The control of rock winders for maximum demand management on deep South African mines

PH Bosman

A dissertation submitted to the Faculty of Engineering
in fulfilment of the requirements for the degree

Magister Ingeneriae
in
Electrical Engineering

at the North West University, Potchefstroom Campus

Promoter: Dr MF Geyser

2006
Pretoria

ABSTRACT

Title: The control of rock winders for maximum demand management on deep South African mines
Author: Petrus Hendrik Bosman
Supervisor: Dr MF Geyser
Degree: Master of Engineering (Electrical)

In South Africa, electrical energy is taken for granted. The low electricity price has helped electricity intensive industries to be competitive. Unfortunately it has also prevented industries to become energy efficient.

During the National Electrification Programme, more than 3.1 million homes were supplied with electricity. This has mainly increased the peak demand for electricity supplied by Eskom. Projections show that peak demand will be higher than Eskom's current generating capacity by as early as 2007.

In order to curb this growth in electricity demand, Eskom launched a Demand Side Management programme in accordance with regulations drawn up by the Department of Minerals and Energy and the National Energy Regulator. The main purpose for this programme is to reduce electrical energy usage during evening peak demand times, as well as to encourage an energy efficient society.

One way of implementing this evening peak reduction is to shift the load to other times of the day. An inherent problem with this method is the possible increase of an electrical energy user's maximum demand. Such an increase could incur additional costs to an electricity user.

In order to limit this maximum demand, certain systems could be shut down when the electrical energy use is on the verge of reaching peak levels. It will be shown that rock winders are the most suitable of all the systems used on a mine to manage the maximum demand.

All underground mines make use of winders to extract excavated ore. Winder motors are usually large electrical energy consumers. As such, they provide an efficient and fast means of limiting the maximum demand. It is intended to switch off winder motors whenever the overall electricity demand of the mine reaches a peak level – as long as production is not influenced.

This system was successfully implemented at AngloGold Ashanti’s Kopanang gold mine in South Africa. During the first month of installation, the system managed the mine’s maximum demand at a level of 88 MVA. A calculated annual saving of R 137 000 was achieved, with a maximum potential saving of R 349 000.

This research showed that rock winders can be successfully used to manage a mine’s maximum demand. It can be implemented on most deep level mines that use rock winders. Suitable sites include gold, platinum and diamond mines.

SAMEVATTING

Titel:	Die beheer van rotshysers vir maksimum aanvraagbestuur op diep Suid-Afrikaanse myne
Outeur:	Petrus Hendrik Bosman
Promotor:	Dr MF Geyser
Graad:	Magister in Ingenieurswese (Elektries)

In Suid-Afrika word elektriese energie as vanselfsprekend aanvaar. Lae elektrisisteitskostes het meegebring dat elektrisiteit-honger industrieë mededingend kan wees. Dit het egter ook bygedra tot ’n laksheid in terme van effektiewe energieverbruik.

Gedurende die Nasionale Elektrifiseringsprogram is meer as 3.1 miljoen huise van elektrisiteit voorsien. Dit het hoofsaaklik die piekaanvraag vir elektrisiteit wat deur Eskom verskaf word, verhoog. Voorspellings toon dat die piek aanvraag teen 2007 hoër sal wees as wat Eskom kan voorsien.

Om hierdie groei in elektrisiteit hok te slaan, het Eskom ’n aanvraagbestuursprogram geloods in samewerking met die Departement van Energie en Mineralesake en die Nasionale Energiereguleerder. Die hoofdoel van die program is om die verbruik van elektriese energie gedurende aandpieke te verlaag, asook om ’n energiedoeltreffende samelewing te bevorder.

Die verlaging in die aandpiek kan onder andere teweeggebring word deur elektrisiteitslas te verskuif na ander tye van die dag. ’n Wesenlike probleem met hierdie metode is die moontlike verhoging in ’n elektrisiteitsverbruiker se maksimum aanvraag. Só ’n verhoging kan ekstra kostes vir ’n verbruiker beteken.

Om die maksimum aanvraag te verlaag kan sekere stelsels afgeskakel word wanneer die elektrisisteitsaanvraag dreig om 'n hoë vlak te bereik. Dit sal gewys word dat uit al die stelsels wat op 'n myn gebruik word, rotshysers die beste gepas is om die maksimum aanvraag te beheer.

Alle ondergrondse myne maak gebruik van rotshysers om die ontginde erts na die oppervlak te bring. Die rotshysermotors is normaalweg van die grootste elektrisiteitsverbruikers op 'n myn. Dit verskaf dus 'n vinnige en effektiewe uitweg om die maksimum aanvraag te beperk. Daar word beoog om die rotshysermotors stil te laat staan wanneer die myn se algehele elektrisiteitsverbruik te hoog is – solank produksie nie beïnvloed word nie.

Die stelsel is suksesvol implementeer op AngloGold Ashanti se Kopanang goudmyn in Suid-Afrika. Gedurende die eerste maand wat die stelsel installeer is, is die myn se maksimum aanvraag op 88 MVA beheer. 'n Berekende jaarlikse besparing van R 137 000 is bereik, met 'n moontlike maksimum besparing van R 349 000.

Die navorsing het getoon dat 'n myn se rotshysers suksesvol gebruik kan word om die maksimum aanvraag te beheer. Die stelsel kan op die meeste diep myne gebruik word wat rotshysers gebruik. Dit sluit goud-, platinum- en diamantmyne in.

TABLE OF CONTENTS

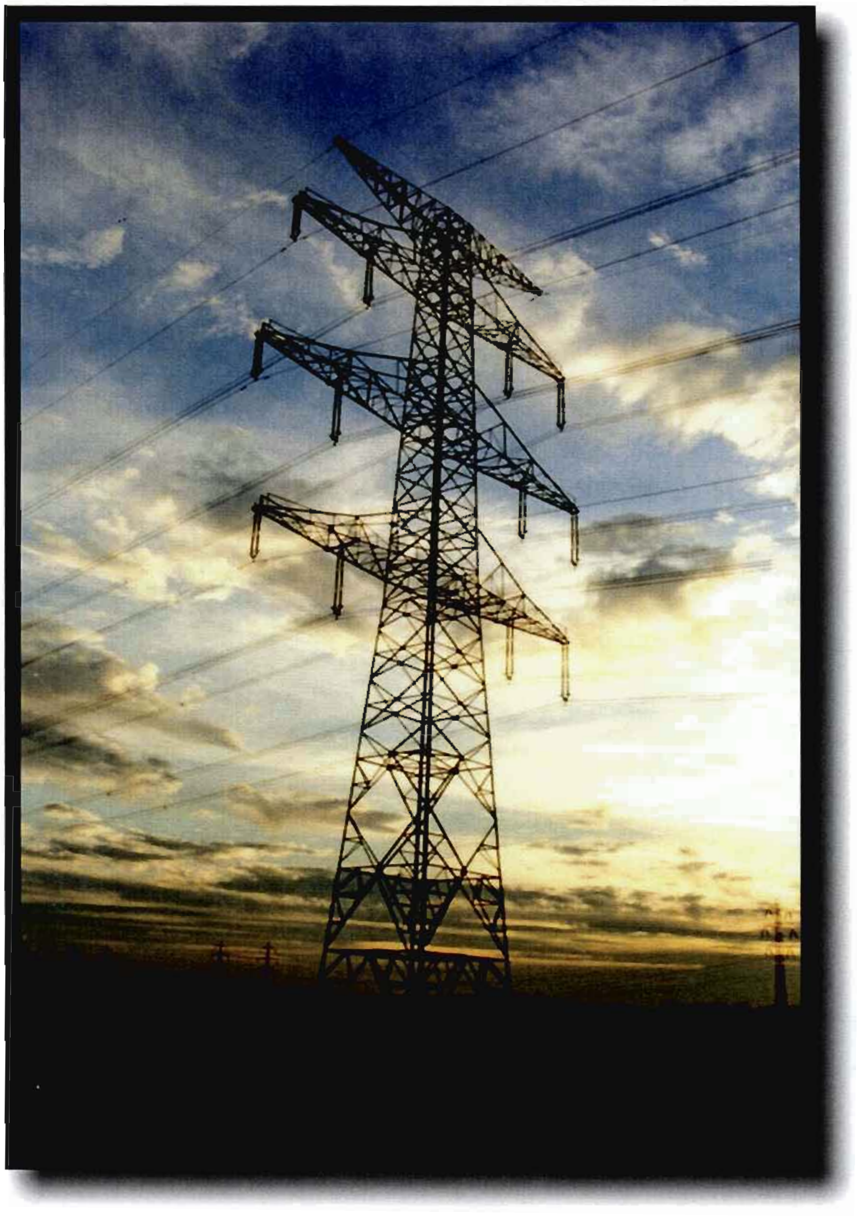
LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ANN	Artificial Neural Network
AUC	Annual Utilised Capacity
DME	Department of Minerals and Energy
DSM	Demand Side Management
IRP	Integrated Resource Plan
MD	Maximum Demand
kVA	Kilovolt ampere
kVAh	Kilovolt ampere-hour
kW	Kilowatt
kWh	Kilowatt-hour
MD	Maximum Demand
MVA	Megavolt ampere
MUC	Monthly Utilised Capacity
MW	Megawatt
NER	National Energy Regulator
NIRP	National Integrated Resource Plan
NMD	Notified Maximum Demand
OLE	Object Linking and Embedding
OPC	OLE for Process Control
PLC	Programmable Logic Controller
RTP	Real-Time Pricing
SCADA	Supervisory Control And Data Acquisition
TOU	Time-of-use
UC	Utilised Capacity

CHAPTER 1: INTRODUCTION TO THE SOUTH AFRICAN ELECTRICITY PROBLEM



1.1 BACKGROUND ON THE ELECTRICITY SITUATION IN THE RSA

Electrical energy needs are growing all over the world [1]. Emerging economies such as India, China and Korea have significant heavy industries, which are inherently electricity intensive. The same situation exists here in South Africa, but is augmented by the electrification of housing in rural areas during the National Electrification Programme (NEP). This is part of the Reconstruction and Development Programme (RDP) which targeted 3 million new household connections from 1994 to 2000 [2]. Eskom and local governments were able to supply new electricity connections to more than 3.1 million households during this period, (See Figure 1).

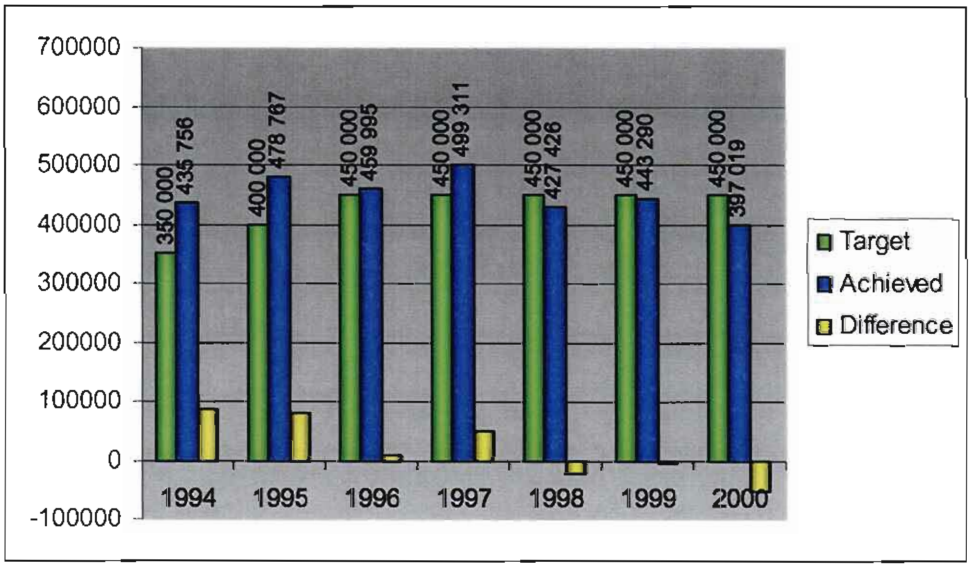


Figure 1: *Electrification targets and connections made from 1994 to 2000 [1]*

A direct result of this electrification is that Eskom is now close to the point where it cannot supply the required electricity during peak periods anymore.

