, then spare capacity is available. The main concept behind a load management strategy is to use this spare capacity to minimise utilisation of more expensive TOU periods. Therefore, the first simulation procedure is to determine the steady state feasibility of load management across an extended horizon.

Forecasting main energy driver

Production is the main energy driver on a gold plant and, more specifically, its milling section. As discussed in the preceding sections, if the ore supply can be forecasted then it is possible to forecast energy demand. In order to accomplish this, it is necessary to quantify the steady-state ore supply from mining operations.

Forecasting ore supply can be arduous due to the dynamic and challenging environments often experienced on mines. There are numerous factors that can interrupt mining operations and consequently ore supply. However, when in steady-state production it is possible to forecast ore supply from mining surveys and historic trends.

Since a gold plant is fundamentally dependent on mining operations, it is important to identify and characterise the mining operations that supply the plant. These operations may include underground mines with high head grade material, but also lower grade surface and marginal rock dump operations. The ore supply distribution of a typical plant under investigation is illustrated in Figure 3-14. The data used to compile such a distribution can acquired from mining surveys or investigation questionnaires.

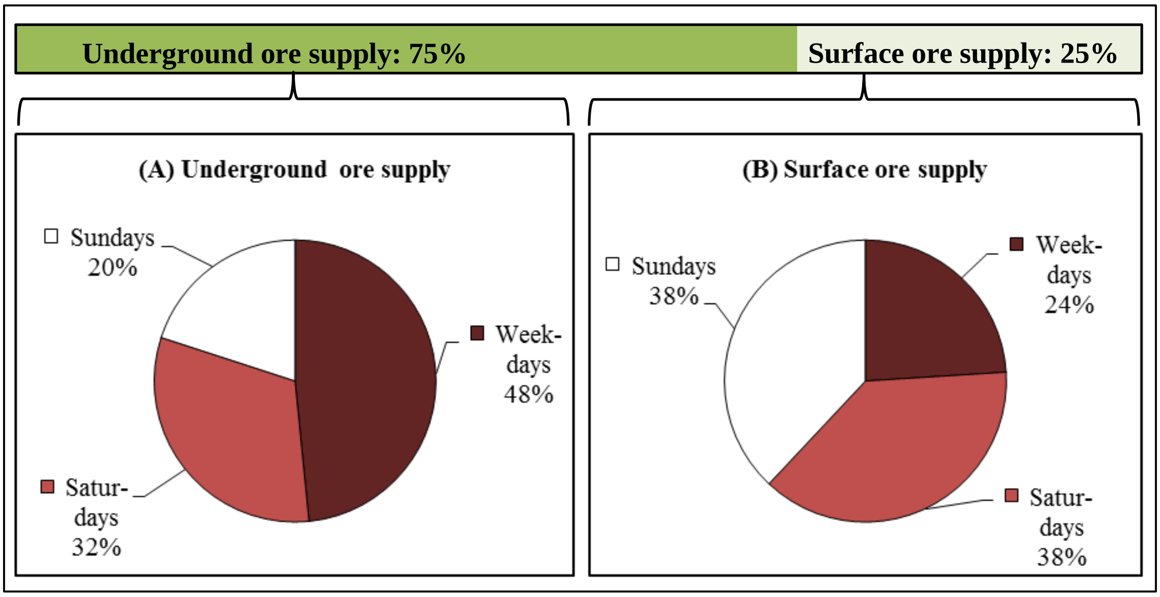

Figure 3-14: Typical ore supply distributions for (A) underground and (B) surface ore resources

Figure 3-14 illustrates that underground operations supply the bulk of the ore supply to the plant. This is usually the case, however, some plants may only receive ore from underground operations. Contrarily, other plants may be dedicated to process only surface resources. The ore supply can be further distinguished by trends across different days of the week, i.e. weekdays, Saturdays and Sundays. It can be observed from Figure 3-14 that the bulk ore is supplied from underground sources (75%) and mostly during weekday periods (48%).

The production demand of gold processing operations is essentially driven by downstream supply. Upstream production triggers, such as metal prices and market demands, are generally not limiting factors in the gold processing industry in the short term. Therefore, the main production target will always be to maximise production volumes permitting the available ore supply. In order to determine the area with spare capacity for load management it is required to identify the bottleneck of production.

Identifying production bottleneck

The milling section is considered the production bottleneck on most gold plants and hence also for the remainder of the methodology. The overall production bottleneck will therefore be either the plant's milling capacity or the downstream ore supply. Since the ore supply has been quantified, the next step is to quantify the plant's milling capacity. This is done by determining the effective milling rate (R_{Eff}) and accounting for equipment reliability (I_{Re}) and availability (I_{Av}).

The effective milling rate is calculated by multiplying the empirically determined mill feed rate (R_{Emp}, see section 3.2.3) and reliability index (I_{Re}). The overall milling capacity (M) is calculated by multiplying the effective milling rate with the available production hours. These calculations are illustrated by Equations 3-2 to 3-5. (Maintenance periods are accounted for by the reliability and availability indexes. Maintenance periods are not used as an indication of load management potential since in general practice weekday morning peak periods are already optimally used for scheduled maintenance. Evening peak periods are not considered for maintenance since it is an inconvenient labour shift for artisans.)

(Eq. 3-2) The effective milling rate (R_e) is calculated by

$$R_{Eff} = R_{Emp} \times I_{Re}$$

(Eq. 3-3) where equipment reliability (I_{Re}) is given

$$I_{Re} = 1 - \frac{unplanned\ stoppage\ hours}{calendar\ hours}$$

(Eq. 3-4) and the overall milling capacity (M) is calculated by

$$M = R_{Eff} \times I_{Av} \times Calendar\ hours$$

(Eq. 3-5) where equipment availability (I_{Av}) is given

$$I_{Av} = 1 - \frac{planned\ maintenance\ hours}{calendar\ hours}.$$

The milling *demand/capacity ratio* is used as an indicator of the production throughput required based on the upstream ore supply. If the ratio exceeds a value of 100% it means that the plant may cause a bottleneck in the overall gold process line. In such a case the feasibility of load management should be re-evaluated due to the limited spare capacity that can be used for TOU cost optimisation.

The *demand/capacity ratio* (Equation 3-6) across a monthly horizon is illustrated in Figure 3-15.

(Eq. 3-6) The demand/capacity ratio is calculated by

$$\frac{Demand}{Capacity} = \frac{Ore\ supply}{Milling\ capacity}.$$

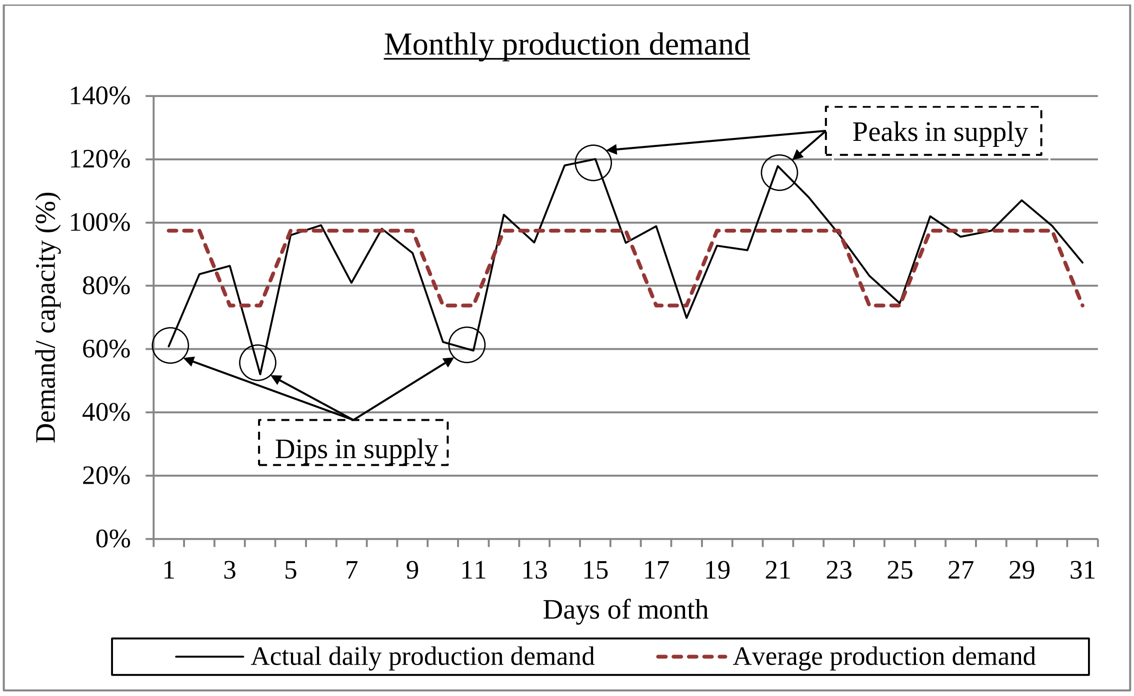

Figure 3-15: Historic production demand on a typical gold processing plant

Across the monthly horizon the average *demand/capacity ratio* is 91%. This indicates that the ore supply is the overall production bottleneck and, consequently, that spare capacity is available on the gold processing plant for load management. However, the *demand/capacity ratio* can range between 50% and 120%. These peaks and dips in supply can make the effective management of spare capacity difficult. Therefore, operations forecasting and simulation of storage buffers are essential in implementing a load management strategy.

3.4.3. Operations forecasting

Once steady-state feasibility is confirmed, as discussed in section 3.4.2, it is necessary to perform a more detailed simulation in order to ensure implementation of the identified load management opportunities. This requires simulation to forecast and ensure that the relevant process parameters are within set constraints. The most important parameters for forecasting are the storage buffers upstream and downstream to the manageable load. These buffers ensure that the overall process line remains in steady-state despite load management interventions.

Generally, the simulation method relies on the control of certain parameters on the plant, such as mill power and relative density (RD) of the milling circuit discharge and thickener underflow. The effective control of these parameters makes steady-state assumptions reliable for operations forecasting. The simulation also needs to account for time delays and holdup accounting. Figure 3-16 illustrates a schematic layout of the simulation of a plant.

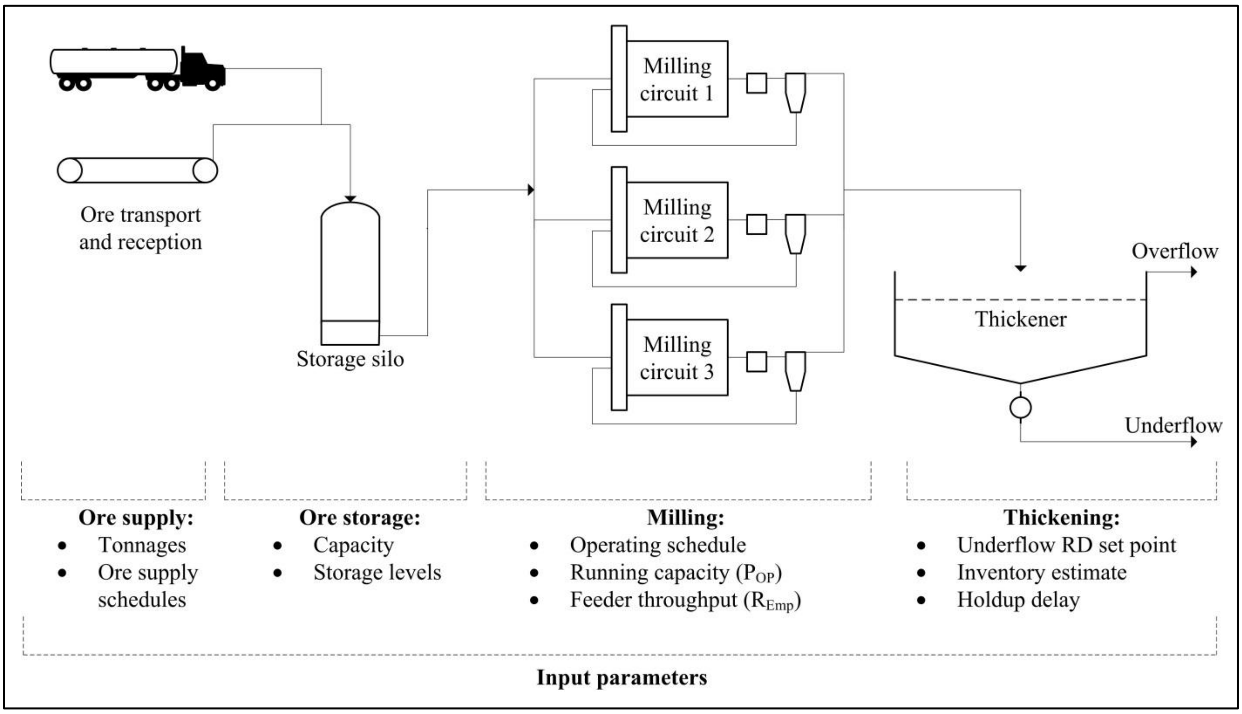

Figure 3-16: Layout of plant simulation

The milling section receives ore feed from either mining operations or adjacent surface ore stockpiles. Buffer storage capacity is provided by the ore storage silos. The milling circuits are all assumed to be closed loop with hydro-cyclone classifiers which ensure that consistent undersize (80% cut size passing 75μm) ore particles are provided for downstream thickening and recovery.

The thickener circuit provides sufficient downstream storage capacity to ensure that the recovery processes are provided with a consistent feed. This ensures steady-state operation in the case of disturbances, such as maintenance stoppages on the milling circuits. The milling section also needs to adhere to a minimum ore throughput in order to prevent choke conditions at the thickener underflow.

A scheduling method that utilises *n* time intervals is used for calculations in the simulation method. Mainly three types of components are used for simulation purposes, namely, silo, milling and thickener components. These simulation components are utilised to assure that load management events will not negatively influence up- and downstream processes. Without this assurance load management strategies will not be implemented due to the risk associated with uncertainty.

Silo component

The ore reception and storage section is simulated by a simplified silo component. Ore supply is regarded as silo inflow ($R_{SILO\text{-}IN}$) while feed to the milling section is regarded as outflow ($R_{SILO\text{-}OUT}$). The purpose of the simulation is to forecast if the silo level will range between the maximum ($Level_{MAX}$) and minimum ($Level_{MIN}$) levels. Figure 3-17 illustrates the layout of the silo simulation.