While Eskom is struggling to supply electricity to South Africa, as well as to some other parts of Africa, it is predicted that their reserve generating capacity will be reduced to lower than safe limits by 2007 (see Figure 2) [3], [4]. Serious black-outs in the Western Cape during the winter of 2006, caused by the problem with the Koeberg power station, are early signs of Eskom's pending capacity crisis [5], [6].

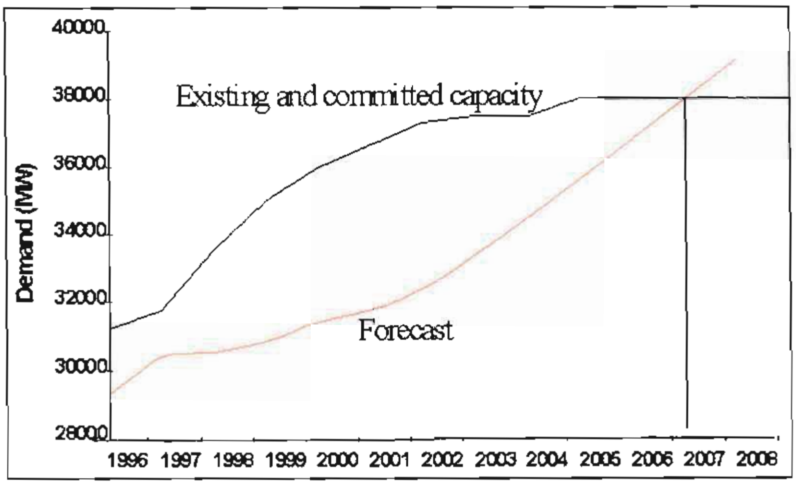


Figure 2: *Eskom Capacity Status and Maximum Demand Forecast [3]*

South African electricity demand is currently estimated to be growing at 1 000 MW per year [7]. Generating capacity totals 37 056 MW and surplus capacity is expected to run out during peak demand periods in 2007, followed by the base load in 2010 [8].

Although the housing sector is one of the largest electricity users in the country (17% of the total consumption [7]), it is difficult and expensive to implement energy efficiency schemes on such a large scale. There are simply too many homes to make a significant difference in time for the problem facing us in 2007.

Figure 3 is a dissection of the main electricity users in the country. Each sector's usage is indicated by a percentage value to compare them with the total electricity demand.

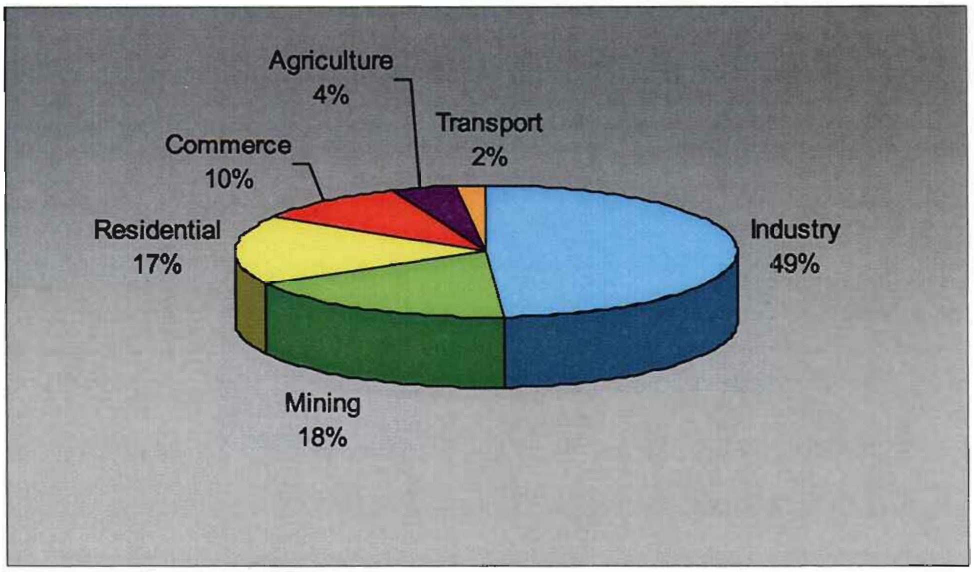


Figure 3: *Electricity consumption per sector (2003) [7]*

Mining plays a large role in the South African industry, contributing 6.6% to South Africa's gross domestic product (GDP) in 2004 [9]. Indirect multiplier effects, such as transport and power generation, increase the contribution of mining GDP to 16% [9].

The Johannesburg Stock Exchange (JSE) has a large mining component, accounting for 35.3% of R 534 billion of the market capitalisation for 2004. Mining contributed to R 90.3 billion in exports, representing a total of 29.3% of South Africa's total merchandise exports. It was thus the foremost user of South Africa's railways and ports, moving 98.9 million tons of ore. This represents 53% of Transnet's volume of transport in 2003 [9].

South African gold mines were in a crisis and some were on the brink of closing down due to the impact of the strong rand and rising input costs. In 2004, the gold sector's production dropped by 7.2%. On average, 450 000 workers were directly employed during 2004, with an estimated 200 000 workers employed in related industries. Almost 6 million people are directly dependent on mining for their daily survival [9].

Significant infrastructure development in South Africa is a direct result of the mining industry [9]. This includes 3 000 km of railway line, three ports and a large amount of bulk handling infrastructure at other ports, as well as social infrastructures such as clinics, schools and social facilities.

Mines play a major role in the South African economy and infrastructure – it would be disastrous if they had to close down. There is therefore continuous pressure to increase production while decreasing cost. This can be seen from the great number of companies that signed the Energy Efficiency Accord in 2005 [10], [11].

1.2 THE NEED FOR DEMAND SIDE MANAGEMENT (DSM)

The term Demand Side Management was first used during the 1970's in the United States of America. DSM is described as the "*planning and implementation of utility activities designed to influence the time, pattern and/or amount of electricity demand in ways that would increase customer satisfaction, and co-incidentally produce desired changes in the utility's load-shape*" [12]. It is therefore beneficial to both the customer and the electricity utility. Eskom formally recognised DSM in 1992, but the first plans were only introduced during 1994 [12].

DSM initiatives are possible owing to the fact that electricity usage is not a flat value throughout the day. The use of electricity varies drastically, depending on the time of the day, as well as factors such as the day of the week, office hours, temperature and seasonal changes (see Figure 4 and Figure 5).

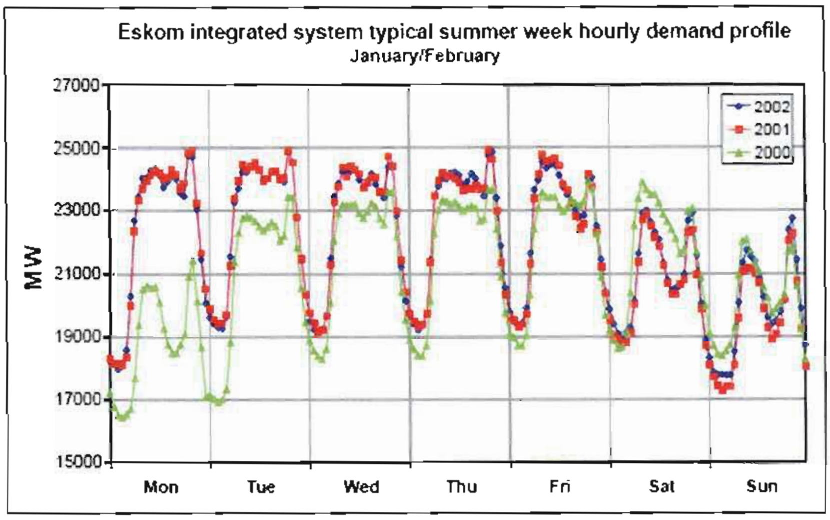


Figure 4: *Summer week hourly demand profile [13]*

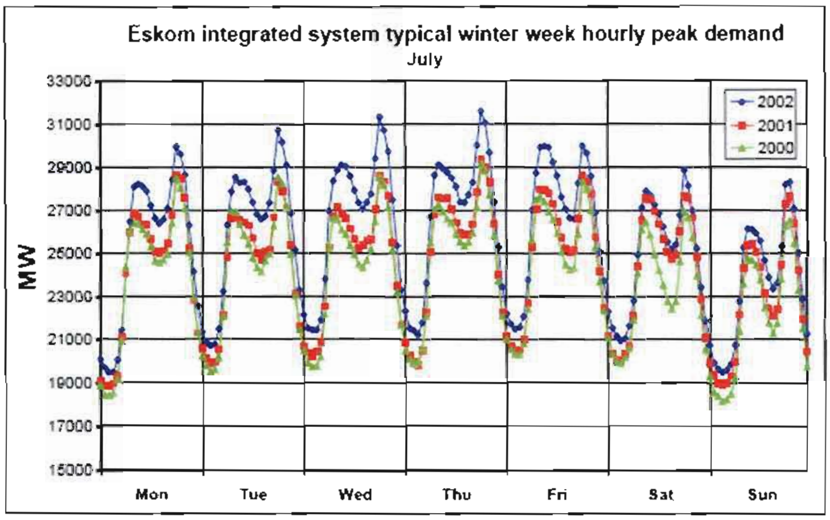


Figure 5: *Winter week hourly demand profile [13]*

The above graphs illustrate clearly that winter demand is much higher than summer demand. It is also clear that the weekend demand is lower than that of weekdays, with Sundays being the lowest. In addition there are two peaks per day – a lower, longer peak in the mornings and a higher, shorter peak in the evenings.

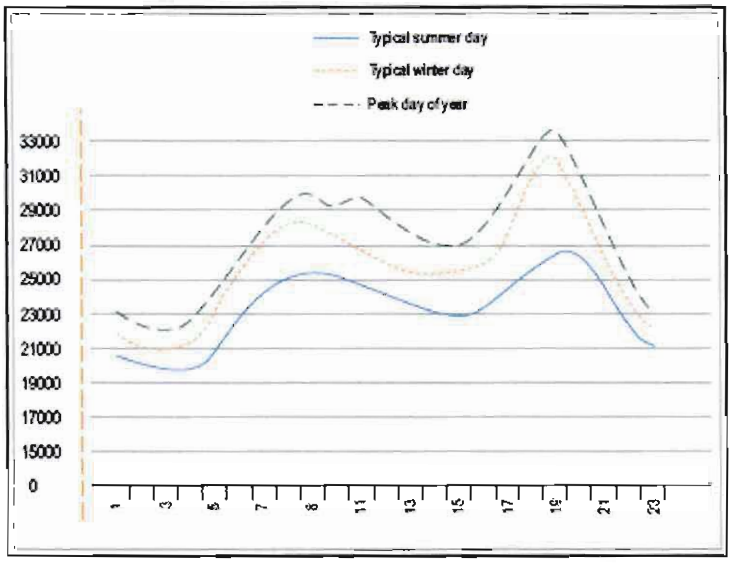


Figure 6: *Daily demand profile [14]*

Figure 6 shows peak demand times. The lower, longer morning peak is from 07:00 to 10:00 and the higher, shorter peak from 18:00 to 20:00.