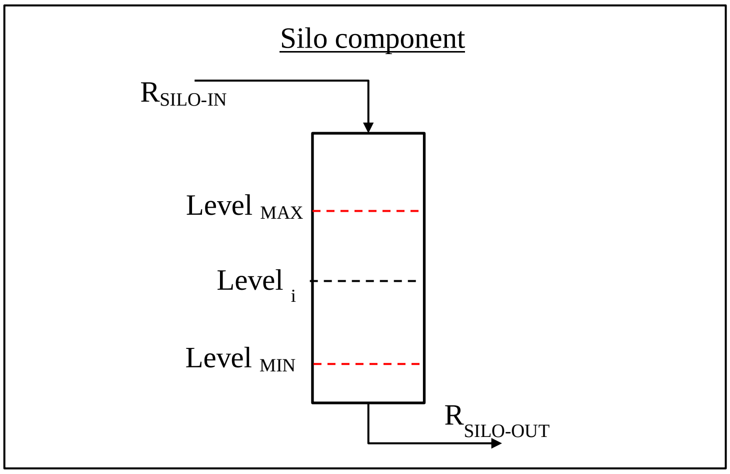

Figure 3-17: Layout of silo simulation component

The silo inflow is a required input that represents the ore reception schedule ($R_{SILO-IN}$). The ore reception schedule accounts for the quantity of ore supply (as determined in section 3.4.2) as well the time of day at which ore is received. This can be determined by observing shift related work that is associated with ore supply, such as hoisting, tipping, reclaiming and transport schedules. A typical schedule input for ore supply sources (R_{SUPPLY}) is illustrated in Figure 3-18.

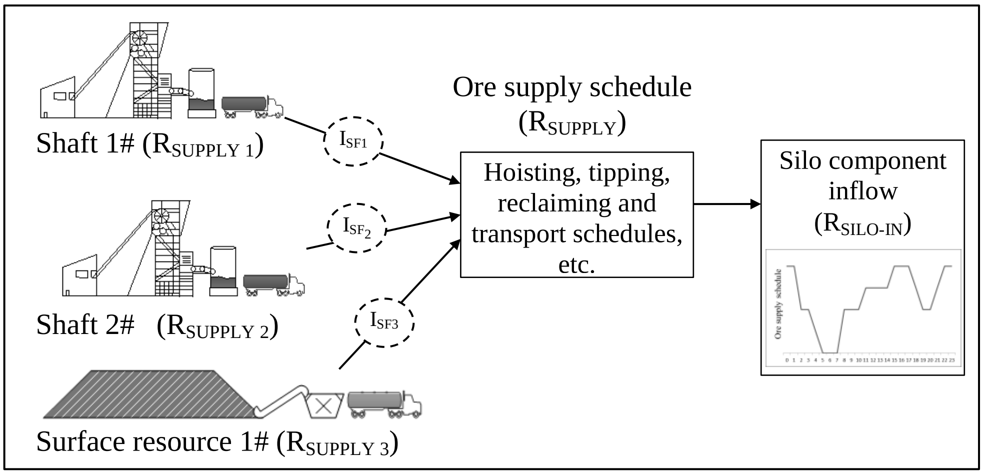

Figure 3-18: Representation of an ore supply input schedule

The inputs for s number of ore supply resources are illustrated by Equations 3-7 to 3-8. The simulation is conducted across n number of time intervals. Each time interval is indicated by *subscript i* and each ore supply resources is indicated by *subscript k.*

(Eq. 3-7) The silo inflow is calculated by: $R_{SILO-IN\,i} = \sum_{k=1}^{s} R_{SUPPLY\,k,i} \times I_{SF\,k}$ $(i = 1,2,\dots n)$

(Eq. 3-8) where the safety factor is given: $I_{SF\,k} = \frac{Actual\ tonnages}{Surveyed\ tonnages}$ $(k = 1,2,\dots s)$.

An ore supply safety factor (I_{SF}) is used in the calculations to account for unpredictable deviations in ore supply. If a gold plant’s silo levels are too high then the risk of it becoming a bottleneck is too high. This should be avoided at all costs since the value of lost revenue will possibly exceed electrical load management cost savings. Hence the safety factor should tend to overestimate ore supply to a certain extent in order to lower the risk of high silo levels. The safety factor is calculated from historic variations between actual and forecasted (surveyed) ore supply.

The silo levels of a gold plant should be kept within minimum and maximum levels in order to keep the overall process line operational. Silo level constraints, i.e. maximum ($Level_{MAX}$) and minimum ($Level_{MIN}$) levels, can be determined on a site specific basis depending on the dynamics of ore supply and equipment reliability. This constraint is illustrated by Equation 3-9.

(Eq. 3-10)
$$Level_{MIN} < Level_i < Level_{MAX} \qquad (i = 1,2, \dots , n)$$

The silo level at time interval *i* is calculated according to Equation 3-10. The starting level for the control horizon should be used as input as described by Equation 3-11.

(Eq. 3-10)
$$Level_i = Level_{i-1} + R_{INi-1} - R_{OUTi-1} \qquad (i = 1,2, \dots n)$$

(Eq. 3-11)
$$Level_i = Starting\ silo\ level \qquad (i = 0)$$

The silo outflow ($R_{SILO\text{-}OUT}$) is determined by the milling schedule. Production targets, maintenance plans as well as TOU costs will determine the details of the milling schedule. A typical schedule input for mills (T_{OP}) is illustrated in Figure 3-19. This is followed by a more detailed discussion of the mill simulation component.

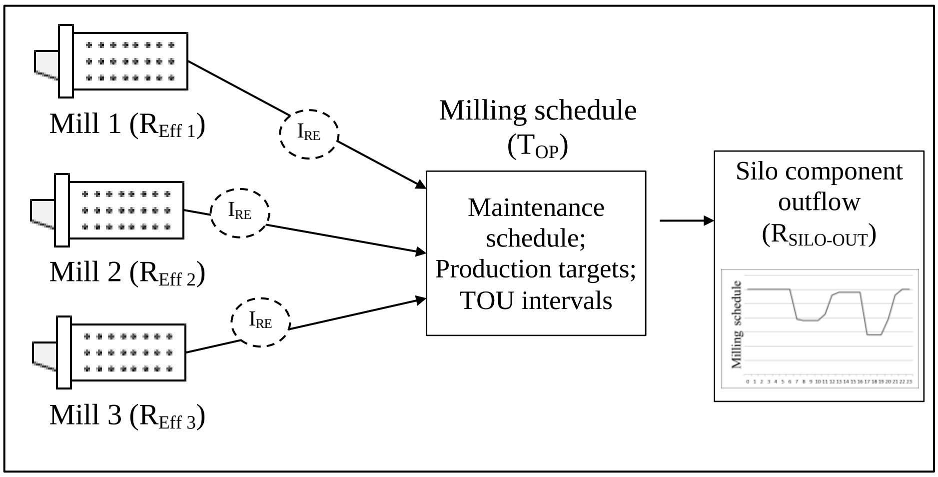

Figure 3-19: Representation of a milling schedule input

Milling component

Milling is a physical process used to decrease the size of feed ore particles. The milling section is simplified by simulating each milling circuit as a steady-state process unit incorporating the total dilution water to the circuit. Figure 3-12 illustrates a generic autogenous milling circuit assumed for simulation purposes.

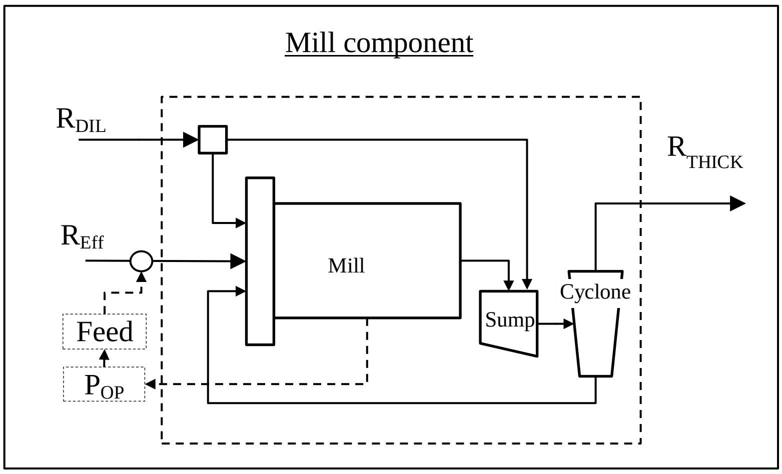

Figure 3-20: A generic milling circuit

The milling simulation accounts for rated ore feed rate capacity (R_{Eff}), addition of dilution water (R_{DIL}) and power operating point (P_{OP}) of mills. The power operating point (P_{OP}) is controlled at set-point value by varying the ore feed rate. The simulation accounts for these two parameters by using empirically determined values (as discussed in section 3.4.2).

The operating periods of mills are determined by a milling schedule which allocates maintenance and operating intervals to mills, as illustrated in Figure 3-19. The inputs for *m* number of mills for the allocated time intervals of operation (T_{OP}) are illustrated by Equations 3-12 and 3-13. Each mill is indicated by *subscript j*.

(Eq. 3-12) $$R_{SILO-OUT\ i} = R_{MILL-FEED\ i} \qquad (\ i = 1,2,\ldots n)$$

(Eq. 3-13) $$R_{MILL-FEED\ i} = \sum_{j=1}^{m}(R_{Eff\ j,i} \times\ T_{OP,i}) \qquad (\ i = 1,2,\ldots n)$$

The outflow from silos ($R_{SILO\text{-}OUT}$) is determined by feed tonnages to the mills ($R_{MILL\text{-}FEED}$) in Equation 3-12. The feed to the mills ($R_{MILL\text{-}FEED}$) is calculated by Equation 3-13 which multiplies the empirically determined effective feed rate (R_{Eff}), from Equation 3-2, with the operating periods stipulated in the milling schedule (T_{OP}).

The overall constraint of the mill simulation is to adhere to the minimum required production throughput. The minimum throughput is determined by the production target (M_{TARGET}). Typically, the production target tonnage would be in the same order as the ore supply tonnages. This constraint is illustrated by Equation 3-14.

(Eq. 3-14) $$M_{TARGET} <=\ \sum_{i=0}^{n} R_{MILL\ FEED\ i}$$

The simulation also needs to calculate the energy consumption of the mills. The electrical energy (Q) consumed by the milling operations is determined by the power operating point (P_{OP}) and according to the milling schedule (T_{OP}). This is illustrated by Equation 3-14.

(Eq. 3-14) $$Q = \sum_{j=1}^{m}(\sum_{i=0}^{n} P_{OP,i} \times\ T_{OP,i})$$

The energy consumption and subsequent energy costs are further discussed in section 3.4.4. The next sub-section discusses the thickener component, which is downstream to the milling process, in more detail.

Thickener component

The primary function of a thickener is to decrease the volume of a solid-liquid process stream by producing a clarified overflow and a thickened underflow. The underflow must adhere to a relative density set-point for downstream leaching. The solids content of the feed stream typically ranges between 6 wt% and 12 wt%[8]. The required underflow is typically 50 wt% solids [39]. Figure 3-21 illustrates the schematic layout of the thickener simulation.

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[8] Weight percentage (wt%) represents the specified mass fraction of a process stream.

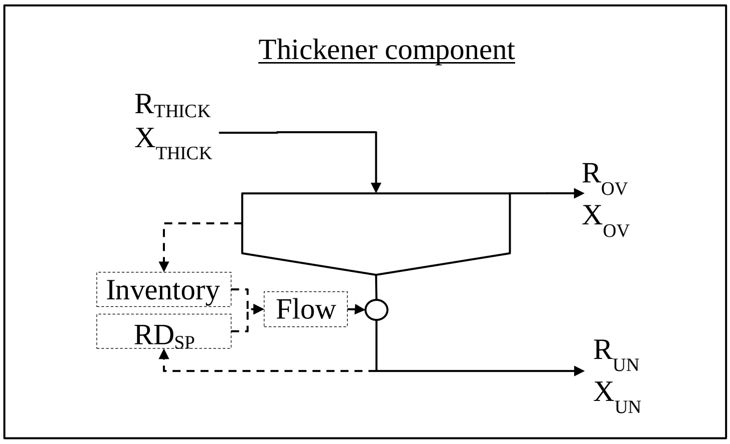

Figure 3-21: Layout of thickener simulation

The feed stream to the thickener (F_{THICK}) consists of a certain solids content as determined by the dilution in the milling section. The solids content can be given as relative density (RD) or solids fraction by weight (X). In this case X_{THICK} is used to indicate the solid fraction of the feed stream. The overflow (F_{OV}) and underflow (F_{UN}) are the product streams of the thickener with respective solid concentrations X_{OV} and X_{UN}.

In practice the rate at which the underflow is withdrawn is typically controlled by a variable flow controller. The controller is setup in a cascade with the required RD for the downstream processes used as the set-point. In addition an inventory estimator is included to account for the contents of the thickener. This ensures a consistent feed rate and RD stream to the downstream leaching circuit.

For simulation purposes a material balance over the thickener is used to determine the level of material in the thickener at each time period. This is used to estimate the flow rate and, consequently, also the RD of the underflow stream. The material balance is described in Equation 3-15.

(Eq. 3-15)
$$Level_i = Level_{i-1} + R_{THICK}X_{THICK} - R_{OV}X_{OV} - R_{UN}X_{UN} \quad (i = 1,2,\ldots n)$$

The derivation of solids fraction by weight (X) from relative density (RD) is given by Equation 3-16. The relative density of ore (RD_{SOLIDS}) and of water (RD_{LIQUID}) are used as fixed inputs.

(Eq. 3-16)
$$X_{UNi} = \frac{RD_{Solids}\,(RD_i - RD_{Liquid})}{RD_i\,(RD_{Solids} - RD_{Liquid})} \qquad (i = 1,2,\ldots,n)$$

The constraint of the thickener simulation is to adhere to the required RD of the underflow stream. This will ensure steady material supply to downstream leaching and subsequently not influence recovery. The purpose of the simulation is to forecast if the underflow RD will range between the minimum (RD_{MIN}) and maximum (RD_{MAX}) levels. This constraint is illustrated by Equation 3-17.

(Eq. 3-17) $$RD_{min} < RD_i < RD_{max} \qquad (i = 1,2,\dots,n)$$

Thickeners are designed so that the downward flow of solids exceeds the upward flow of the liquid. A thickener is critically loaded when the solids flux of the feed stream is equal to the maximum downward flux. At critical conditions a clarified overflow (W_{OV}=0) is possible. This is also the case if the thickener is under loaded, i.e. the feed flux is less than the maximum downward flux. This is the assumption for simulation purposes.

3.4.4. Production scheduling for electricity cost optimisation

Production scheduling is the procedure of allocating production demand to process components. Conventionally, the main aim is to keep the overall process line operational in order to meet end targets. This is done by keeping production schedules within certain constraints, including buffer levels, target throughput, scheduled stoppages and shift related work. This methodology adds an additional objective, namely TOU electricity cost reduction.

Up to this stage the methodology has covered the procedures to investigate and analyse load management opportunities from basic principles. Additionally, simulation procedures were described that allow operations forecasting to the extent that load management becomes practically feasible. The next step in the methodology is to discuss production scheduling that allows for TOU cost reduction. Production scheduling according to TOU tariffs is ideally done according to the following hierarchy:

1. Weekend load filling
2. Weekday night-time off-peak load filling
3. Weekday mid-day standard load filling
4. Weekday peak period load filling

The hierarchy of production scheduling allows for the full utilisation of less expensive TOU periods. As production demand increases, the utilisation of more expensive TOU periods increases. Ideally, production scheduling would only allow for the utilisation of less expensive TOU periods. This is however not always possible due to process constraints as discussed in the preceding simulation procedures. In addition to the process constraints, the number of start and stop cycles as recommended by the specific Original Equipment Manufacturer (OEM) can also limit production scheduling.

A production plan will therefore schedule operations in such a way to minimise TOU costs while adhering to the process and operational constraints. The simulation methods discussed in the preceding text ensure that relevant process parameters remain within set constraints throughout the production scheduling horizon. This integrated approach to compile optimal production plans has been discussed in more detail by Swanepoel *et al.* [69].

Once a feasible production plan is compiled, the next step is to calculate the financial benefit of TOU optimisation. The cost savings by implementing hierarchical production scheduling can be calculated by weighted average cost function (W) which considers the active energy usage during the peak periods (Q_P), standard periods (Q_S) and off-peak periods (Q_{OP}) [7]. The total electrical energy usage (Q) is thereby given by Equation 3-18.

(Eq. 3-18) $$Q = Q_P + Q_S + Q_{OP}$$

The weighted average cost function (W) is described by Equation 3-19 that includes the peak (W_P), standard (W_S) and off-peak (W_{OP}) TOU tariffs (see Appendix B for the applicable tariffs).

(Eq. 3-19) $$W = S_P W_P + S_S W_S + (1 - S_P - S_S) W_{OP}$$

The ratios of electricity consumption during peak periods (S_P) and standard periods (S_S) are determined by Equations 3-20 and 3-21, respectively.

(Eq. 3-20) $$S_P = {}^{Q_P}\!/_{Q}$$

(Eq. 3-21) $$S_S = {}^{Q_S}\!/_{Q}$$

The active energy consumed during the baseline period (Q_{BL}) is scaled to be energy neutral across the scheduled period. Energy neutrality is based on the assumption of consistent specific energy consumption for the milling section (The validity of this assumption is discussed in Appendix C). The electrical energy consumption of the scaled baseline ($Q_{\text{Scaled BL}}$) is illustrated by Equation 3-22.

(Eq. 3-22) $$Q_{Scaled\ BL} = Q_{BL} \times \frac{Q}{Q_{BL}}$$

The overall cost savings (C) of the production schedule is calculated by the difference between the weighted baseline cost function ($W_{\text{Scaled BL}}$) and the weighted load management cost function (W_{LM}), as described in Equation 3-23.

(Eq. 3-23) $$C = Q \times (W_{Scaled\ BL} - W_{LM})$$

Once the electricity cost savings (C) is forecasted, it is possible to proceed with implementation of load management. This is done by adhering to the optimised production schedule as determined by the hierarchical load filling concept. The simulation methods provided aim to forecast key process parameters accurate enough to ensure that the load management strategy will not negatively affect the overall production line.

3.5. Conclusion

The main objective of this chapter was to develop a generic method that enables the investigation and practical implementation of electrical load management opportunities. The comminution section, especially milling, is identified as an area with substantial load management potential. The maintenance of key process and production constraints is, however, essential during the implementation of strategic load management.

The methodology allows for key process constraints to be forecasted. This minimises uncertainty associated with the implementation load management by predicting up- and downstream effects. These include silo levels and thickener underflow conditions. If these parameters are kept within set constraints the TOU electricity usage optimisation can be made possible during production planning.

The next chapter is dedicated to reporting on the results measured during the implementation of the methodology for load management strategies on gold processing plants.

Chapter 4.

Results and applications

Chapter 4 presents results of case studies that were measured during applications in the gold processing industry. These results are presented as verification of the proposed methodology and validation of the research objective.

4.1. Preamble

The methodology provided in Chapter 3 needs to be verified in order to determine the merit of its applicability. This is done by presenting results measured during applications on gold processing plants in South Africa. These applications include load management strategies that were scheduled by incorporating TOU cost optimisation during production scheduling.

The contents of this chapter include the following:

- Verification of simulation procedures on process components. The goal is to verify the feasibility of load management in terms of maintaining key process and production parameters on a short control interval basis.
- Case study implementation on Gold Plant 1 and Gold Plant 2, respectively. The goal is to report on the results of long term implementation of strategic load management.
- Extrapolation of case study results for additional South African gold plants.

4.2. Verification of simulation procedures

The first step in this chapter is to confirm the accuracy of the simulation procedures on process components, i.e. mill, silo and thickener components. This is done by investigating an implementation of a load management schedule and comparing the measured data with results forecasted through the provided simulation techniques.

Results presented in this section were measured at a South African gold processing plant, namely, Gold Plant 1. The specific plant consists of six tumbling mills in parallel closed circuits. The milling section is upstream to thickeners and downstream to storage silos. The layout of the gold plant section is illustrated in Figure 4-1.

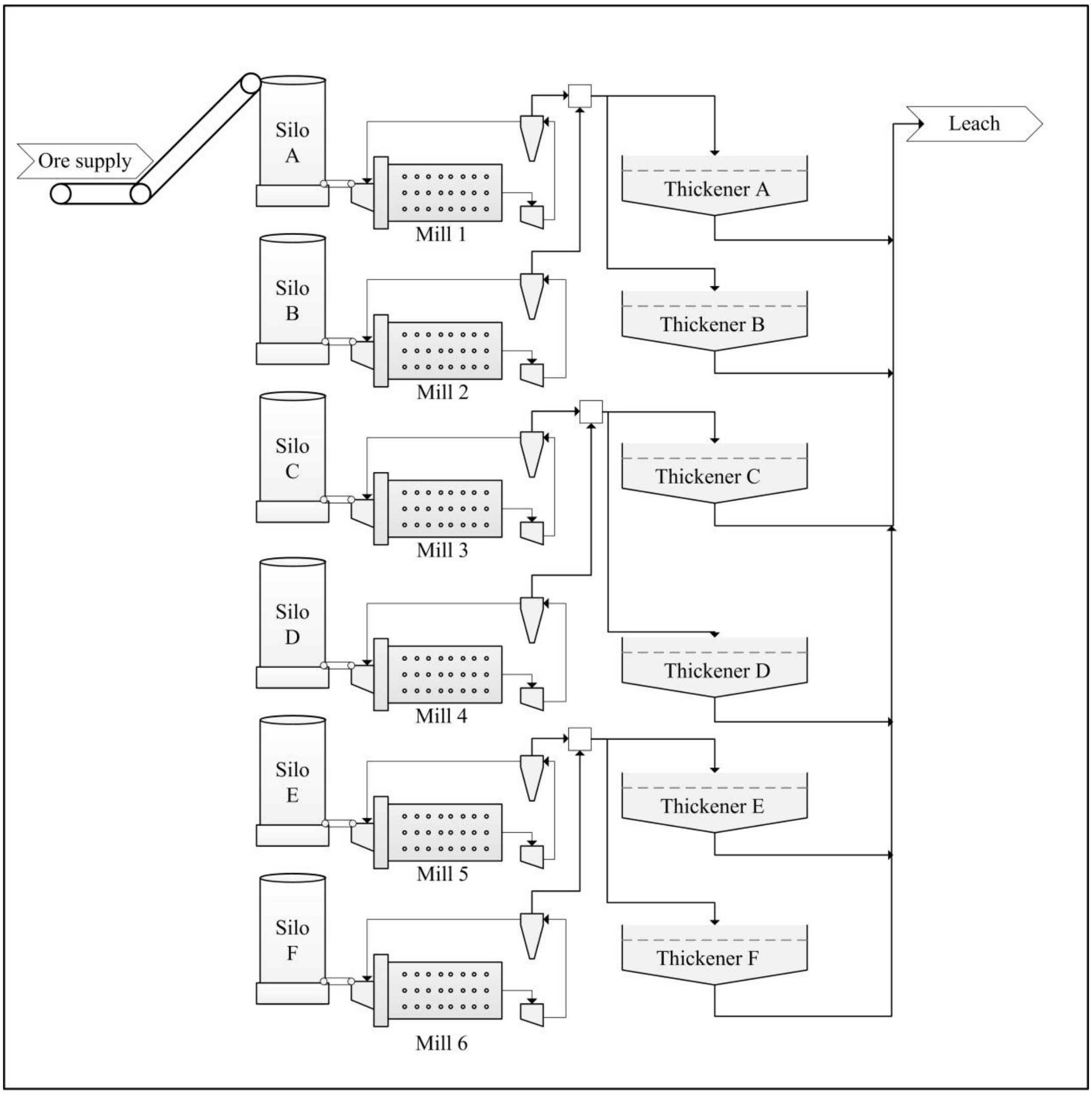

Figure 4-1: Gold Plant 1 comminution section

This section reports on a load management schedule that was implemented over a seven day week horizon. A weekly schedule of seven days is recommended since it includes all the possible TOU periods, i.e. weekdays and weekends. Figure 4-2 illustrates the optimised input schedule used to implement load management on the milling components of Gold Plant 1. The schedule is compared to the forecasted TOU power consumption.

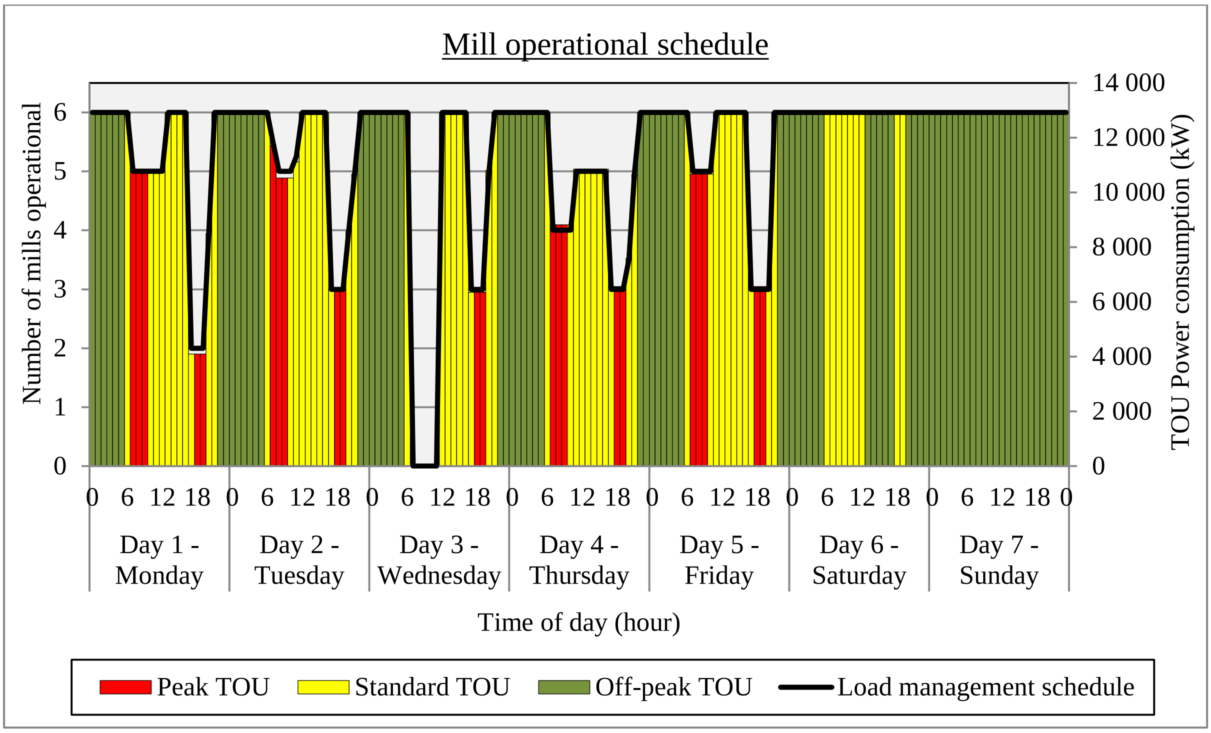

Figure 4-2: Mill operational schedule across weekly horizon

The simulated and actual results obtained during the scheduled load reduction events are further discussed in twofold. Firstly, results on the milling parameters are discussed in terms of the implemented operational schedule, production throughput and electrical power consumption. Thereafter, the effects on the buffer storage components are presented. indicate

4.2.1. Electrical load reduction on milling components

The methodology presented in Chapter 3 proposes the use of empirically determined mill specifications as simulation inputs. Given the inputs, it is possible to forecast the operational parameters of milling components across a control horizon. The specifications and simulation inputs for the milling circuit are summarised in Table 4-1.

Table 4-1: Summary of empirical parameters used as simulation inputs

Parameter	Ref.	Mill 1	Mill 2	Mill 3	Mill 4	Mill 5	Mill 6
Power consumption (kW)	P_{OP}	2 250	2 045	2 385	2 070	2 110	2 055
Average feed rate (tonne/h)	R_{EMP}	102	86	103	86	100	112
Availability index	I_{Av}	87%	90%	84%	93%	89%	83%
Reliability index	I_{Re}	98%	97%	98%	98%	98%	96%

Milling schedule

Electrical load reduction on milling components is implemented by performing scheduled stoppages. The optimised load management schedule proposed specified operating periods for a seven day control horizon. Figure 4-3 illustrates the correlation between the planned load management schedule with the actual milling periods.

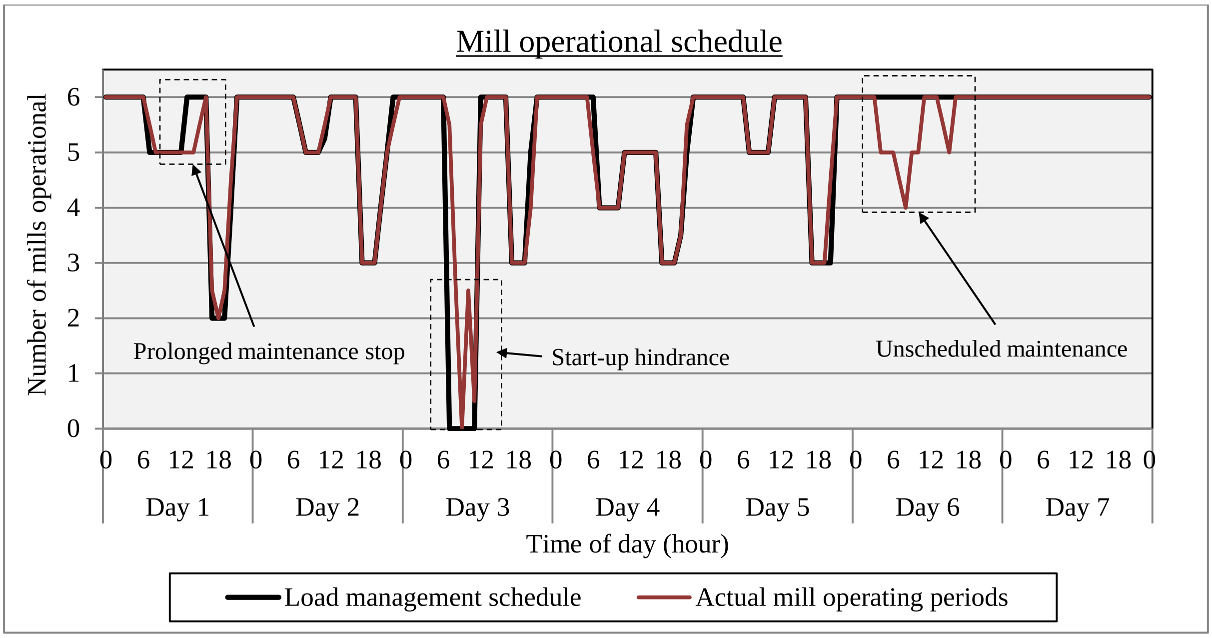

Figure 4-3: Simulated and actual mill operating schedule

Figure 4-3 illustrates that the planned load management schedule was implemented on the milling components. It further indicates that it was possible to accurately forecast the actual operating periods with the exception of unscheduled stoppages as indicated on the figure. Figure 4-4 shows the quantitative comparison between actual and forecasted operating hours for each mill.