In the Department of Minerals and Energy's (DME) *White Paper on Energy Policy* [15], their *Energy Efficiency Strategy* [16] and the National Energy Regulator (NER) of South Africa's *Energy Efficiency and Demand Side Management Policy* [17] Eskom is advised on their strategic necessities regarding the DSM programme. The *White Paper* identifies energy efficiency as one of the areas that urgently needs to be developed and promoted.

An Integrated Energy Plan for the Republic of South Africa [18], developed by the DME, presents a structure within which energy development planning and decisions can be made. This policy provides for the development of a National Integrated Resource Plan (NIRP) that is compiled annually for a forecast perspective of 20 years. Eskom also conducts its own Integrated Energy Plan (IEP), which estimates the increase in electricity demand for a forecast period and decides on how best to meet that demand.

DSM intervention mechanisms can generally be broken down into four broad categories. These are load shifting (Figure 7), strategic load growth (Figure 8), energy efficiency (Figure 9) and interruptibility (Figure 10).

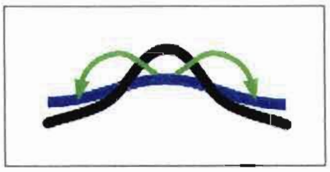


Figure 7: *Load shifting*

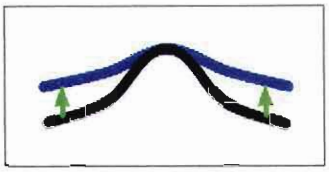


Figure 8: *Strategic load growth*

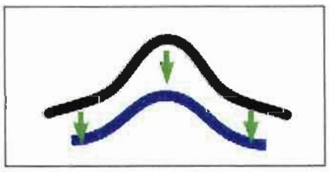


Figure 9: *Energy efficiency*

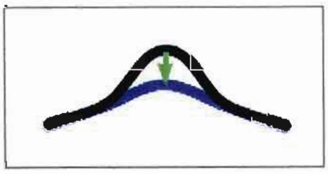


Figure 10: *Interruptibility*

- **Load shifting** involves the revising of the time at which a customer uses electricity. This is achieved with the aid of price-based incentives such as time-of-use (TOU) tariffs and real-time pricing (RTP).
- **Strategic load growth** is used by utilities that have surplus power. Additional electricity sales are created with regard to the time of the day.
- **Energy-efficiency** involves conversion to more efficient end-use technologies and practices. This is beneficial for both the customer and the utility.
- An **interruptible load agreement** allows a utility to cut the power to a portion of the customer's site for a limited period. The customer is compensated for this interruption.

It would be beneficial to mines, Eskom and South Africa as a whole if the mines reduce their operating costs. Mines are a significant user of electricity as supplied by Eskom (18% of the total South African consumption [7]). This makes them an ideal target for the implementation of energy efficiency schemes, such as Demand Side Management (DSM).

South African mines save millions of rand each year as energy efficiency projects, sponsored by the DSM programme, are implemented. One of these mines is AngloGold Ashanti's Kopanang gold mine in the North West Province, which saves approximately R 300 000 per year by pumping water during off peak hours [19]. A projection done for Harmony Gold shows a combined potential savings of 15 MW shifted out of the evening peak demand period – a saving equivalent to R 1.5 million per year [19].

These savings are possible thanks to price-based incentives such as time-of-use (TOU) tariffs. Eskom has three urban tariffs to facilitate DSM. These are Nightsave, Megaflex and Miniflex.

- Nightsave is intended for urban customers with a notified maximum demand (NMD) of at least 25 kVA
- Megaflex for urban customers with an NMD of at least 1 MVA
- Miniflex for urban customers with an NMD of 25 kVA – 5 MVA

Most mines, including Kopanang which was chosen for the case study, are on the Megaflex tariff structure. It is now outlined for illustrative purposes. This tariff is characterised by:

- Seasonally and time distinguished active energy charges
- Three time periods (peak, standard and off-peak)
- A network access charge (NAC), applicable during all time periods
- A network demand charge (NDC), applicable during peak and standard periods
- No electricity demand charge

The NAC is R5,91 + VAT = **R6,74** for each kVA based on the annual utilised capacity (AUC) per premise per month. The NDC for the 2006/07 season is R6,69 + VAT = **R7,63** for each kVA of the chargeable demand supplied during peak and standard periods per premise per month.

The active energy charges are outlined in Table 1, with the Megaflex time periods shown in Figure 12.

Table 1: *Megaflex active energy charges*

High-demand season (June – August)		**Low-demand season (September – May)**
52,22c + VAT = **59,53c/kWh**	**Peak**	14,82c + VAT = **16,89c/kWh**
13,81c + VAT = **15,74c/kWh**	**Standard**	9,20c + VAT = **10,49c/kWh**
7,51c + VAT = **8,56c/kWh**	**Off-peak**	6,52c + VAT = **7,43c/kWh**

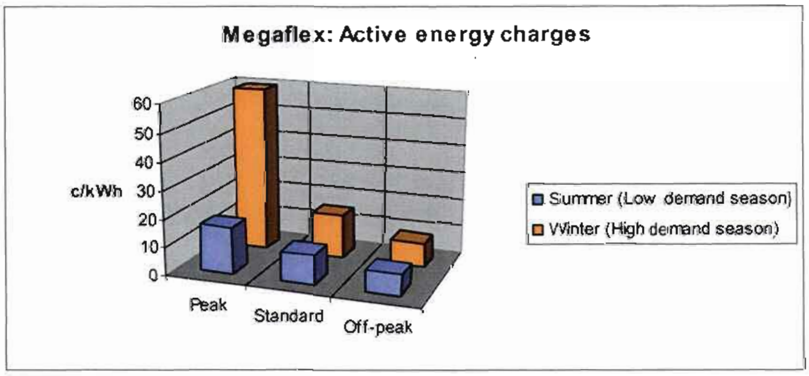


Figure 11: *Megaflex active energy charges*

It is clearly seen from the tariffs in Table 1 and Figure 11 that demand is the highest during peak times in the winter months (June, July and August). The high-demand season's peak tariff is more than 3.5 times higher than the tariff of the low-demand season, compared to the standard and off-peak periods that are respectively 1.5 and 1.1 times higher.

This is an obvious indication that a supply problem exists during the high-demand peak periods. Eskom's electricity is more expensive during these times, as they have to use power stations with a higher running cost, such as gas-based generators. The base load is generated using low-cost coal power stations.

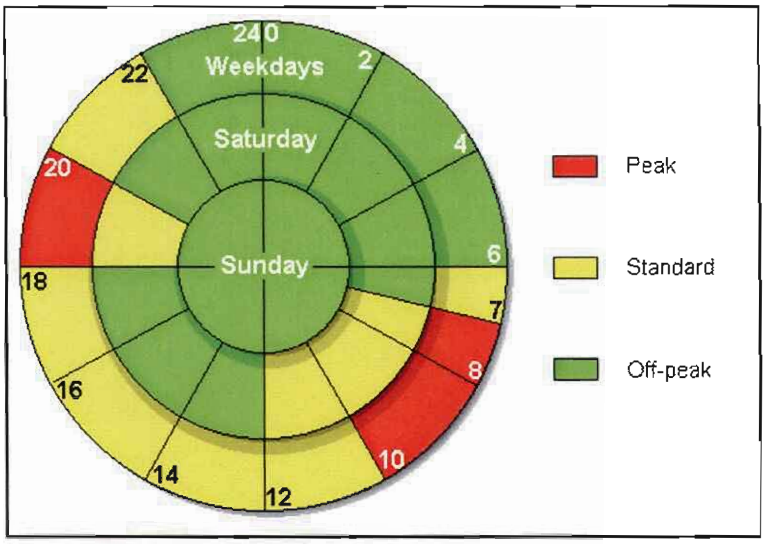


Figure 12: *Megaflex time periods*

The times of peak, standard and off-peak periods are indicated in Figure 12. The only peak periods are during weekdays (7:00 – 10:00 and 18:00 – 20:00). Sunday is an off-peak period for the entire day.

A voltage surcharge is also levied as a percentage of the network demand, network access and active energy charges. This percentage depends on the supply voltage. A transmission surcharge and a rate-rebalancing levy are also payable, but these charges are not affected by the NMD.

Quite a few DSM projects have already been implemented in South African mines [19]. Some of these projects make use of load shift, where electricity usage is shifted out of the daily peak times. Due to this shift of electricity usage into other times of the day, new peaks are created, which could result in the specific mine having a higher maximum demand (MD). This effect is illustrated in Figure 13.

One problem of a higher MD, as illustrated in Figure 13, is a rise in electricity costs for a 12 month period. This is discussed in detail in the next section.

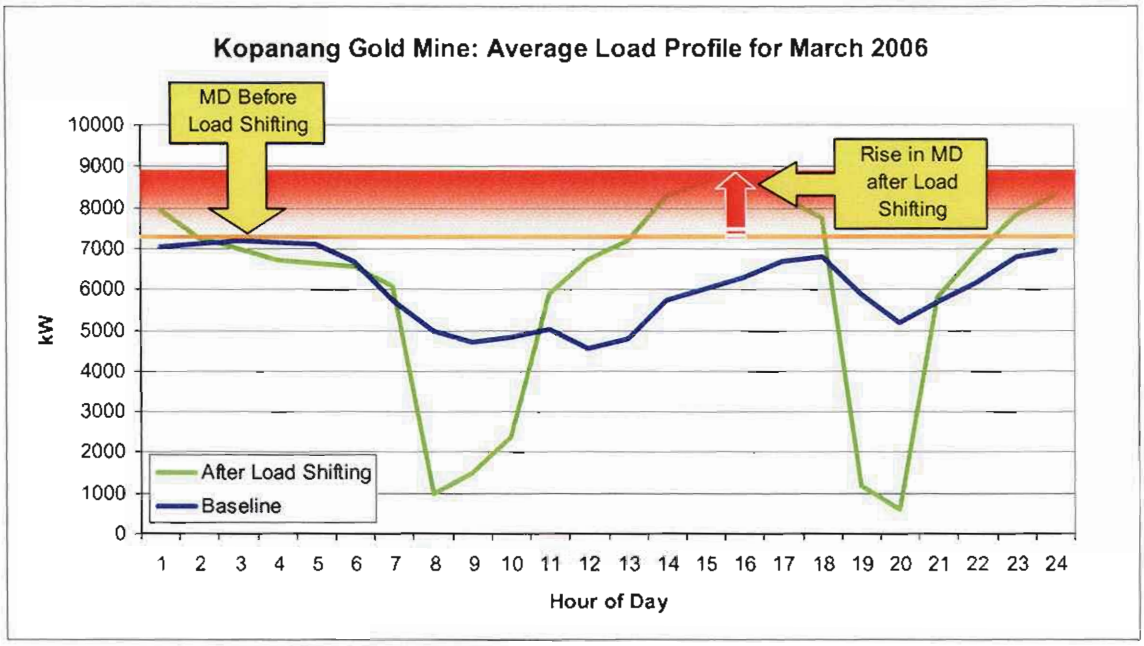


Figure 13: *Case study of Kopanang gold mine's pumping load profile*

1.3 PROBLEMS WITH MAXIMUM DEMAND (MD)

According to rules set by Eskom, electricity consumers whose electricity supplies are higher than 60 A 400 V (3-phase) are required to pay a network access charge during all time periods, as well as a network demand charge during peak and standard periods.