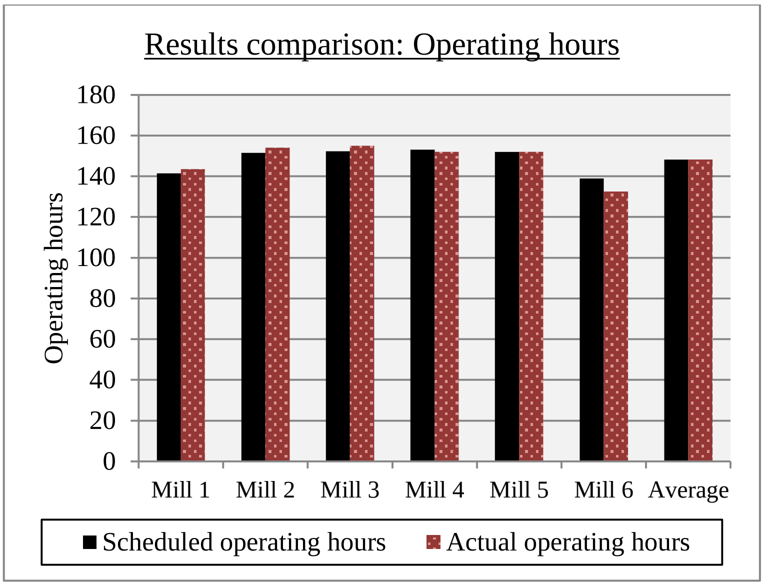

Figure 4-4: Comparison of actual and simulated operating hours

Figure 4-4 shows that the forecasted results compared well with actual operating hours. The deviations between the forecasted and actual results are attributed to unplanned mill stoppages. These deviations are observed on Day 1, Day 3 and Day 6. Unplanned stoppages are described by reliability figures, as illustrated in Figure 4-5.

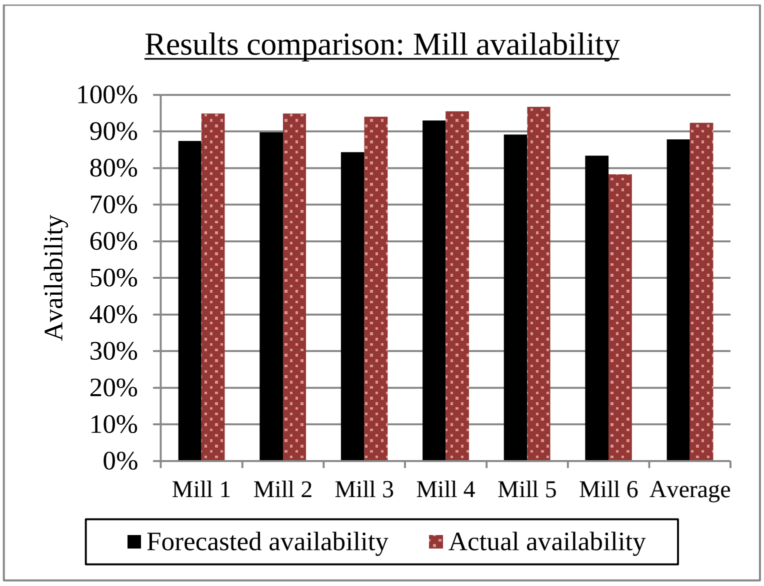

Figure 4-5: Comparison of actual and simulated reliability figures

Figure 4-5 indicates the comparison between forecasted and actual reliability figures. By definition unplanned stoppages cannot be forecasted in the short term, but it can be accounted for by incorporating historic trends. Hence reliability figures will be more accurate when forecasted over an extended period of time, such as on a monthly basis. In this methodology reliability is incorporated during the simulation of production throughput of the milling section.

Production throughput of the milling section

Simulating production throughput is achieved by using empirically determined mill feed rates and reliability figures. Mill feed rates account for production throughput while reliability indexes forecast possible unplanned stoppage time. Figure 4-6 compares the simulated mill feed rates with the actual measured mill feed rates.

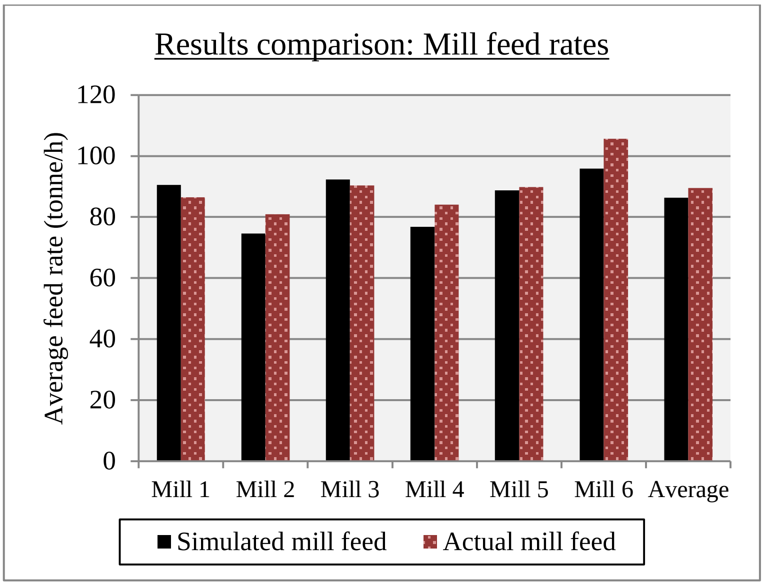

Figure 4-6: Comparison of actual and simulated mill feed rates

Results from Figure 4-6 show that on average the simulated mill feed rates are slightly less than the actual feed rates achieved. This deviation occurs due to the inclusion of reliability figures to account for possible loss of production time. Figure 4-7 illustrates the cumulative milling throughput for the control horizon under investigation.

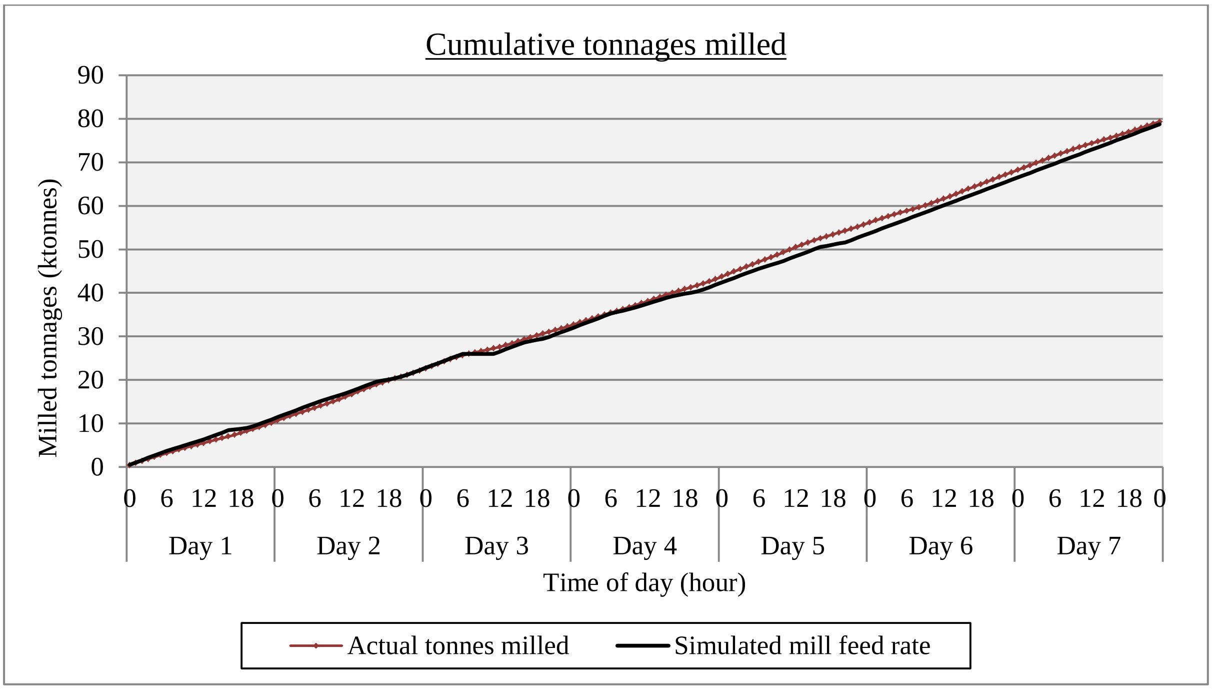

Figure 4-7: Cumulative comparison of actual and simulated milling production figures

The overall objective of production orientated activities is to achieve production targets. Figure 4-7 illustrates that this objective is accomplished since the planned production throughput compares well with the actual milling throughput achieved. The next step is to determine the mill power consumption during the control horizon under investigation.

Power consumption of the milling section

Simulating electrical power consumption of a mill is achieved by using empirically determined running capacities. Since mill loads are set-point controlled, it is possible to forecast mill power consumption according to operating trends. Figure 4-8 compares the simulated mill power consumption with the actual measured power readings for each mill.

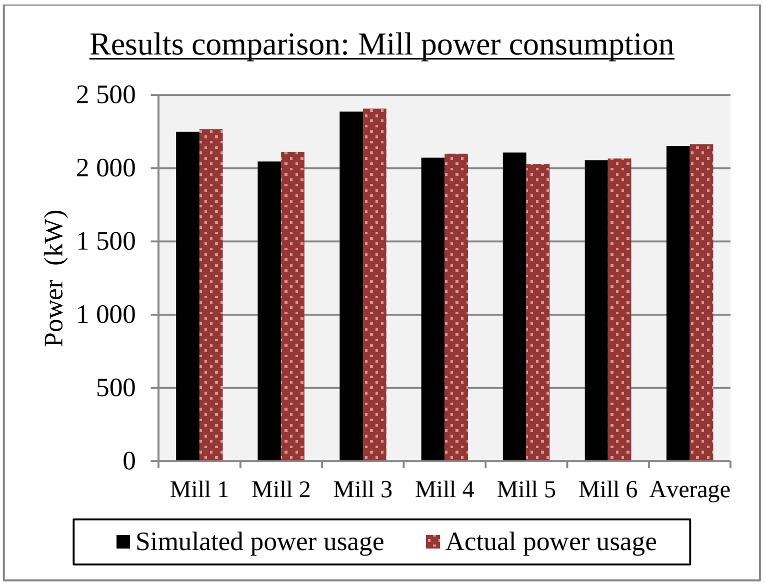

Figure 4-8: Comparison of actual and simulated mill power consumption

Figure 4-8 reaffirms that consistent power consumption is a safe assumption since mills are controlled at uniform loads and consequently uniform running capacities. These consistent power readings are used to forecast power consumption according to the milling schedule. Figure 4-9 illustrates the simulated mill power consumption compared to measured data.

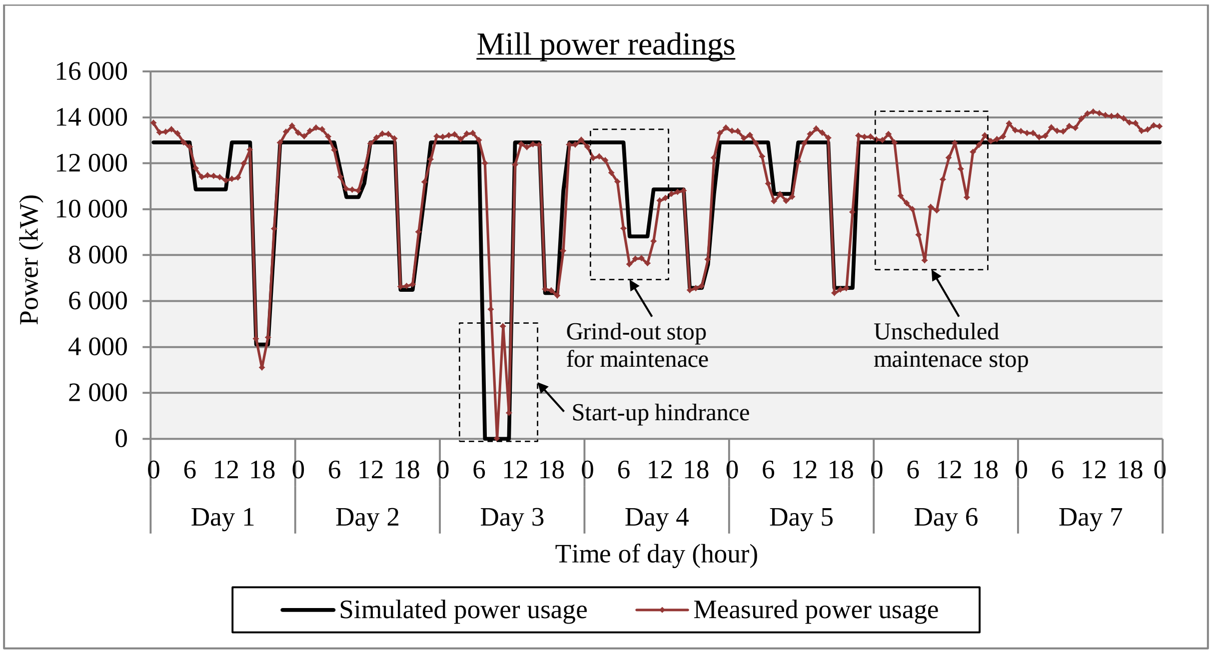

Figure 4-9: Comparison of actual and simulated mill power consumption

Figure 4-9 shows an acceptable correlation between simulated and actual power readings. Exceptions to the correlations are marked on Day 3, Day 4 and Day 6. The deviations on Day 3 and Day 6 are attributed to deviations from the planned load management schedule due to reliability reasons. The deviation on Day 4 is due to premature mill feeder stoppages to reduce mill contents for planned maintenance. The reduction in mill contents that caused lower power draw was not included in the simulation inputs.