These consumers also have to specify a notified maximum demand (NMD), which is the MD notified in writing by the consumers and accepted by Eskom. The consumer expects Eskom to be in a position to supply this MD on demand during all time periods. It is normally the capacity that Eskom will reserve for a customer for the short term, i.e. the following year [20].

The NMD is non-simultaneous maximum demand in kVA for every point of delivery Eskom is contracted to supply during all time periods, measured in 30 minute integrated periods. In cases where a customer has multiple points of delivery, the NMD will be vectorially summed for each point of supply.

A customer's utilised capacity (UC) is applicable to the network access charges. In respect of a relevant point of delivery, this is the maximum value between:

a) the highest of the recorded maximum demand in all time periods, vectorially summed at the point of supply, or

b) the contracted NMD.

Where (a) is the highest due to an unusual occurrence, certain exemptions are applicable. These exemptions are explained in clause 5, *Exemption for increase in utilised capacity or chargeable demand*, of Eskom's NMD rules [21].

A higher MD, as described in Figure 13 above, means the mine has to increase their NMD with Eskom for the following twelve month period [21]. Therefore, the mine has to pay more on their electricity bill (see Figure 14 and Table 2).

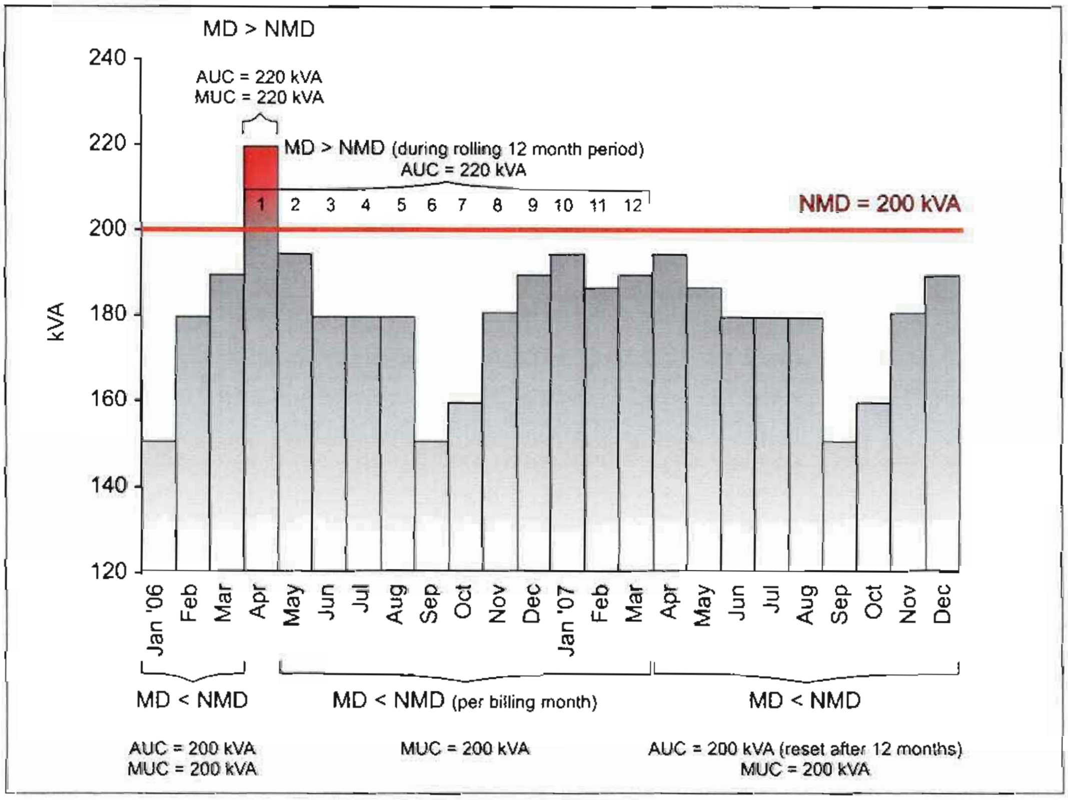


Figure 14: *Illustration of monthly (MUC) and annual utilised capacity (AUC)*

In the illustration of the monthly and annual utilised capacity (Figure 14), both the AUC and MUC were 200 kVA in January 2006. It's also seen that the MD (220 kVA) was higher than the NMD (200 kVA) during April 2006. The MUC and AUC were therefore increased to 220 kVA for April 2006. In May 2006, the MUC was reset to the NMD of 200 kVA, as the MD of 195 kVA was lower than the NMD. The AUC however stays at 220 kVA for a rolling 12 month period. It will only reset again in April 2007.

Table 2: *Illustration of monthly and annual utilised capacity*

Month	**MD (kVA)**	**NMD (kVA)**	**Comments**	**MUC (kVA)**	**AUC (kVA)**
January 2006	150	200	NMD is higher than MD for billing month and over a rolling 12 month period	200	200
February 2006	180	200			
March 2006	190	200			
April 2006	***220***	***200***	***MD is higher than NMD***	***220***	***220***
May 2006	195	200	NMD is higher than MD for billing month – the MUC is therefore reset MD registered in April 2006 is higher than NMD over a rolling 12 month period – AUC remains at higher level	200	***220***
June 2006	180	200			
July 2006	180	200			
August 2006	180	200			
September 2006	150	200			
October 2006	160	200			
November 2006	180	200			
December 2006	190	200			
January 2007	195	200			
February 2007	185	200			
March 2007	190	200			
April 2007	195	200	NMD is higher than MD for billing month and over a rolling 12 month period; MD registered in April 2006 is no longer applicable – AUC is reset	200	200
May 2007	185	200			
June 2007	180	200			
July 2007	180	200			
August 2007	180	200			
September 2007	150	200			
October 2007	160	200			
November 2007	180	200			
December 2007	190	200			

Table 2 provides a detailed description of the effect the MD and NMD have on the AUC and MUC. The values used are the same as those in Figure 14.

1.4 PURPOSE OF THIS RESEARCH

The objective of this research is to develop a system that can manage a mine's MD below a specified level. This would be done in harmony with other DSM activities. An increase in MD would result in increased costs to the mine for a twelve month period effective from the month the increase occurred.

Winders prove to be the best suited for controlling the MD. The winder motors have a high installed capacity, can be stopped quickly to lower electricity use and are easy to control via the mine's Supervisory Control and Data Acquisition (SCADA) system. The winder motor is also designed to cycle frequently – an attribute that is critical in MD management.

It should be emphasised that winders are directly linked with production of the mines. If the winders are stopped when silo levels are low, waste (rock that does not contain gold or other minerals) has to be added to the plant to keep it running. This would lower the grade of the ore and therefore decrease the mine's production.

There is also an opportunity to *lower* the NMD as well as AUC, as defined in the previous section. This possibility depends on the load the winders can shed combined with production targets. If the production targets are very high, or if the size of the load that the winders can shed is too small, the winders alone would not be able to lower the NMD.

1.5 OUTLINE OF THIS DOCUMENT

An introduction to the South African electricity situation is provided in Chapter 1. Research on maximum demand is done, presenting the cause and consequences of MD. The viability of certain mine systems to manage MD is briefly considered.

Various systems are researched in Chapter 2 and compared for MD management potential. MD conditions are investigated on AngloGold Ashanti's Kopanang gold mine. The effects of controlling different systems are evaluated for potential savings.

MD control in South African mines is discussed in Chapter 3. This includes the mining process, the usage of winders for MD control and the potential for maximum demand management.

In Chapter 4, a new MD controller is researched. This incorporates development principles, the implementation of MD control on winders and simulated results.

A case study on possible savings is done at Kopanang gold mine in Chapter 5. Results attained with the implementation of the new MD controller as well as problems encountered and expected results are reviewed.

CHAPTER 2: RESEARCHING VARIOUS SYSTEMS FOR MD MANAGEMENT

2.1 PREAMBLE

DSM schemes that make use of load shifting techniques could cause a rise in the mine's MD. This is illustrated in Chapter 1's Figure 13. The problem with a rise in MD can consequently be nullified if the scheme is controlled in such a way as to manage the MD while performing normal load shifting operations.

Some of the DSM ventures at the mines include lighting, pumping systems, fridge plants, compressed air and winders. As these systems would have the necessary infrastructure for automatic control, additional installations will not be needed for MD management.

The possibility of MD control on these systems is discussed in the course of the chapter. Their influence on a mine's MD is assessed, as well as the results achievable when they are used for MD management.

2.2 INVESTIGATING MD CONDITIONS

A study was done at AngloGold Ashanti's Kopanang gold mine to ascertain the influences that various systems would have on the MD. Data for this investigation was obtained from AngloGold Ashanti's Vaal River control room.

Plotting a graph of the mine's total demand for one month gives a clear indication of areas where there might be a problem with the MD. These areas can be examined to find the time of day when there is a problem.

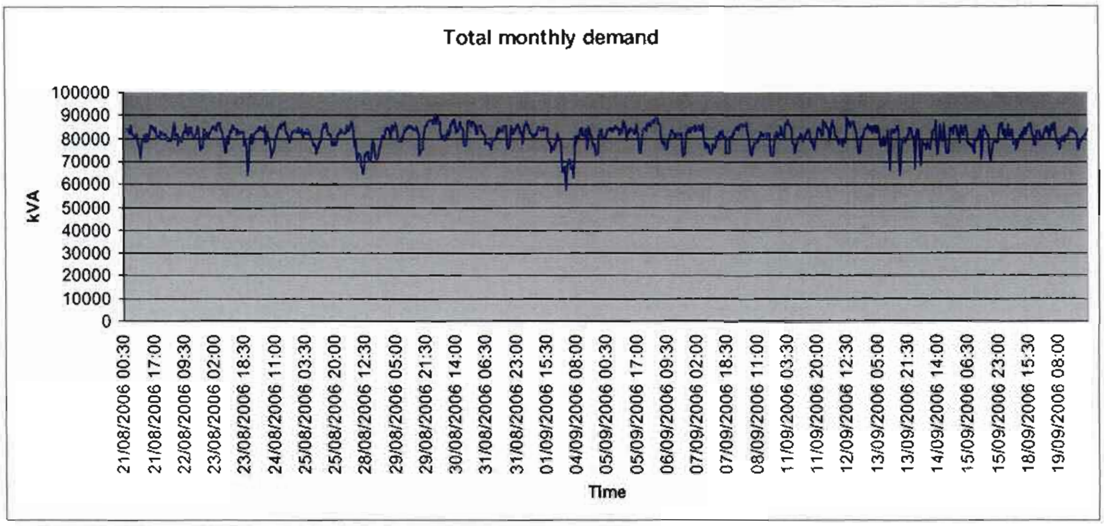


Figure 15: *Total monthly demand (21 August 2006 – 20 September 2006)*

The values of Figure 15 are obtained by summing the electricity demand of all the components on the mine. Separate peaks are not clearly visible in this graph. The graph is scaled in order to clarify the peaks. Figure 16 shows this scaled graph.