In this section the effects of load management on the milling components were reported. Additionally, the simulation procedure developed in Chapter 3 was proven to be effective in forecasting the relevant milling parameters during the implementation of load management. The next step is to investigate the results relevant to the storage buffer components.

4.2.2. Storage buffer constraints

Implementing load management on mills entails scheduled mill stoppages during more expensive electricity usage periods. It is important to predict the upstream and downstream effects of mill stoppages and to comprehend the overall effect on the process line. In order to determine the effects of load reduction stoppages, the storage buffer components are also investigated across the load management implementation period.

Silo component results

Silos are used as a storage buffer between mining operations and the gold plant. Firstly, the ore supply from downstream mining operations needs to be accurately forecasted in order to simulate silo levels.

This can be done by collecting quantities from mining surveys from both underground and surface resources. A typical mining survey will state the amount of material that is planned to be mined and transported to the gold plant. Figure 4-10 shows results accrued for the control horizon under investigation.

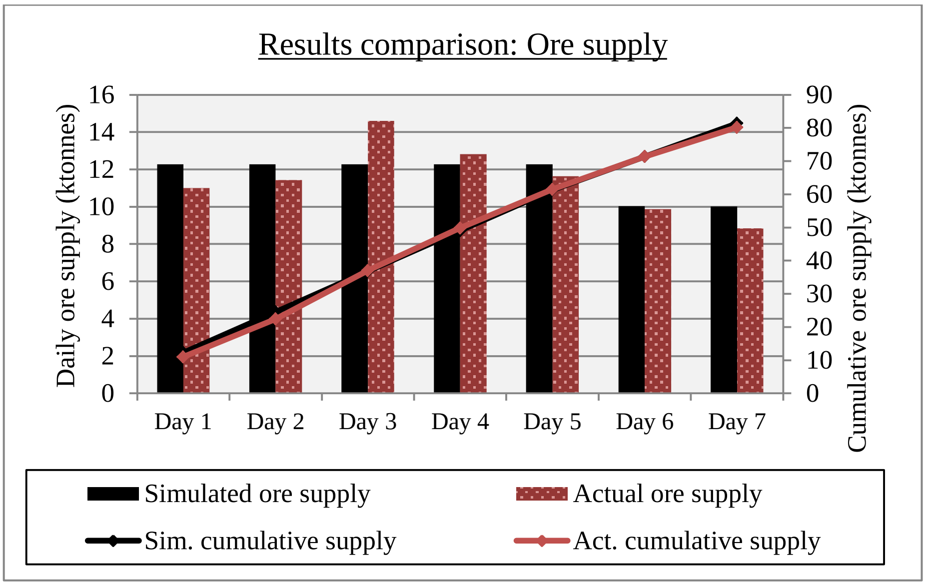

Figure 4-10: Comparison of actual and simulated ore supply figures

Figure 4-10 illustrates that the ore supply forecast was relatively accurate when compared with the actual ore supplied to the gold plant. Given the accurate ore supply forecasting, it is possible to implement load management by managing silo storage levels. The silo simulation technique represents all the silos on the plant conveniently as a single storage unit. Figure 4-11 illustrates the forecasted and measured storage levels during the load management period.

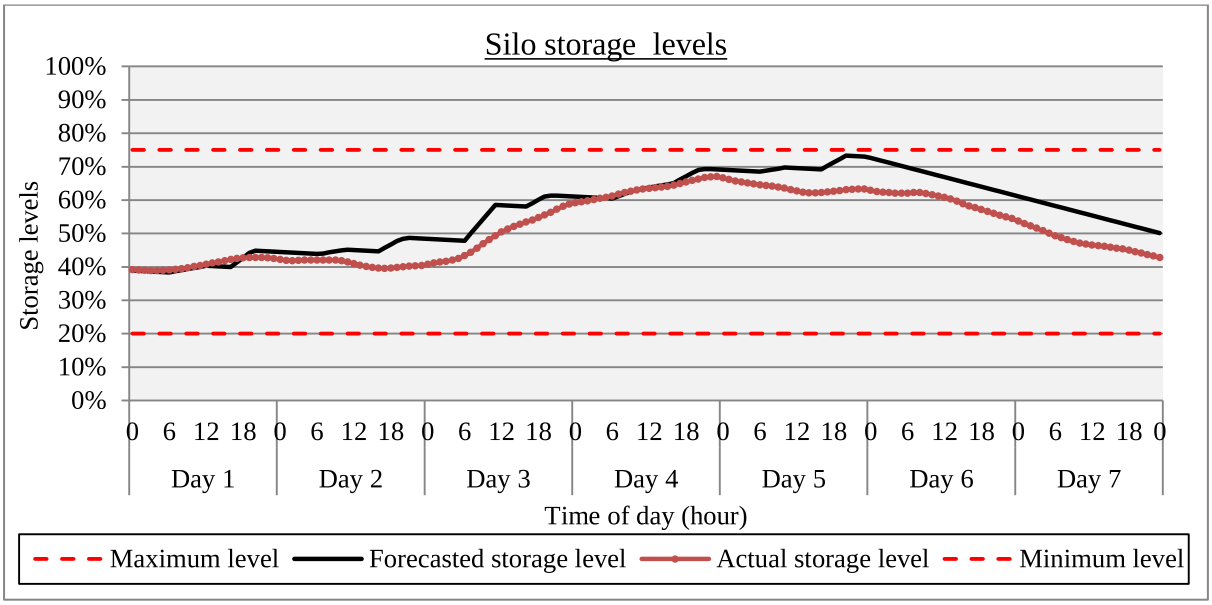

Figure 4-11: Comparison of actual and forecasted silo storage levels

Figure 4-11 illustrates that both the actual and forecasted silo levels remained within the minimum and maximum constraints. These constraints assure that the gold plant will be able to adhere to steady–state production targets despite implementing load management stoppages. The deviation between the actual and forecasted values is due to difficulty of predicting ore supply tonnages on a short interval basis.

Silo levels at the end of the control horizon show a 7% deviation between actual and forecasted silo levels. If a gold plant's silo levels are too high then the risk of it becoming a bottleneck is too high. The forecasted silo level is therefore on the "safer side" by predicting higher than actual ore supply. This result is attributed to the safety factor incorporated to minimise the risk of high silo levels (see section 3.4.2).

Figure 4-11 indicates increasing silo levels across the horizon from Day 1 to Day 5. This was done in order to allow maximum mill utilisation across the horizon from Day 6 to Day 7, which was a weekend period. Weekends consists of less expensive TOU periods. This gives insight into the load management strategy that was followed on the gold plant.

Thickener component results

Thickeners are used to dewater the milled slurry to a relative density (RD) with a set-point of typically 1.55 tonne/ m^3. It also provides a storage buffer for the supply to the downstream leaching section. Figure 4-12 illustrates the cumulative tonnages that were measured at the thickener underflows compared with the forecasted tonnages for the period under investigation.

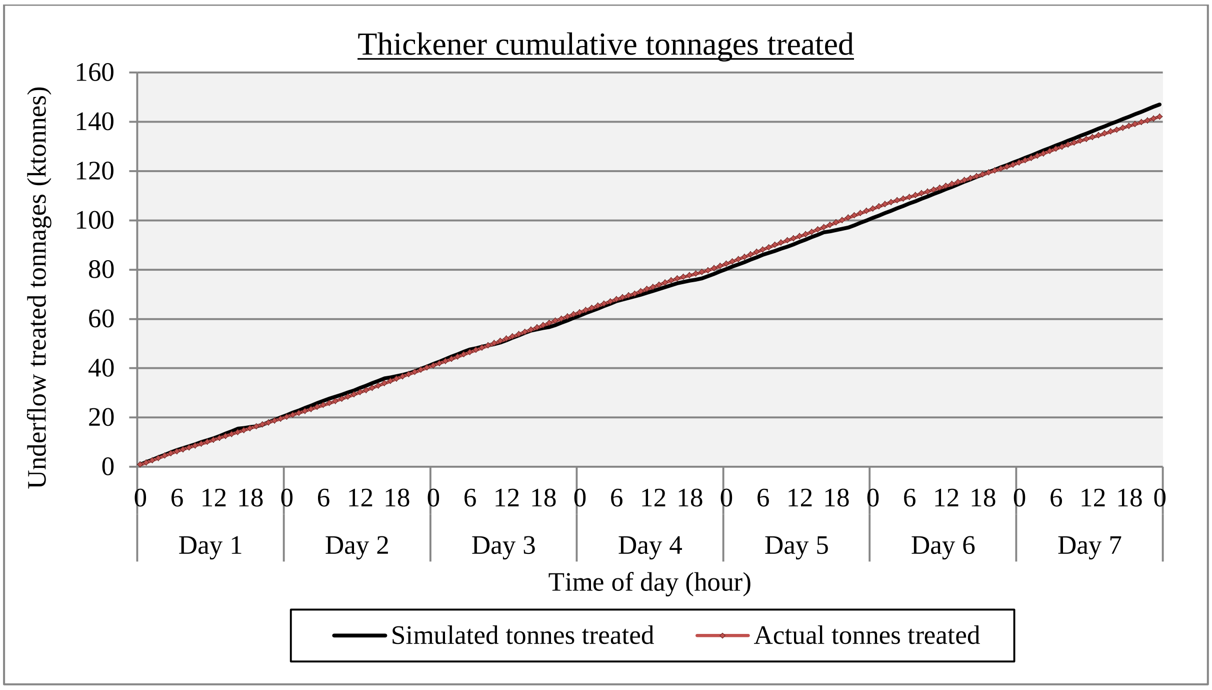

Figure 4-12: Cumulative comparison of actual and simulated thickener production figures

Similar to the milling section, the thickener section also needs to achieve a certain production throughput. The overall objective of production orientated sections is to achieve production targets. Figure 4-12 illustrates that this objective is accomplished since the planned production throughput compares well the actual underflow tonnes treated.

It is essential that the thickener underflows adhere to the set-point RD. Failure to achieve this will result in unwanted process disturbances on the downstream leaching process. RD control is done by dynamically controlling the underflow flow. A reduction in flow results in a higher RD, however flow can only be reduced to a certain extent. Excessive flow reduction will cause the underflow to choke. Therefore the flow into thickener circuit needs to be sufficient to avoid choke conditions.

The simulation procedure developed aims to keep the underflow RD within set constraints. This means that the simulated RD should not exceed the maximum or minimum values during the control horizon. Figure 4-13 illustrates the simulated underflow RD compared to the actual underflow RD measured during the period under investigation.

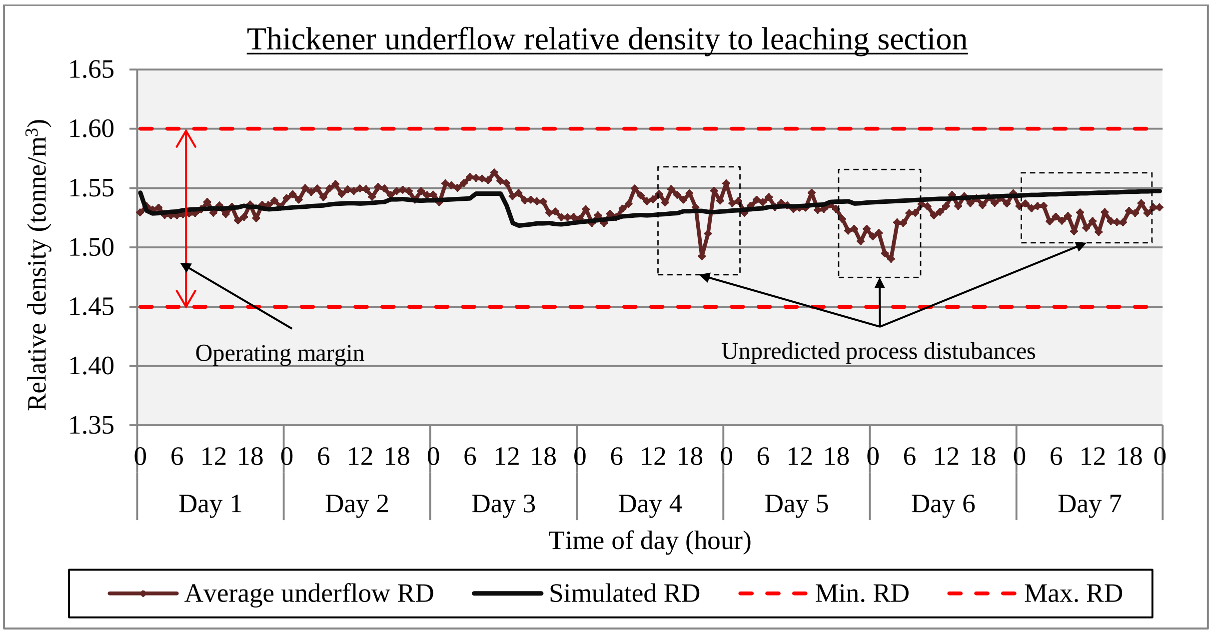

Figure 4-13: Comparison of actual and forecasted underflow RD

Figure 4-13 shows that both the forecasted and actual RD of the thickener underflow remained relatively stable with limited deviations from the set-point. The deviations from the simulated RD are due to unpredicted process disturbances. These disturbances cannot be predicted by the simulation model, hence deviations between the actual and forecasted RD values occur as indicated on Figure 4-13. This is due to lower than predicted mass flow into the thickener setup.

The main aim of the simulation was to forecast whether the underflow would consistently remain within maximum and minimum constraints during the load management period. If the thickener underflow remains within the set constraints it is possible for the automated control to ensure a consistent density, because the conditions are within the control boundaries. The automated control can then reduce the underflow flow rate of the thickener, thereby making up for the reduced mill throughput by increasing the residence time in the thickener setup. This stabilises the flow to the leaching circuit.

4.2.3. Summary of simulated results

In this section the effects of load management on the milling components were reported. Additionally, the simulation procedure developed in Chapter 3 was proven to be effective in forecasting the relevant process parameters during the implementation of load management. Table 4-2 summarises the parameters that can be forecasted coupled with the average deviation from actual values.

Table 4-2: Summary of simulation results

Parameter	Average deviation
Mill operational schedules (operational hours)	2%
Mill feed rates (tonnes/h)	6%
Milling production figures (tonnages)	4%
Mill power consumption (kW readings)	2%
Ore supply figures (tonnages)	8%
Silo storage levels (level %)	5%
Thickener production figures (tonnages)	3%
Thickener underflow RD (tonnes/m^3)	1%
Average overall	**4%**

Deviations range between 1% and 8% for the simulated parameters on average. The results indicated that the key process parameters were forecasted accurately enough in order to avoid impeded constraints. This ensured the overall functionality of the production line. It is therefore concluded that the margins of the deviations are within an acceptable range.