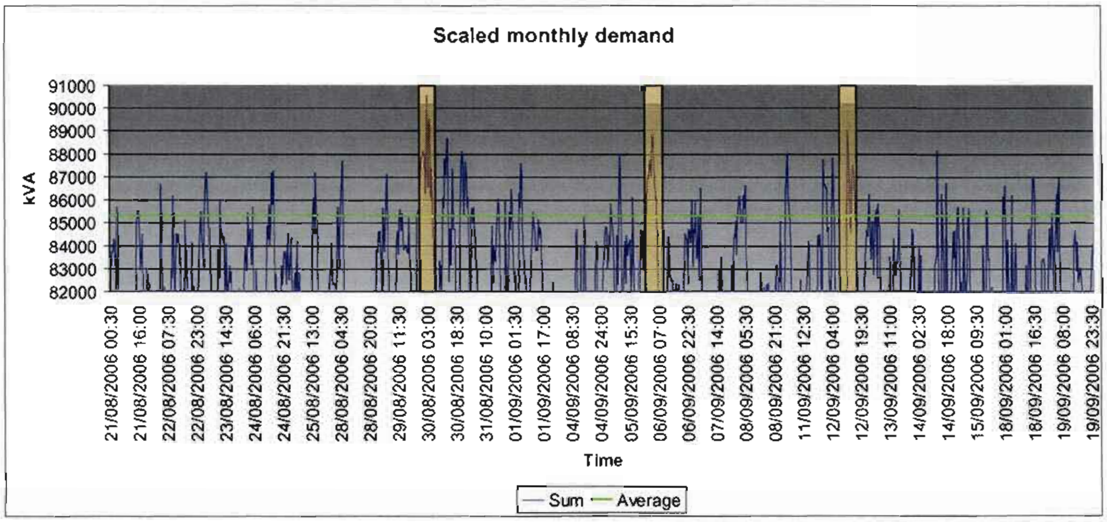


Figure 16: *Scaled total monthly demand*

The peaks in the scaled graph of Figure 16 are now much easier to see. The y-axis is scaled to a minimum value that is equal to the average of the month's data points. A new average is obtained to find the deviation of the peaks. This average is shown in green. The three highest peaks are highlighted in Figure 16. These peaks are 4 000 kVA – 6 000 kVA higher than the monthly peak average.

Figure 17, Figure 18 and Figure 19 show the days where the highlighted peaks of Figure 16 occurred. These profiles include the average for the specific day.

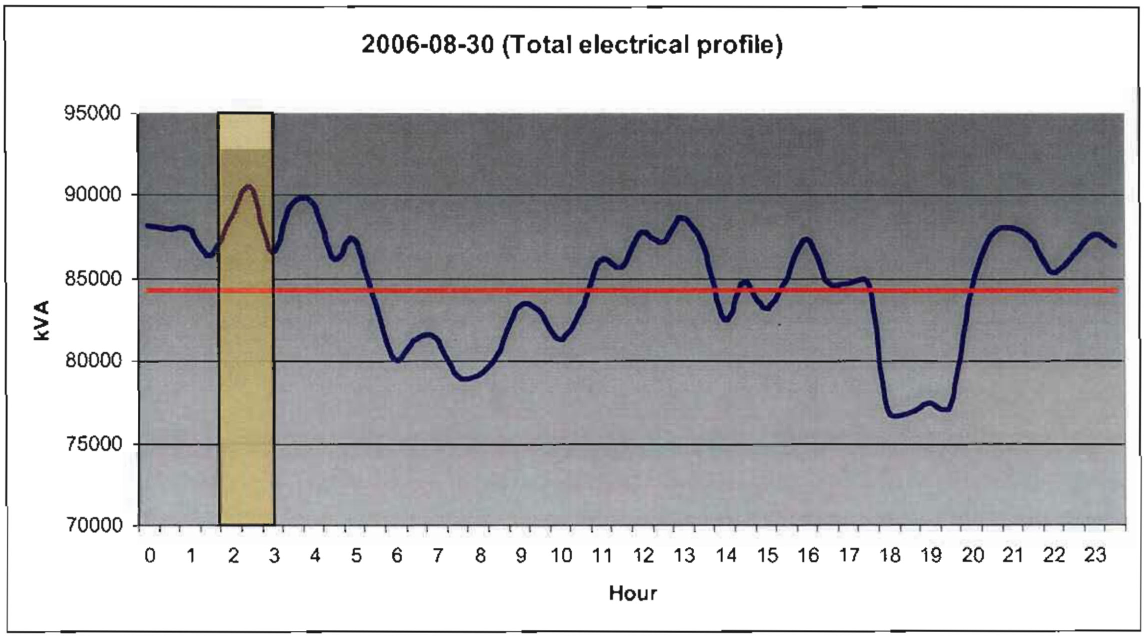


Figure 17: *Total electrical profile of Kopanang on 2006/08/30*

The highlighted area in Figure 17 shows the highest peak that occurred on 2006/08/30. This peak occurred around 02:00. The other peaks, such as the one around 04:00, were not investigated, as they are lower than the highlighted one. Only the highest peak would influence the maximum demand – as explained in Section 1.3.

Figure 18 and Figure 19 show the peaks for 2006/09/06 and 2006/09/12 respectively. As in Figure 17, the highlighted peaks are not necessarily the only peaks – they are merely the highest ones.

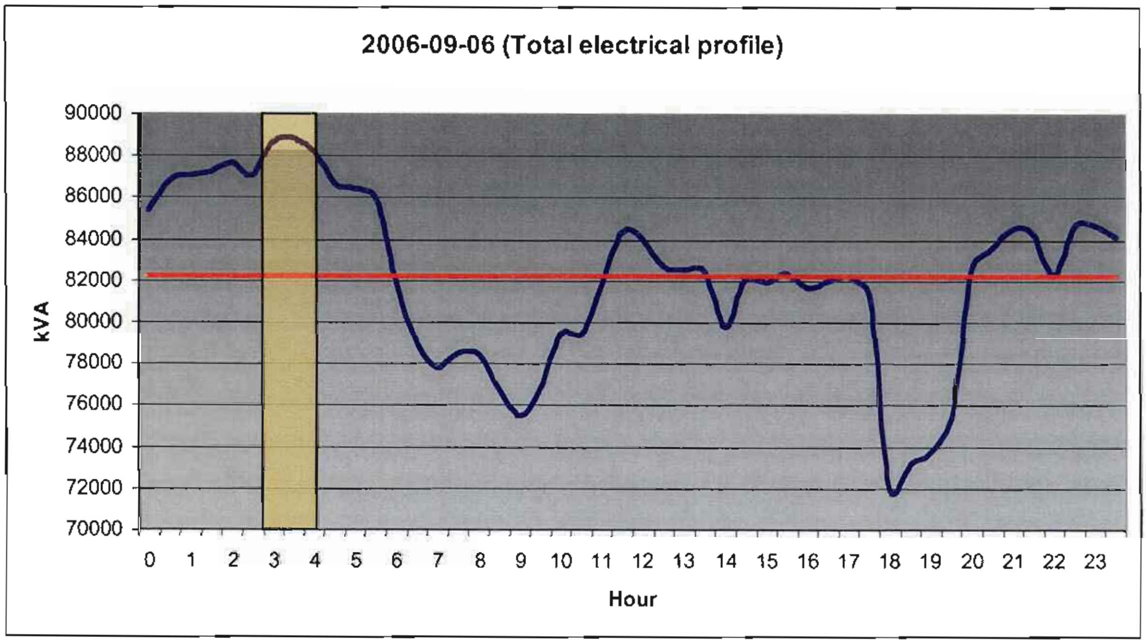


Figure 18: *Total electrical profile of Kopanang on 2006-09-06*

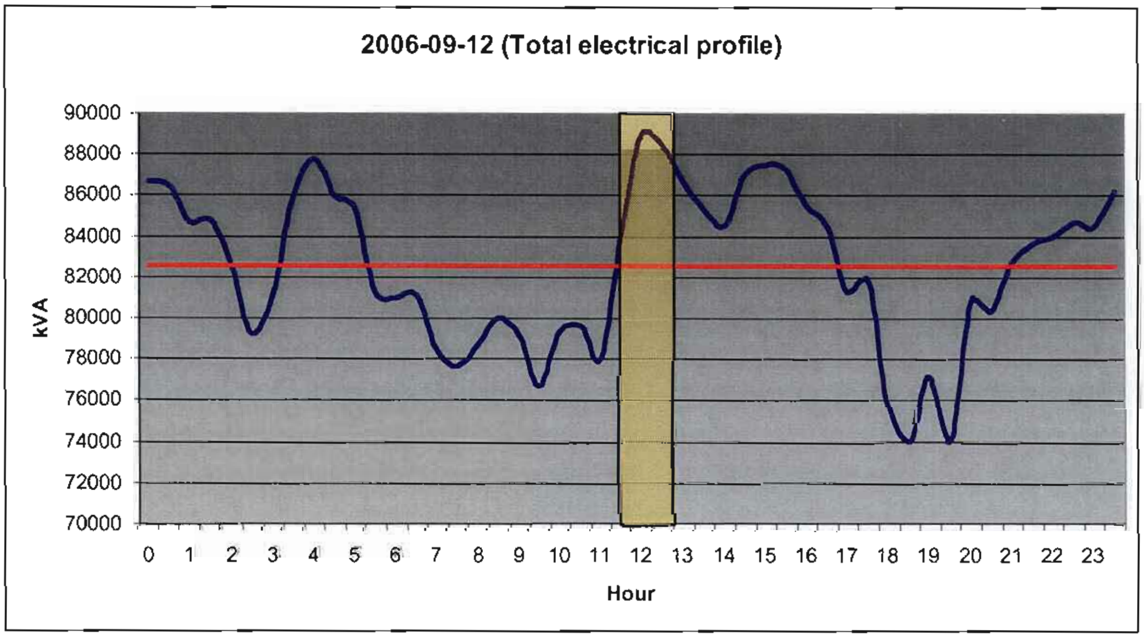


Figure 19: *Total electrical profile of Kopanang on 2006-09-12*

It can be seen from Figure 17, Figure 18 and Figure 19 that the peaks are not bound to a particular time of day. The reason why a peak occurs needs to be investigated further. Comparing the electrical profiles of different systems on a mine could give an indication why peaks might occur.

2.3 COMPARISON OF DIFFERENT SYSTEMS

By plotting graphs of the individual electricity consumers, it can be established which system could cause peaks. As an example, Kopanang's main fans (see Figure 20) and pumping system (see Figure 21) are compared.

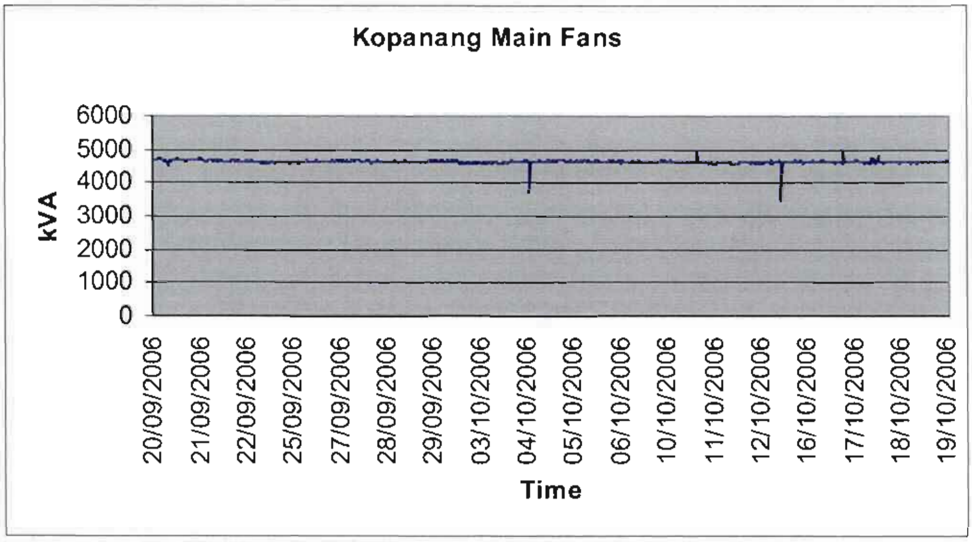


Figure 20: *Kopanang's main fans profile*

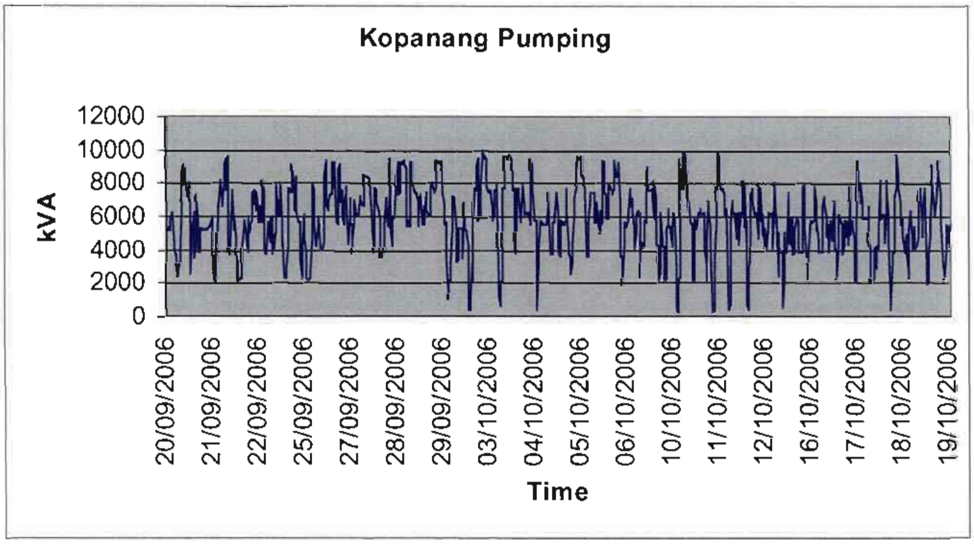


Figure 21: *Kopanang's pumping profile*

It can be seen in Figure 20 that the main fans don't cause large and frequent peaks – the electricity profile is reasonably constant. The profile of the pumping system, in contrast with the fans' profile, has many peaks throughout the month. It can therefore be presumed that the pumping system contribute to the peaks encountered in Figure 16.

Repeating this process for the other systems, it can be concluded that the following systems contribute to the peaks of Figure 16:

- Pumping
- Refrigeration
- Rock winding
- Man winding

Of these, only the pumps, fridge plants and rock winders can be controlled for electricity management. Control of the man winders would be too much of a logistical problem, as shift changes would have to be changed to coincide with Eskom's peak times.

The total daily profiles of Figure 17, Figure 18 and Figure 19 are now investigated in detail. Each day's pump, fridge plant and rock winder profile is examined to find a reason for the peaks. These three separate profiles for Figure 17 are shown in Figure 22, Figure 23 and Figure 24.

The highlighted times in Figure 22, Figure 23 and Figure 24 are the same as in Figure 17. This gives a clear indication of the time where the peak occurred on 2006/08/30.

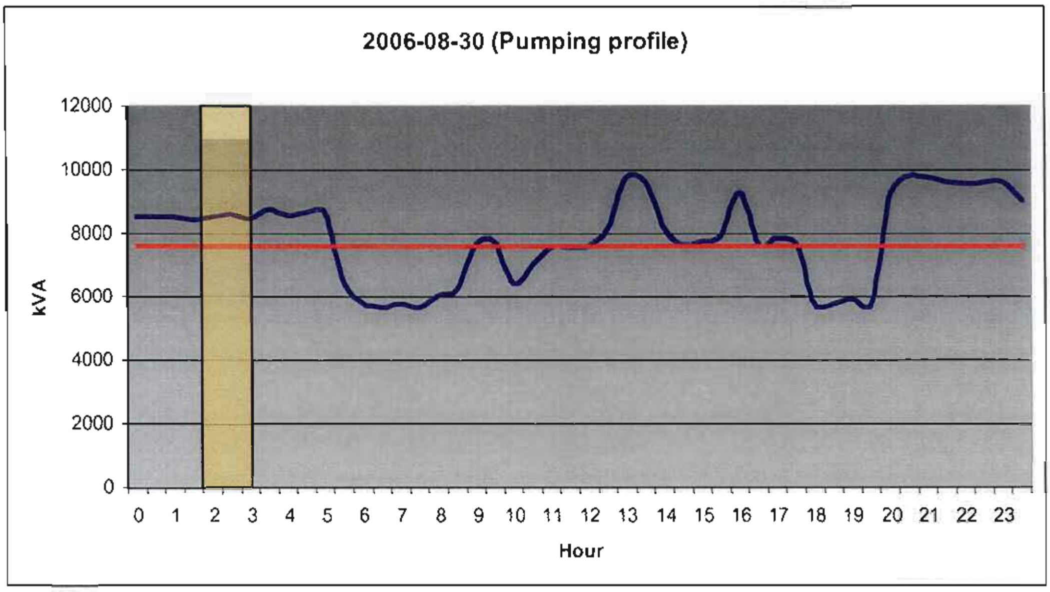


Figure 22: *Kopanang's pumping profile on 2006-08-30*

Figure 22 shows the pumping profile of Kopanang on 2006/08/30. Although the electrical demand is more than 8 000 kVA, the graph shows that there is not a peak during the highlighted time – the demand is close to the average pumping load. It can therefore be deduced that the pumping system did not contribute that much to the peak of Figure 17.

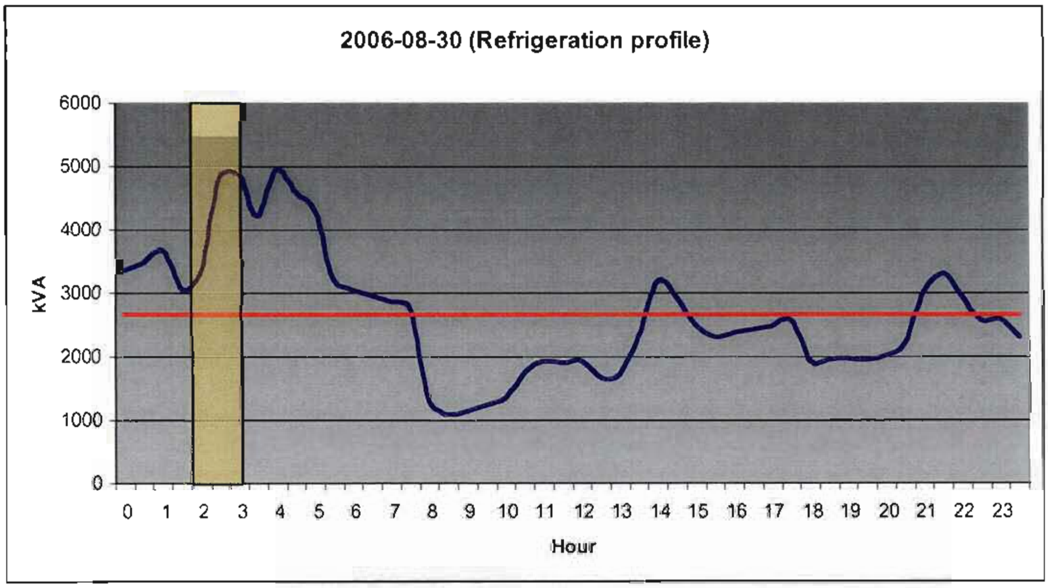


Figure 23: *Kopanang's refrigeration profile on 2006-08-30*

The refrigeration profile is shown in Figure 23. There is a peak during the last part of the highlighted time. The fridge plants consequently contributed to the peak of Figure 17. The peak is approximately 2 000 kVA higher than the average refrigeration profile.

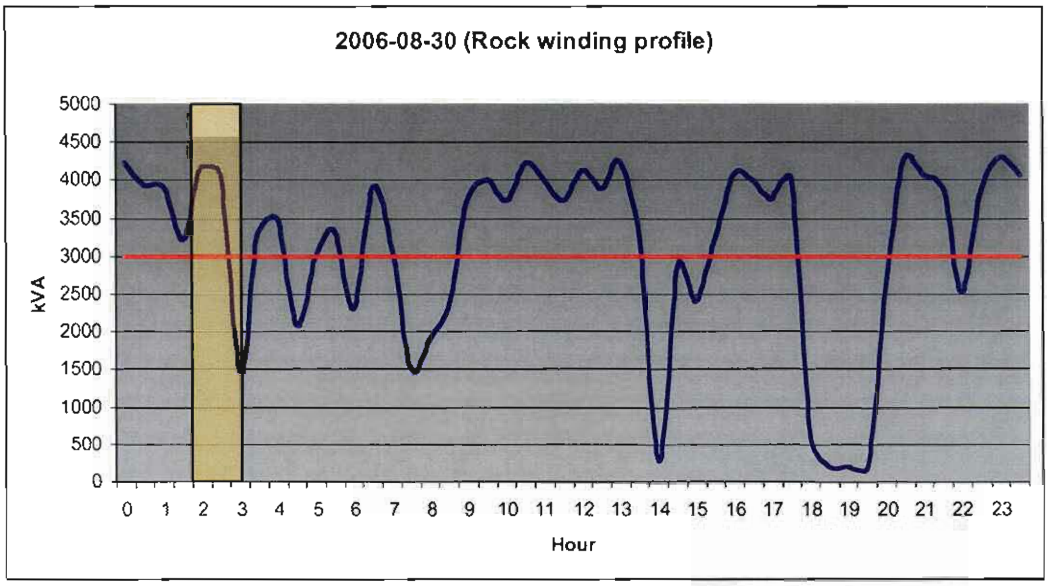


Figure 24: *Kopanang's rock winding profile on 2006-08-30*

In the profile of Figure 24, it can be seen that the rock winders contributed to Figure 17's peak as well. Should the winders be switched off completely during this peak, a possible 4 000 kVA could be shed.

A similar investigation was done on the days displayed in Figure 18 and Figure 19. On 2006/09/06 (see Figure 18), a peak was created by the pumping system (see Figure 25). This peak is also about 2 000 kVA higher than the average pumping load for the day. During the highlighted time, the rock winders peaked at around 4 000 kVA (see Figure 24). Figure 25 to Figure 27 shows the graphs used in the investigation.