The accuracy of the simulation results are however dependent on the accuracy of the input parameters, such as milling specifications, reliability and ore supply figures. If the input parameters cannot be accurately determined, then it will be necessary to increase the safety factors or decrease the control horizon of the simulation.

The simulation procedure was implemented successfully for a control horizon of a seven day week. During this period several operational scenarios took place. These included six scheduled maintenance events, five planned load management events and three reliability issues. The simulation results showed that these events could be forecasted and accounted for within reasonable accuracy.

The next step is to report on load management that was implemented on two South African gold processing plants for a long term period of three months.

4.3. Case study 1: Load management on Gold Plant 1

This case study reports on electrical load management that was implemented on the comminution section of a South African gold plant, namely Gold Plant 1. The comminution section consists of six tumbling mills in parallel closed circuits, as presented in section 4.2.1 (Verification of simulation procedures). The results presented in this case study cover a three month period during which strategic load management was implemented.

The methodology in Chapter 3 identifies production forecasting as a key element in implementing load management on a gold plant. For this reason the ore supply trend needs to be accurately forecasted. Figure 4-14 illustrates the forecasted and actual ore supply trends during the three month period of the case study.

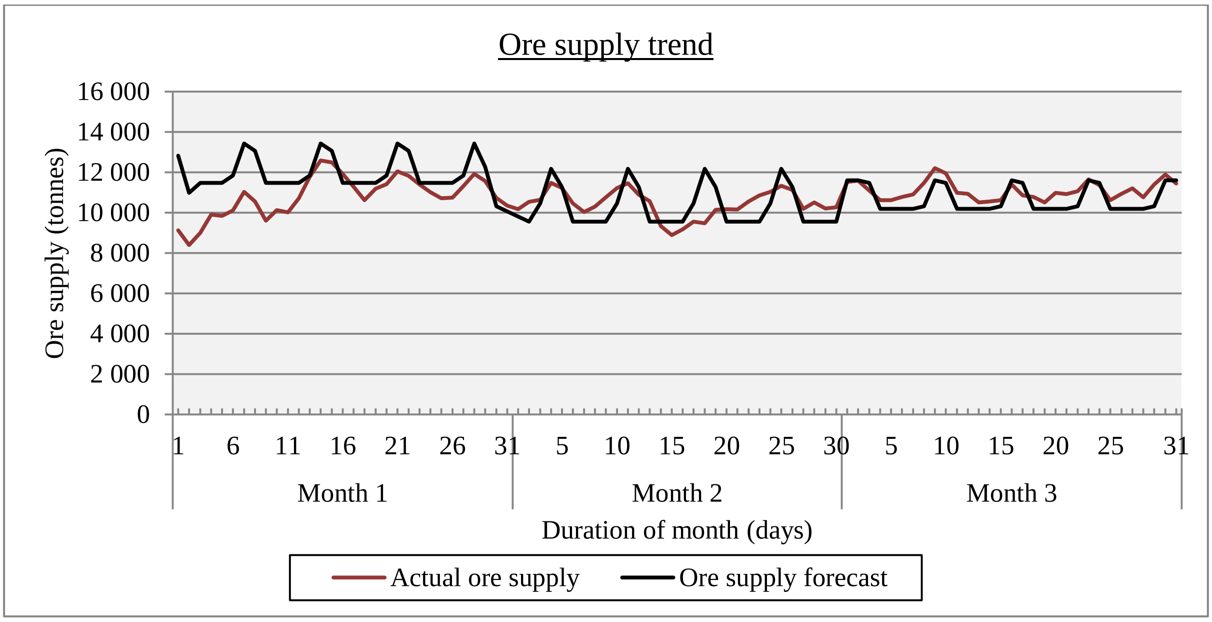

Figure 4-14: Ore supply trend of Gold Plant 1

The ore supply forecast is based on mining surveys that are collected on a monthly basis. A mining survey is a prediction of ore tonnages that will be supplied by mines. It can be collected on a monthly basis from an investigation questionnaire (Appendix A) or from the ore reserve manager of the specific mining operations.

Figure 4-14 indicates the mining surveys enabled relatively accurate forecasting of ore supply during the duration of three months. Since ore supply could be forecasted, it was possible to determine the amount of spare production capacity on the plant’s milling section. This is illustrated in Figure 4-15 by comparing the actual ore supply, forecasted ore supply and rated production capacity.

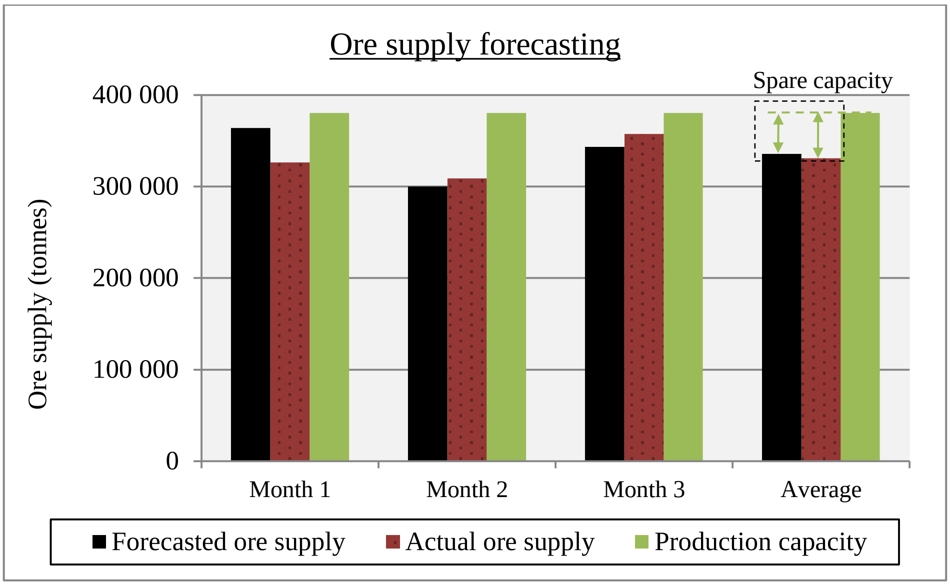

Figure 4-15: Comparison of actual and forecasted ore supply to Gold Plant 1

The production capacity of Gold Plant 1 exceeded the ore supply during all three months of the case study period, as illustrated in Figure 4-15. This indicated that spare production capacity was available and, consequently, that strategic load management was feasible. The key concept of strategic load management is to allocate operating hours to less expensive TOU periods. As indicated in Chapter 3 (Methodology), the following load scheduling options can present cost savings on the Megaflex tariff structure:

A. Weekend load filling

B. Weekday night-time off-peak load filling

C. Weekday mid-day standard load filling

These production filling options were implemented on Gold Plant 1 by weekly production scheduling forecasts, such as the seven day forecast presented in section 4.2 (Verification of simulation procedures). Figure 4-16 illustrates the resultant electricity usage profile for weekdays averaged for the three month period. This profile is compared to the baseline profile in order to measure the savings of the load management application.

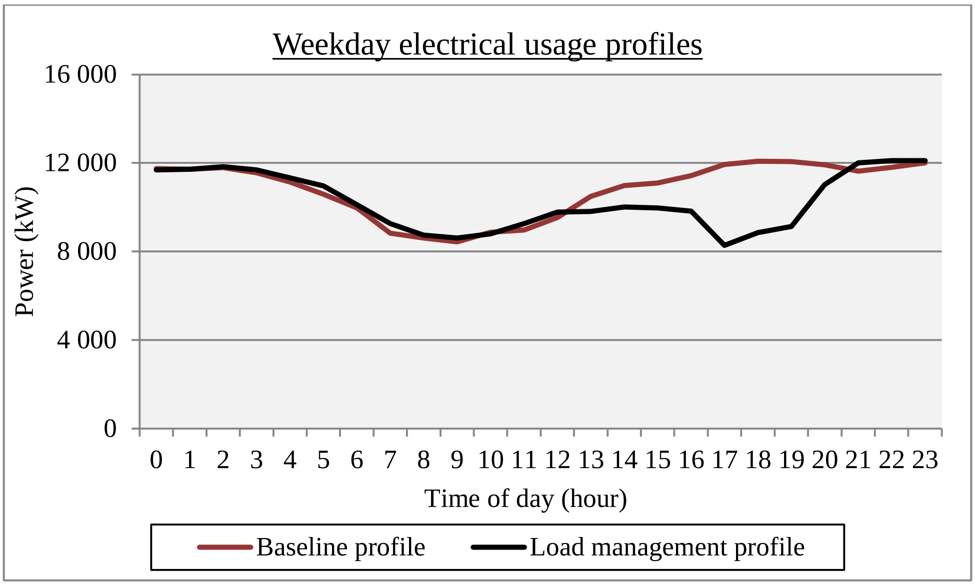

Figure 4-16: Resultant weekday electricity usage profiles of Gold Plant 1 milling section

A clear weekday load reduction is observed in Figure 4-16. The load reduction is particularly evident during the afternoon standard and evening peak TOU periods. The electricity usage during the other weekday TOU periods remains consistent with the baseline profile. The reason being the load from the afternoon standard and evening peak TOU periods is shifted to weekend periods, as illustrated in Figure 4-17.

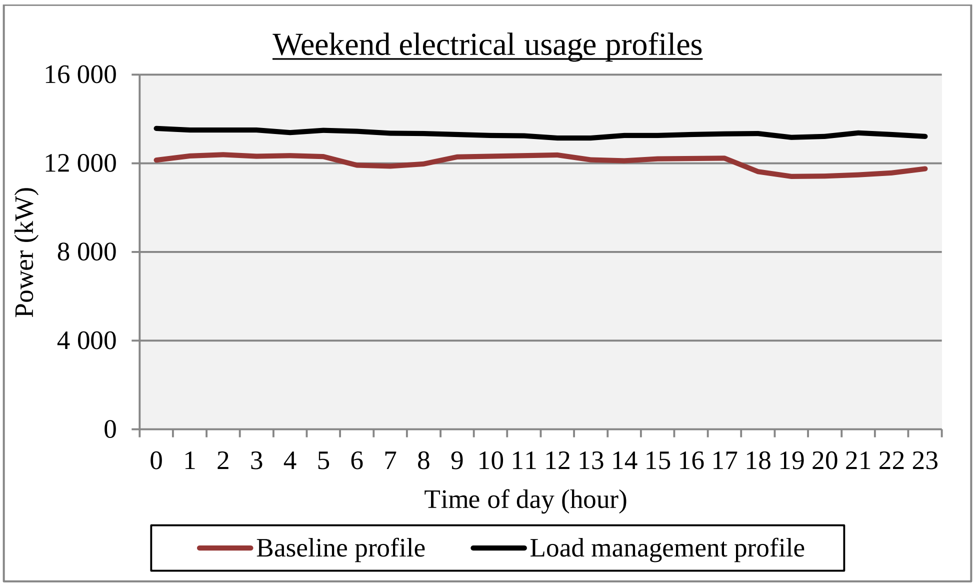

Figure 4-17: Resultant weekend electricity usage profiles of Gold Plant 1 milling section

Figure 4-17 reaffirms that weekend load filling was implemented during the duration of the case study. This is beneficial since weekends consist of less expensive TOU periods than weekdays. The overall TOU load shift is presented in Figure 4-18.

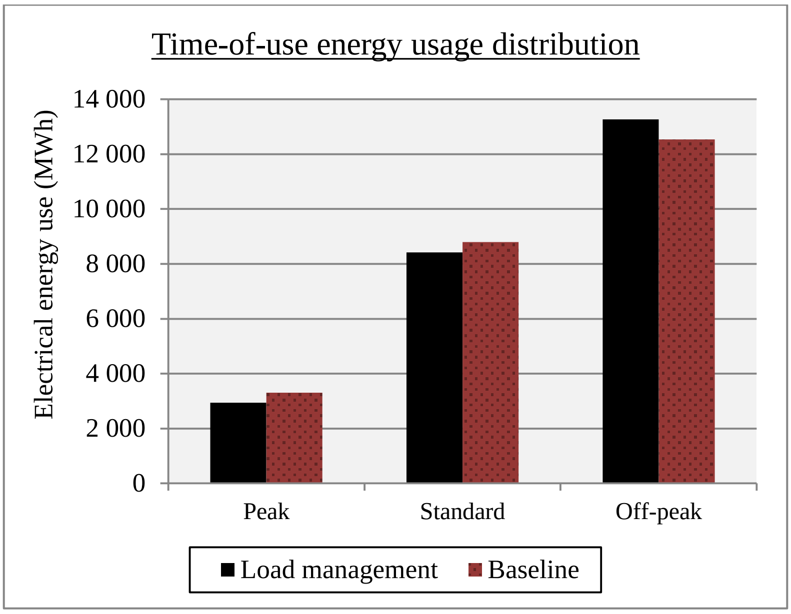

Figure 4-18: TOU electricity usage distribution of Gold Plant 1 milling section

Figure 4-18 illustrates the electricity energy usage distribution across the peak, standard and off-peak periods. It is evident that peak and standard load was shifted to the less expensive off-peak periods. The cost savings associated with the load shift is summarised in Table 4-3.

Table 4-3: Summary of electricity cost savings on Gold Plant 1

Indicator	Baseline period	Load management period
Peak energy partition (S_P)	13 %	12 %
Standard energy partition (S_S)	36 %	34 %
Off-peak energy partition (S_{OP})	51 %	54 %
Average peak load reduction (MW)	0	3.6
Weighted average cost function (R/kWh)	R 0.71	R 0.68
Electrical energy consumption (MWh)	24630	24630
Specific energy costs (R/tonne)	R 17.59	R 16.82

The weighted average cost function shows cost saving of R 0.03 per kWh of electrical energy consumed. This led to a 5% decrease in the specific energy costs of the milling section. Overall the cost savings amounted to R 762 000 for the three month high demand season (winter period). If these electricity usage trends are extrapolated the annual savings would to amount R 1.4-million.

4.4. Case study 2: Load management on Gold Plant 2

Gold Plant 2 is a South African gold processing plant that treats ore supplied by adjacent mine shafts. This case study reports on electrical load management that was implemented on the comminution section of the plant. The results presented in this case study cover a three month period during which strategic load management was implemented.

The comminution section of Gold Plant 2 consists of two tumbling mills in parallel closed circuits. Each mill is upstream to thickeners and downstream to storage silos. The layout of the section under investigation is illustrated in Figure 4-19.