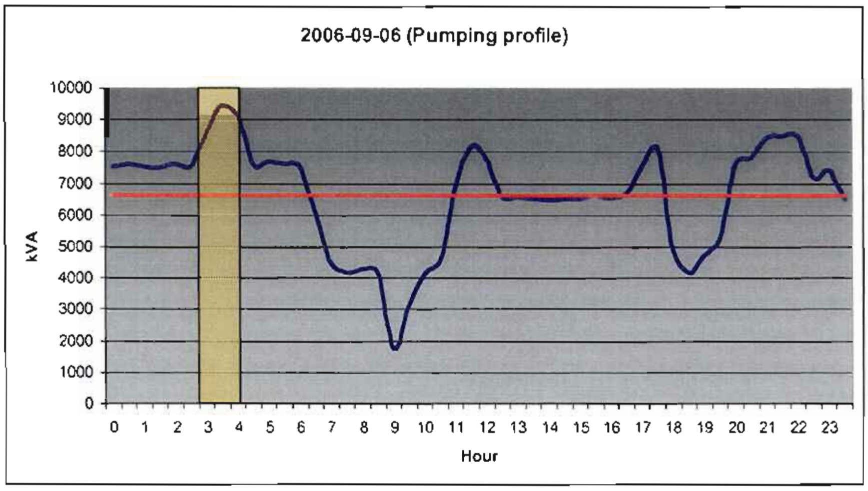


Figure 25: *Kopanang's pumping profile on 2006-09-06*

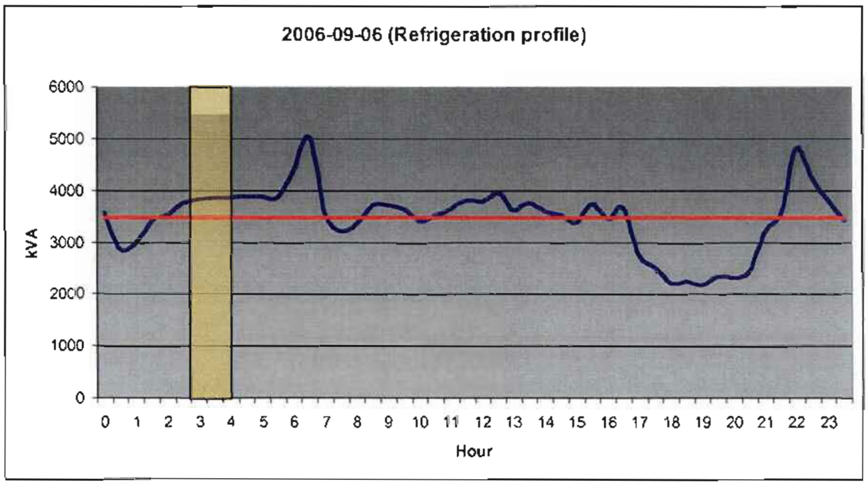


Figure 26: *Kopanang's refrigeration profile on 2006-09-06*

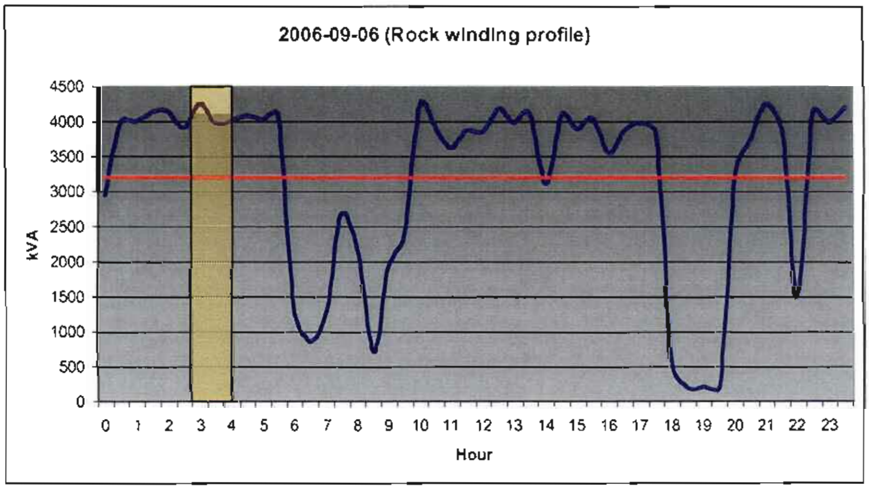


Figure 27: *Kopanang's rock winding profile on 2006-09-06*

On 2006/09/12 (Figure 28), a peak was created by the pumping (Figure 29), refrigeration (Figure 30) and winding systems (Figure 31). Again, the winders would be able to shed 4 000 kVA. The total peak of the pumping and refrigeration systems is therefore about 2 000 kVA, as can be seen in Figure 28.

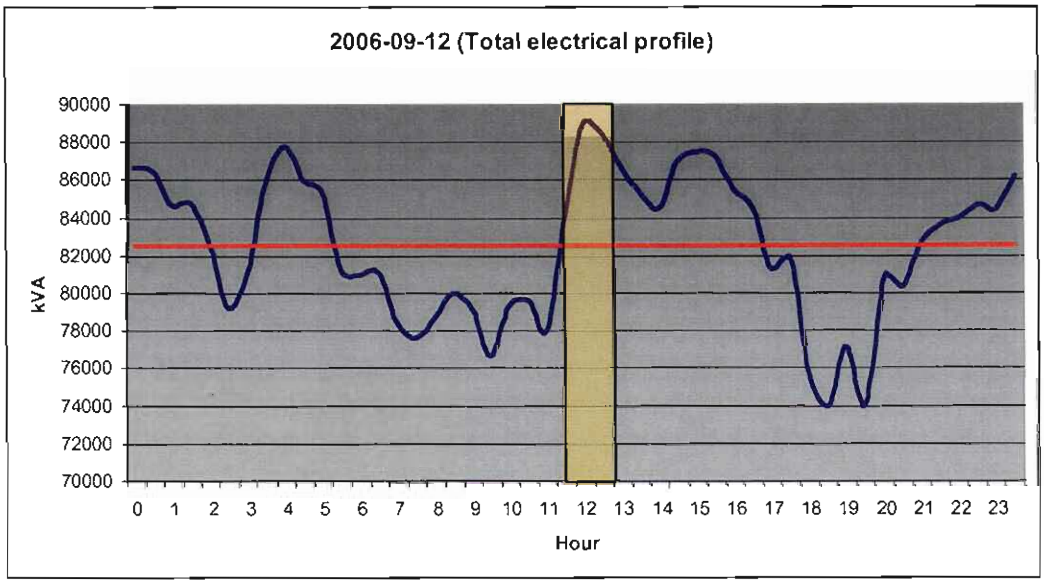


Figure 28: *Total electrical profile of Kopanang on 2006-09-12*

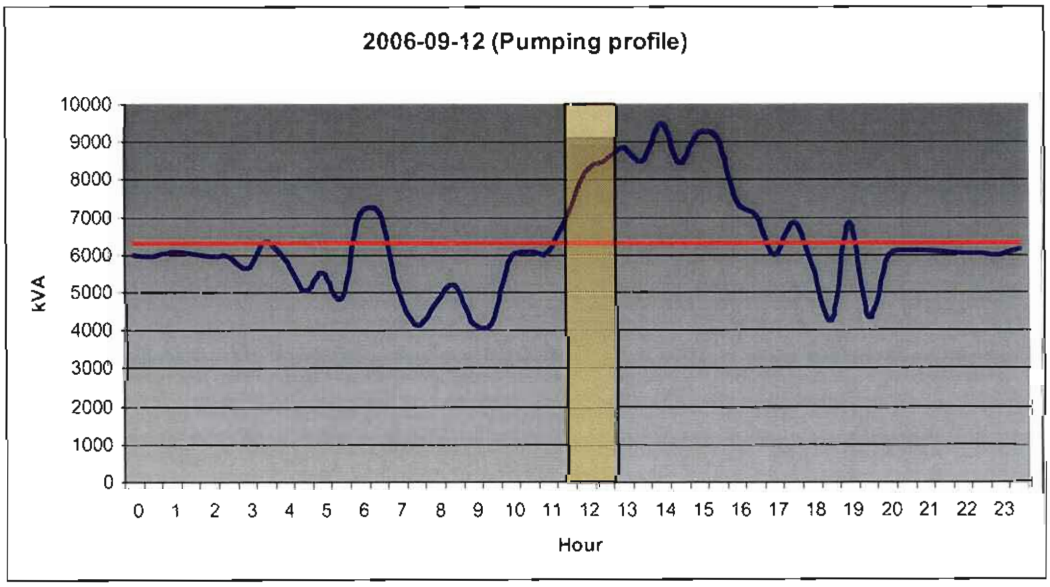


Figure 29: *Kopanang's pumping profile on 2006-09-12*

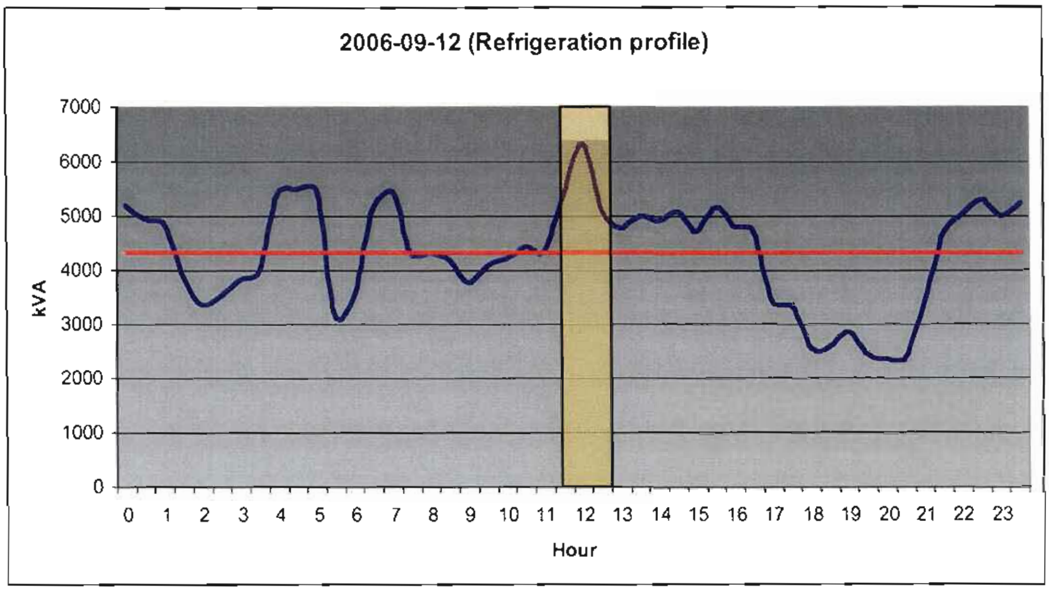


Figure 30: *Kopanang's refrigeration profile on 2006-09-12*

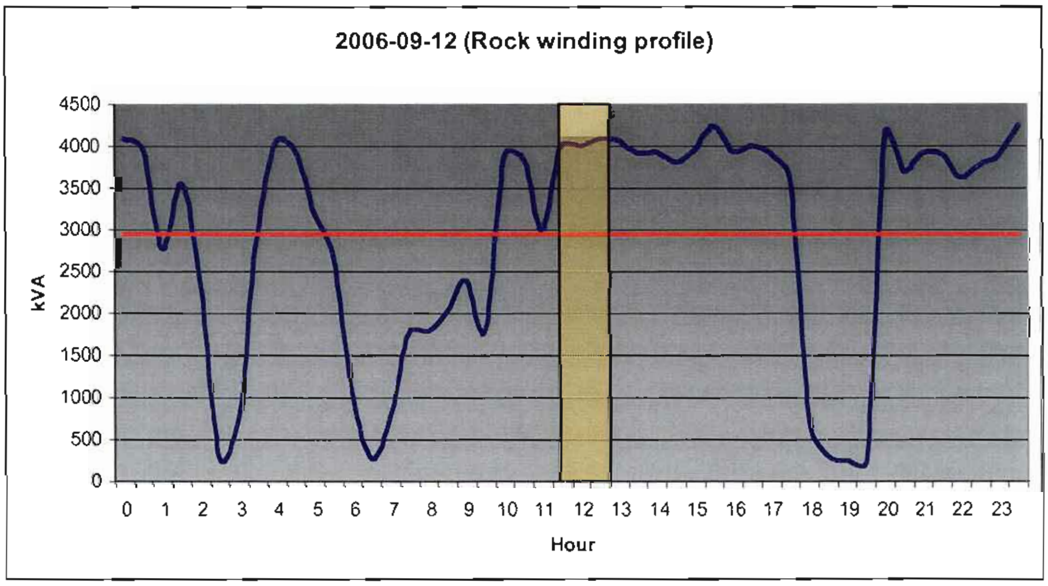


Figure 31: *Kopanang's rock winding profile on 2006-09-12*

A trend found in these graphs is that the peaks normally fall in times where the rock winders were running in unison with the pumps, fridge plants or both. There is a tendency for the pumps and fridge plants to be around 2 000 kVA higher than the average profile for a specific day. The rock winder peaks are roughly 1 000 kVA higher than the daily average, but are able to shed 4 000 kVA in most cases.