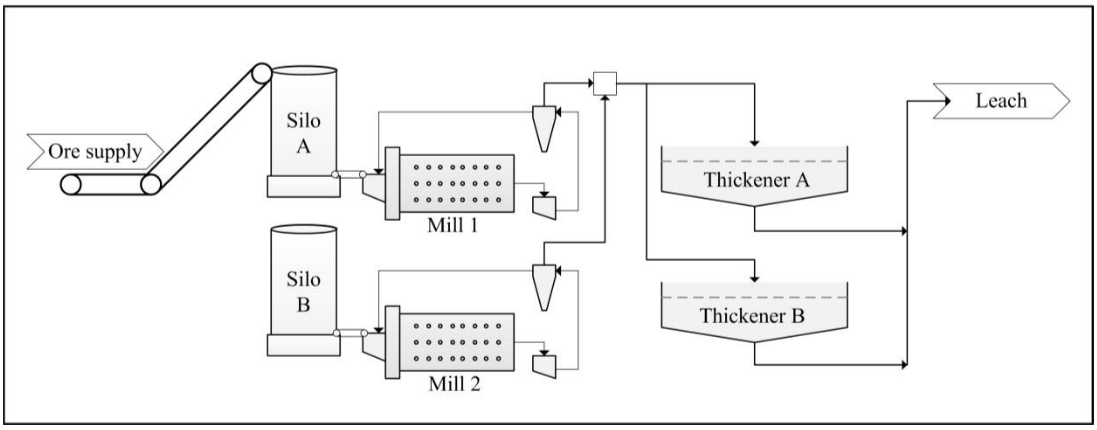

Figure 4-19: Gold Plant 2 comminution section

The specifications for the milling equipment are summarised in Table 4-4. These specifications were empirically obtained as discussed in the methodology.

Table 4-4: Summary of milling parameters on Gold Plant 2

Parameters	Mill 1	Mill 2
Running cap. (kW)	1345	1300
Feed rate (tonne/h)	72	64
Availability	88%	81%
Reliability	96%	92%

As in the case of Gold Plant 1, the concept of load management entails production planning in order to optimise TOU electricity costs. Production forecasting is a key element in implementing load management. For this reason the ore supply trend needs to be accurately forecasted. Figure 4-20 illustrates the forecasted and actual trends of the ore supplied to Gold Plant 2 during the three month period of the case study.

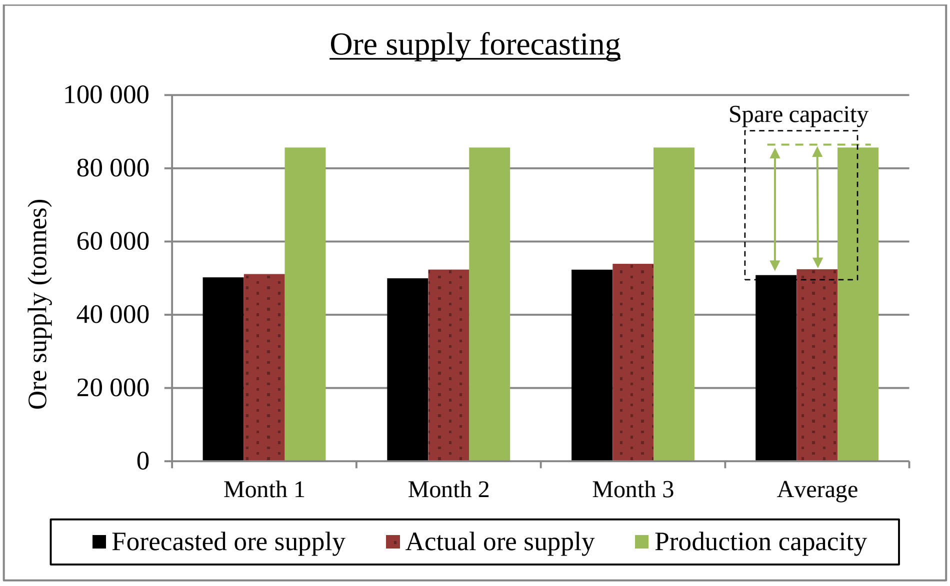

Figure 4-20: Comparison of actual and forecasted ore supply to Gold Plant 2

Figure 4-20 indicates that the production capacity of Gold Plant 2 was substantially more than the ore supply during the three months of the case study period. This indicated that significant spare production capacity was available that allowed the implementation of strategic load management on the mills at the gold plant.

As the case of Gold Plant 1, the load scheduling options that can present cost savings on the Megaflex tariff structure include weekend load filling, weekday off-peak and standard load filling. Figure 4-21 illustrates the weekday electricity usage profile resulting from the production filling options that were implemented on Gold Plant 2. The resultant profile is averaged across a three month period and is compared to the baseline profile in order to measure the savings of the load management strategy.

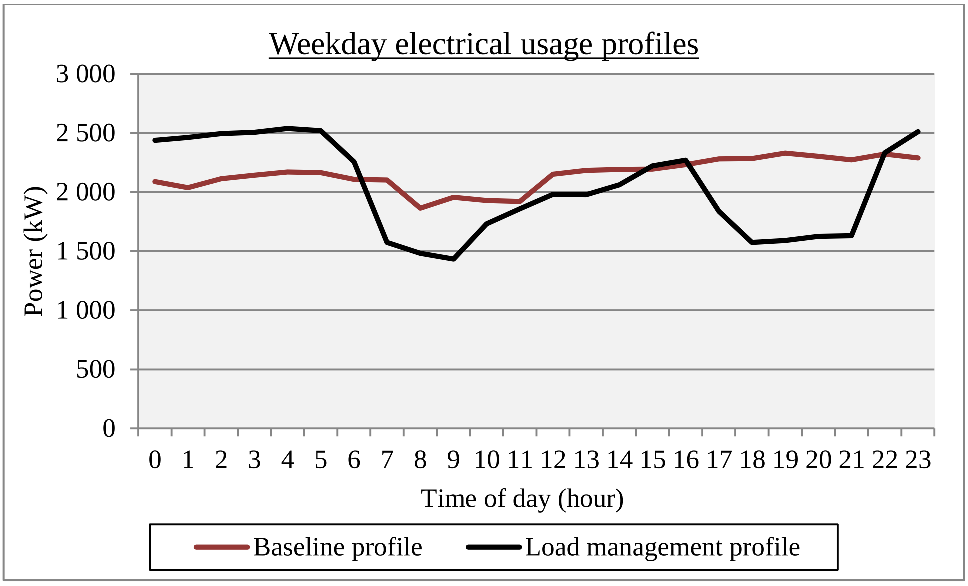

Figure 4-21: Resultant weekday electricity usage profiles of Gold Plant 2 milling section

A clear weekday load reduction is observed in Figure 4-21. The load reduction is evident during the morning peak, mid-day standard and evening peak TOU periods. The electrical load was shifted to weekday off-peak periods. However, a substantial amount of electrical load was also shifted to weekend periods. This is illustrated in Figure 4-22.

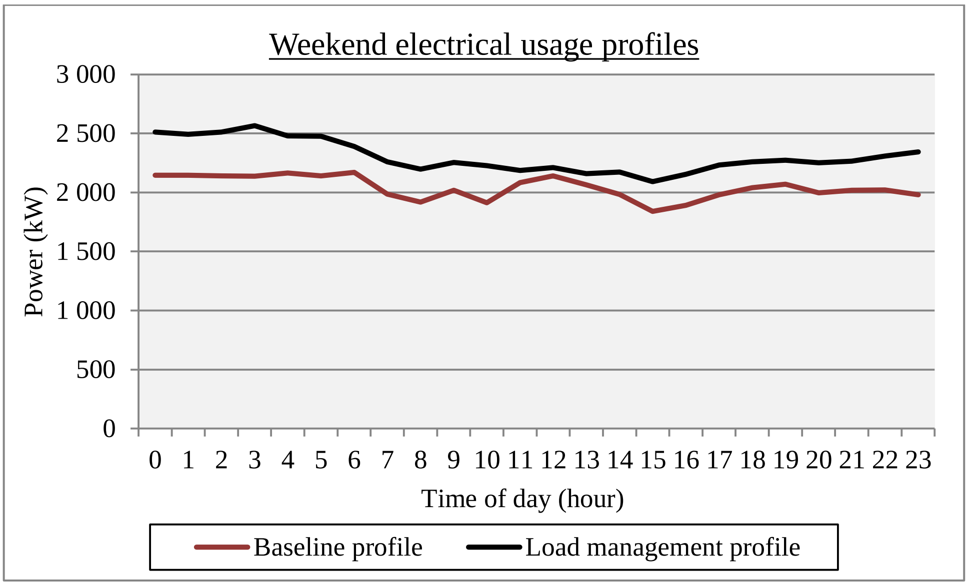

Figure 4-22: Resultant weekend electricity usage profiles of Gold Plant 2 milling section

Figure 4-22 confirms that weekend load filling was implemented during the duration of the case study. This is beneficial since weekends consist of less expensive TOU periods than weekdays. The overall TOU load shift is presented in Figure 4-23.

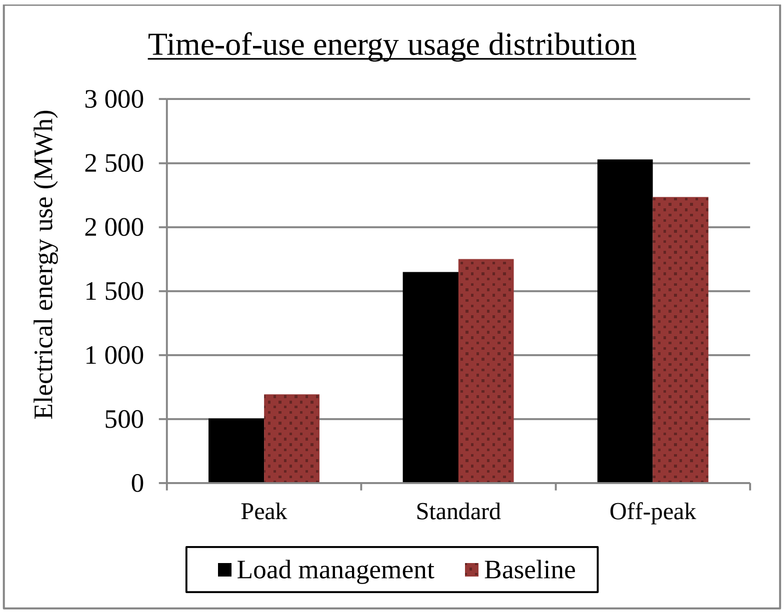

Figure 4-23: TOU electricity usage distribution of Gold Plant 2 milling section

Figure 4-23 illustrates the electricity energy usage distribution across the peak, standard and off-peak periods. It is evident that peak and standard load was shifted to the less expensive off-peak periods for the three month period. The cost savings associated with the load shift is summarised in Table 4-5.

Table 4-5: Summary of electricity cost savings on Gold Plant 2

Indicator	Baseline period	Load management period
Peak energy partition (S_P)	15 %	11 %
Standard energy partition (S_S)	37 %	35 %
Off-peak energy partition (S_{OP})	48 %	54 %
Average peak load reduction (MW)	0	0.6
Weighted average cost function (R/kWh)	R 0.74	R 0.66
Electrical energy consumption (MWh)	4680	4680
Specific energy costs (R/tonne)	R 22.04	R 19.65

The weighted average cost function shows a cost saving of R 0.08 per kWh of electrical energy consumed. This led to an 11% decrease in the specific energy costs of the milling section. Overall the cost savings amounted to R 375 000 for the three month winter period. If these electricity usage trends are extrapolated for a calendar year, then the annual savings would amount to R 660 000.

4.5. Extrapolation of case study results

In two separate case studies it was shown that load management on comminution circuits is feasible by presenting results measured on South African gold processing plants. Furthermore, the results across three month periods show that significant cost savings were achieved. Specific electricity costs (R/tonne) on the milling sections were reduced by 5% and 11% for Gold Plant 1 and Gold Plant 2, respectively. The load management applications were implemented without additional capital or operational expenditure.

The case study results presented were recorded during a three month winter period (high demand season). During this period electricity tariffs are substantially higher than in the remaining 9 summer months of a calendar year (low demand season). Hence, the specific electricity cost savings when calculated according to average annual tariffs are 3% and 7% for Gold Plant 1 and Gold Plant 2, respectively.

Results from two isolated case studies are presented. It can therefore be an indication that potential for electrical load management also exists on other South African gold processing plants. This indication is supported by statistics that show a 44% reduction in tonnages ore treated from 2003 to 2012 [33]. If an average specific electricity cost saving of 5% is extrapolated across the South African gold processing industry, then the potential cost savings could amount to R 25-million per annum.

4.6. Summary of results

Results indicated that the application of the methodology provided in Chapter 3 can be used to forecast process and production parameters in such a way that strategic load management is feasible. This was proven accurate for the silo, mill and thickener simulation components across a weekly interval. It is evident the dynamics associated with ore supply and equipment reliability can influence the implementation of load management. This makes production forecasting essential for practical application.

Two case studies show the implementation of load management on gold processing plants. The three month implementation period indicated that load management was executed without negatively influencing production targets. The resultant annual cost savings amounted to R 1.4-million and R 660 000 for case study 1 and case study 2, respectively. The load management strategies were implemented without additional capital or operational expenditure. The estimated potential of load management intervention could amount to annual savings of R 25-million if the results are extrapolated for the entire South African gold processing industry.

Chapter 5.

Conclusion and recommendations

Chapter 5 compiles a conclusive discussion which reviews the key concepts, results and recommendations of the study. A final conclusion is also made on the findings of this study.

5.1. Revision of research objective

Substantial electricity cost inflation coupled with production challenges faced in the gold processing industry have prompted the investigation of electricity cost savings opportunities. It is however essential to evaluate the relevancy of these opportunities in accordance with the following considerations:

- Potential of cost savings;
- Capital expenditure required;
- Ease of implementation and operational feasibility within existing systems; and,
- Priority to production, quality and other operational targets.

The identification and subsequent implementation of cost saving opportunities will be feasible by adhering to the constraints presented by the above mentioned considerations. This study aimed to recognise and implement such opportunities by suitable analyses techniques.

5.2. Summary of findings

The first objective of this study was to identify and evaluate electricity cost saving opportunities from available literature. Key opportunities that can present substantial savings were found in the form of energy efficiency and electrical load management on processing plants. The main deterrent to such initiatives, in addition to capital costs and operational ease, is the risk associated with new concepts and technologies.

Further investigation concluded that electrical load management projects are preferred due to the relatively low inputs required. Additionally, the risk associated with load management applications can be minimised by accurate forecasting and production planning techniques. The remainder of the study was dedicated to develop a methodology specifically for gold processing plants to identify and implement load management opportunities.

The methodology was proven valuable within a control horizon of seven days given the availability of accurate ore supply forecasts. This allowed optimised utilisation of milling equipment in terms of time-of-use electricity tariffs while adhering to the production volumes required from upstream mining operations. The methodology also addressed downstream considerations by ensuring that consistent density flow to leaching and recovery processes can be maintained.

Electrical load management was subsequently implemented on gold processing plants. This study reports on two case studies where strategic load management was implemented on milling components. The case studies show that load management by production scheduling did not adversely affect the production and quality outcomes of the respective plants. In lieu, significant electricity cost savings were achieved.

The first case study on Gold Plant 1 indicated that an average of 3.6 MW peak electrical load reduction was attained. The load was shifted mostly to weekends that consist of less expensive TOU periods. This intervention resulted in a 5% reduction in the specific electricity costs of the milling section for a three month winter period.

Similar results were obtained in the second case study on Gold Plant 2. In this case peak electrical load reduction of 600 kW was achieved. The load was shifted to weekday and weekend off-peak periods. This resulted in optimised TOU utilisation that reduced the specific electricity costs of the milling section by 11% for a three month winter period.

The implementation of the load management applications did not require substantial infrastructure upgrades since essential control structures were already in place as part of normal operations planning. Load management was also proven to be a long term solution since the results represented three consecutive months of operation for both case studies. The estimated potential of load management on South African gold processing industry could amount to cost savings of R 25-million per annum.

5.3. Recommendations

During the undertaking of this study several areas of investigation could not be fully covered due to scope and time restrictions. The following recommendations are noted for further research purpose:

- The study focussed on electricity cost savings based on TOU active energy tariffs and simple payback periods. However, additional cost savings models and financing incentives can be considered to motivate the implementation of additional DSM opportunities. Areas of further investigation may include the effect DR, CDM and carbon tax on cost benefit analysis models.

- The methodology assumes that mills are operating optimally at ideal set-points. However, literature indicated that mill optimisation can significantly improve milling performance. Further research is therefore recommended to investigate how expert control systems, instead of conventional control methods, can improve electricity consumption and costs.

- Load management of process equipment can cause additional wear and tear on equipment due to increased stop-and-start cycles. Although mentioned, this study did not observe increased maintenance costs due to load management activities. A more detailed study that incorporates OEM guidelines is recommended.

- The study only proposed methods to simulate the effects of load management through production planning. A further study is proposed to develop an optimisation model that is updated with real time measurement. This will ensure more accurate production plans that will improve the implementation of load management. This can also be useful to determine a best case scenario for load management in terms of cost savings.

5.4. Final conclusion

Numerous electricity cost savings opportunities through DSM are available within the gold processing industry. However, many of the DSM opportunities require substantial capital expenditure and may be operationally intensive during implementation. It is therefore essential to analyse these opportunities to ensure it is relevant to gold processing plants.

Electrical load management provides a good opportunity to save electricity costs without substantial capital and operational inputs. The feasibility of load management is strongly influenced by ore supply dynamics, reliability of the equipment and the effective use of storage buffers. The key intervention is therefore based on accurate forecasting and subsequent production planning with the consideration of electricity usage optimisation.

The effective forecasting and planning of production operations can result in substantial electrical load being shifted to less expensive TOU periods. This can be done without compromising key production and operational targets. Ultimately, the benefit of electrical load management can be translated to a reduction in specific electricity costs.

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Appendix A: Investigation questionnaire

Appendix A presents a generic questionnaire that can be used to perform an energy audit on a gold processing plant, as illustrated in Figure A-1.

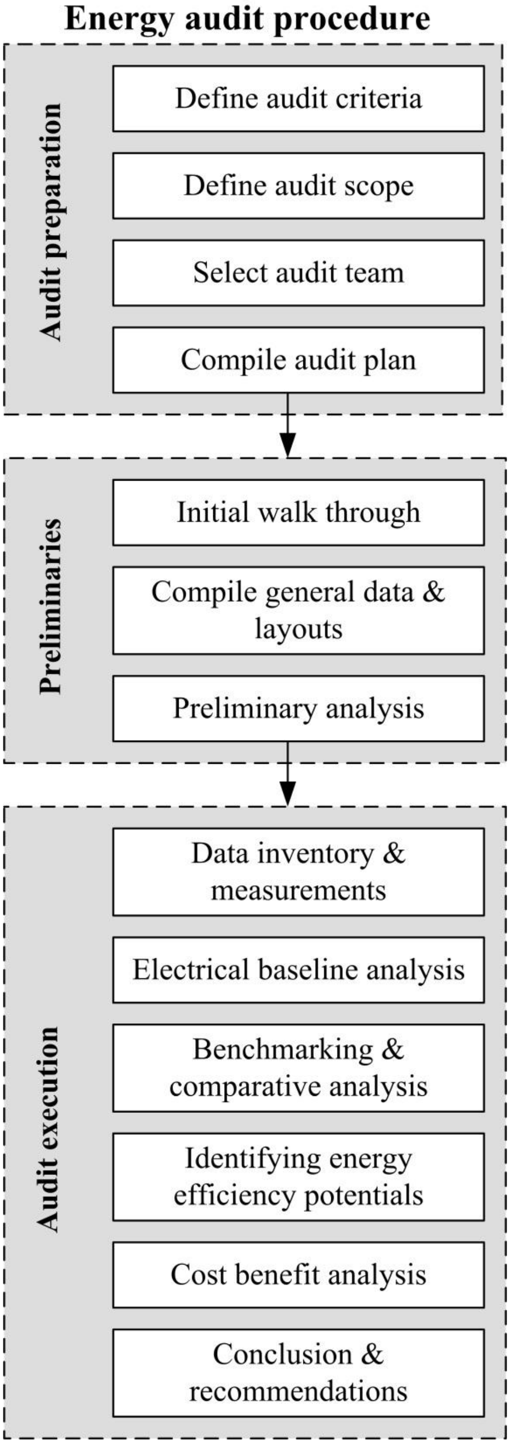

Figure A-1: Overview of industrial energy audit (adapted from [56])

A. 1. General information

Date: ______________________________

Name of plant:

Contact Person: ______________________

Job title: ____________________________

Contact details: (cell) (e-mail)

Contact Person: ______________________

Job title: ____________________________

Contact details: (cell) (e-mail)

A. 2. Basic operations

Operational capacity (tonnes/year): ______________________________
Electricity baseline (MWh/year): ______________________________
Energy sources ______________________________
Electricity supplier: ______________________________
Electricity tariff structure: ______________________________
Other fuel types: ______________________________
Current energy saving measures: ______________________________
____
____

Basic plant layout:

A. 3. Data inventories

	Ore reception and storage	**Comminution**	**Dewatering**	**Treatment & Recovery**
SCADA system available	(Yes/no)	(Yes/no)	(Yes/no)	(Yes/no)
Historic database available	(Yes/no)	(Yes/no)	(Yes/no)	(Yes/no)
Power metering	(Yes/no)	(Yes/no)	(Yes/no)	(Yes/no)
Flow rates	(Yes/no)	(Yes/no)	(Yes/no)	(Yes/no)
Storage levels	(Yes/no)	(Yes/no)	(Yes/no)	(Yes/no)
Temperature sensors	(Yes/no)	(Yes/no)	(Yes/no)	(Yes/no)

A. 4. Ore reception & storage

Capacity (tonne/month)	
Underground ore supply: Weekdays – **Saturdays –** **Sundays –**	
Surface ore supply: Weekdays – **Saturdays –** **Sundays –**	
Number of silos	
Storage capacity of silos (tonnes)	

A. 5. Comminution

Equipment	Crusher 1	Crusher 2	Mill 1	Mill 2	Mill 3	Mill 4
Type						
Installed capacity of mill motor (kW)						
Running capacity of mill motor (kW)						
Mill feed rate (tonne/h)						

Comminution (continued)

Equipment	Crusher 1	Crusher 2	Mill 1	Mill 2	Mill 3	Mill 4
Planned maintenance schedule						
Planned maintenance duration (hours)						
Weekdays running hours						
Saturday running hours						
Sunday running hours						

A. 6. Dewatering

Number of thickeners	
Thickener diameter (m)	
Settling rate (tonne/m^2/h)	
Relative Density (RD) control	(Yes/no)
Relative Density (RD) set-point	

A. 7. Downstream recovery sections

<u>Leaching circuit</u> **- CIP/CIL:** **- Number of tanks:** **- Residence time in modules:** **- Agitation (Mech./ Comp. air):** **- Number of plant compressors on plant:**	
<u>Compressors</u> **- Isolated from compressed air network (Y/N):** **- Number of compressors:** **- Installed capacity/ load (kW):**	

Downstream recovery sections (continued)

<u>Boilers</u> **- Number of boilers:** **- Fuel source:** **- Installed capacity/ load (kW):** **- Heat recovery (Yes/no):** **- Insulation (Yes/no):**	
<u>Elution</u> **- Number of columns:** **- Set-point temperature:** **- Duration of elution sequence:** **- Frequency of elution sequences:**	
<u>Regeneration:</u> **- Number of kilns:** **- Utilisation of kilns:** **- Set-point temperature:** **- Fuel source:** **- Heat recovery (Yes/no):**	
<u>Electrowinning:</u> **- Set-point temperature:** **- Heat recovery (Yes/no):**	

A. 8. Other areas of investigation

Concerns or comments

Appendix B: Megaflex TOU tariffs

Table B-1: Eskom Megaflex tariffs

Eskom Megaflex tariff						**Non-local authority**	
		Active energy charge [c/kWh] VAT excluded					
		High demand season [Jun - Aug]			**Low demand season** [Sep - May]		
Transmission zone	**Voltage**	**Peak**	**Standard**	**Off Peak**	**Peak**	**Standard**	**Off Peak**
≤ 300km	< 500V	204.55	62.23	33.97	66.98	46.22	29.46
	≥ 500V & < 66kV	201.33	60.99	33.12	65.68	45.20	28.68
	≥ 66kV & ≤ 132kV	194.96	59.06	32.07	63.60	43.77	27.77
	> 132kV	183.75	55.66	30.23	59.94	41.25	26.18
> 300km and ≤ 600km	< 500V	206.21	62.48	33.93	67.27	46.31	29.38
	≥ 500V & < 66kV	203.34	61.60	33.45	66.34	45.65	28.96
	≥ 66kV & ≤ 132kV	196.88	59.64	32.38	64.22	44.19	28.04
	> 132kV	185.58	56.22	30.52	60.53	41.66	26.43
> 600km and ≤ 900km	< 500V	208.27	63.08	34.25	67.94	46.76	29.66
	≥ 500V & < 66kV	205.38	62.22	33.79	67.00	46.11	29.25
	≥ 66kV & ≤ 132kV	198.88	60.25	32.71	64.87	44.65	28.32
	> 132kV	187.45	56.78	30.84	61.15	42.08	26.70
> 900km	< 500V	210.36	63.74	34.61	68.63	47.23	29.97
	≥ 500V & < 66kV	207.43	62.83	34.11	67.66	46.56	29.54
	≥ 66kV & ≤ 132kV	200.88	60.85	33.04	65.52	45.10	28.61
	> 132kV	189.29	57.37	31.17	61.78	42.53	27.00

Appendix C: Energy neutral assumption

During the implementation of this study the assumption was made that load management doesn't affect the energy intensity of operations. Hence the energy baselines that were used to calculate cost savings were scaled energy neutral. This appendix shows the calculations used to motivate the validity of the energy neutral assumption.

The energy intensities of the two case study gold plants were calculated by means of the specific electricity consumption (kWh/tonne) of the milling operations. This was done over a period of eight months which included the three month baseline period and three month case study period. This is illustrated in Figure C-1.

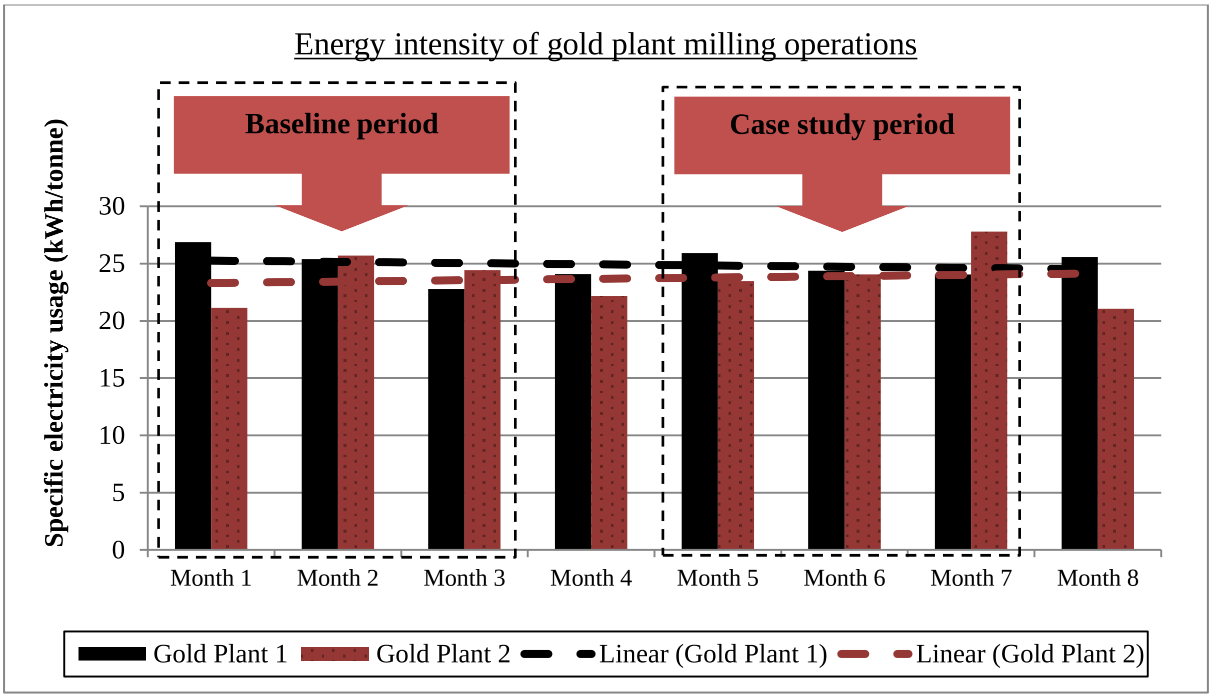

Figure C-1: Energy intensity of gold plant milling operations

It is evident from Figure C-1 that the energy intensities over the eight month period experienced some fluctuation. The fluctuation can be described by the standard deviations that amount to 1.3 kWh/tonne (Gold Plant 1) and 2.3 kWh/tonne (Gold Plant 2) for the two respective data sets. However, the difference between the baseline period and the case study period is on average 0.2 kWh/tonne (Gold Plant 1) and 1.3 kWh/tonne(Gold Plant 2) , respectively, which is lower than the respective standard deviations.

This means that the fluctuations in energy intensity cannot be exclusively attributed to the implementation of load management during the case study period. The fluctuations are rather attributed to variations that are inherent to the plant operations, such as ore quality, equipment reliability, process control, operator inputs, maintenance, etc. Table C-1 summarises the statistical references made in this section.

Table C-1: Statistical summary of energy intensity data

	Gold plant 1 (Case study 1)	**Gold plant 2 (Case study 2)**
Baseline period specific energy usage (kWh/tonne)	25.0	23.7
Case study period specific energy usage (kWh/tonne)	24.8	25.1
Difference between baseline and case study periods (kWh/tonne)	0.2	-1.3
Standard deviation over 8 month period (kWh/tonne)	1.3	2.3