The highest peak for the month of 21 August to 20 September is nearly 6 000 kVA higher than the average for the period. A total of 4 000 kVA would therefore be saved if the rock winders are used to lower this demand over the 30 minute integrated period.

As outlined in Section 2.1, lights, pumps, fridge plants, compressors and winders are used in DSM ventures. Table 3 shows the viability of these systems for MD control.

Table 3: *Viability of certain systems for MD management*

System	**MD management possibility**
Lighting	Impractical to switch off lights for MD management
Pumping	Cannot stop in certain instances – dams might be overflowing Cycling should be minimised to lower maintenance costs
Fridge plants	Critical to keep mine cool and in workable condition Cycling should be minimised to lower maintenance costs
Compressed air	Needed for drills – production would slow down Cycling should be minimised to lower maintenance costs
Winders	Instant reduction in electricity use Designed to cycle – there is therefore no increase in maintenance costs

One of the problems with MD control is that motors are switched on and off frequently for short periods. This results in cycling of motors, which is destructive for certain motor types. When a pump is switched on, the balancing disks grind against one another before the water flows in between them, causing the disks to wear out.

Similar problems could occur on other motor applications. Winders, on the other hand, have an inherent cycle in the operation of the system. Each skip that is hoisted in the shaft moves only from one end of the shaft to the other. This means that the winder motor starts when the skip is at one end of the shaft, and stops when it reaches the opposite end. A typical winder cycle is three to four minutes. Thanks to this design of winder motors, the problem of cycling is negated, which makes the control of winder motors ideal for MD management.

Rock winders are needed at most deep level underground mines to extract ore. Table 4 shows a list of the major South African gold mining houses and the number of mines that each group has.

Table 4: *Some of the South African mining houses*

Mining house	Number of mines	Reference
AngloGold Ashanti	7	[22], [23]
Goldfields	15	[25]
Harmony	25	[26]

With more than 40 gold mines in South Africa, there is therefore more than enough opportunity to implement a maximum demand management system at South African mines.

2.4 POTENTIAL SAVINGS

The only potential MD problem would be the 2 000 kVA peak of the pumping and refrigeration systems. These systems would not necessarily be able to stop for MD management, as they are used for load shifting purposes. As an example, the pumping system has to prepare dam levels for peak times. The following calculations are made to compare savings for the case where the pumps and fridge plants were to be used for MD management, instead of load shifting:

$$
\begin{aligned}
\text{Winter peak time savings} &= (\text{Winter tariff} \times \text{kWh}) \times \text{Days in month} \times \text{Winter months} \\
&= (\text{R } 0.5222 \times 4\,000 \text{ kWh}) \times 20 \times 3 \\
&= \text{R } 2\,088.80 \times 20 \times 3 \\
&= \text{R } 125\,328.00
\end{aligned}
$$

$$
\begin{aligned}
\text{Summer peak time savings} &= (\text{Summer tariff} \times \text{kWh}) \times \text{Days in month} \times \text{Summer months} \\
&= (\text{R } 0.1482 \times 4\,000 \text{ kWh}) \times 20 \times 9 \\
&= \text{R } 592.80 \times 20 \times 9 \\
&= \text{R } 106\,704.00
\end{aligned}
$$

$$
\begin{aligned}
\text{Total savings} &= \text{R } 125\,328.00 + \text{R } 106\,704.00 \\
&= \text{R } 232\,032.00
\end{aligned}
$$

A power factor of 1 is assumed to simplify calculations. Total savings for two hours' load shift would amount to approximately R 230 000.

If the MD was managed instead of shifting load out of the evening peak times, the MD would rise with 2 000 kVA. The maximum possible savings achieved would then be around R 155 000. Calculations are shown:

$$
\begin{aligned}
\text{NDC} &= \text{R } 6.69 \times 2\,000 \text{ kVA} \\
&= \text{R } 13\,380.00
\end{aligned}
$$

$$
\begin{aligned}
\text{NAC} &= \text{R } 5.91 \times 2\,000 \text{ kVA} \\
&= \text{R } 11\,820.00 \text{ per month}
\end{aligned}
$$

$$
\begin{aligned}
\text{Total savings} &= (\text{NAC} \times 12) + \text{NDC} \\
&= (\text{R } 11\,820.00 \times 12) + \text{R } 13\,380.00 \\
&= \text{R } 141\,840.00 + \text{R } 13\,380.00 \\
&= \text{R } 155\,220.00
\end{aligned}
$$

Comparing the annual load shift savings of R 230 000 with the annual MD savings of R 155 000 gives a difference of R 75 000. The mine would therefore save R 75 000 more if the fridge plants and/or pumps were not used for MD management, but rather for load shifting.

2.5 CONCLUSION

Demand profiles for different systems used by mines were compared to determine their effect on a mine's MD. These graphs indicated that a peak in electricity demand does not necessarily occur at a specific time of day.

It was also shown that peaks are not always caused by the same systems. Pumps, fridge plants, rock winders and man winders contribute to a mine's peaks. When these systems run at the same instance, peaks created are much higher than when their loads are distributed throughout the day. It was indicated that rock winders are most suitable to manage a mine's MD, especially when the other systems are used to implement load shifting schemes.

Rock winders are needed at most deep level underground mines to extract ore. Judging by the number of deep level gold mines currently operated by the major players in the South African gold industry, there are more than enough opportunities to implement MD management schemes at South African mines.

CHAPTER 3: USING WINDERS FOR MD CONTROL

3.1 PREAMBLE

The mining process and its effect on the mine's maximum demand are described in this chapter. It is shown that winders are an integral part of this process. Different types of winders are investigated, showing their power usage during a cycle. The feasibility of different types of winders and possible savings that can be achieved are investigated.

The simulation model is developed and verified. This model will then be used to confirm the possibility of MD management at a specific mine.

3.2 THE MINING PROCESS

A mine is started by sinking a shaft from the surface to a point just below the reef. During this process, workers and material are carried up and down the shaft in buckets called *kibbles*. A second or third shaft is sometimes sunk from an underground level in order to access deeper reefs.

Figure 32: *Entrance to an underground sub-shaft in development [24]*

After the shaft has been sunk, it is divided into separate sections – transporting of rock; moving workers, machinery and materials and handling of emergencies. Rock is transported to the surface from underground using containers known as skips. Workers and equipment are carried in elevators known as cages.

In both cases, the cargo is suspended from heavy wire rope and raised or lowered by large hoists. The maximum speed at which these cages travel is about 60 km/h [29]. Each cage typically has three decks, with capacity of 40 people per deck [24].

Gold is obtained by blasting and removing gold-bearing ore from the stope area. Holes are drilled in the gold-bearing face of the stope and charged with explosives. The blasted rock is scraped away from the stopes into a hole, known as a *box hole*. The box hole is equipped with a chute and door to control the flow of rock. The rock is drawn off from these box holes onto underground railroad carts, known as *hoppers*, and then hauled by locomotives to the shaft area.

The rock is then dropped down large openings, known as *orepasses*, where it falls to the lowest level of the mine. At this point, the rock is transferred into skips and then raised to the surface. This is where the rock winding process starts.

Figure 33: *An orepass at one of the levels in a mine [24]*

The winder motor's function is to simultaneously wind one end of the rope while rewinding the other end. The result is that the skip at the one end of the rope moves up as the other moves down the shaft.

The winder motor theoretically only has to overcome the moment of inertia to move the skips up and down, due to the fact that the motion is balanced. Therefore the winder motor consumes the most electricity when starting the skip's motion. See Figure 34.

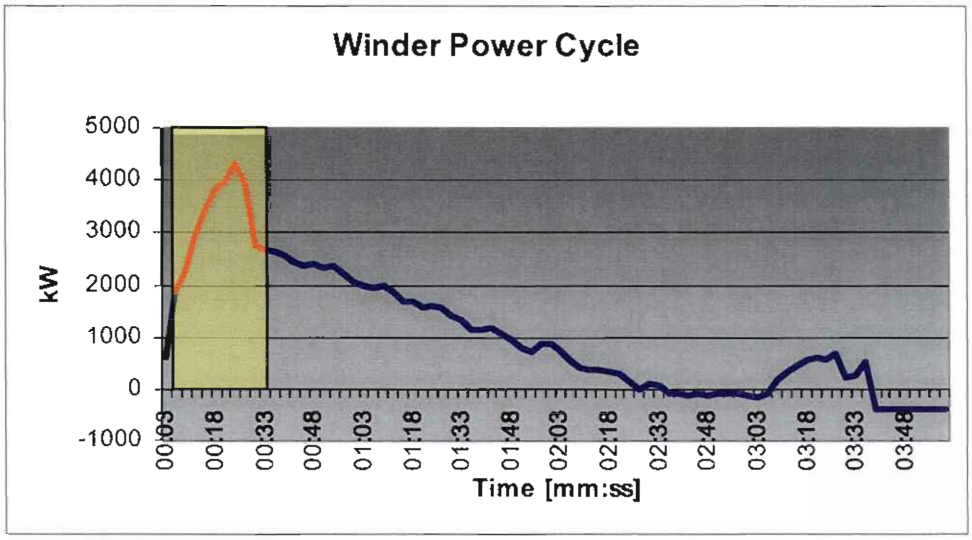


Figure 34: *Typical winder cycle*

The highlighted peak during the first 30 seconds of the graph of Figure 34 illustrates that a winder uses the most electrical energy when starting the movement. As soon as the system has overcome its moment of inertia, the electricity usage drops until the skip has reached its destination. Electrical energy is then required to stop the movement of the skips. Some winders regenerate as the skips slow down. This means that the winder motor reacts as a generator that produces electricity that is fed back into the grid. The winder cycle of Figure 34 regenerates at the end of the cycle, where the kW value drops below zero.

When the skip arrives at the surface of the shaft, the rock is automatically thrown onto a conveyer belt which transports the ore to the gold plant.

The following figure represents the major components of a winder system:

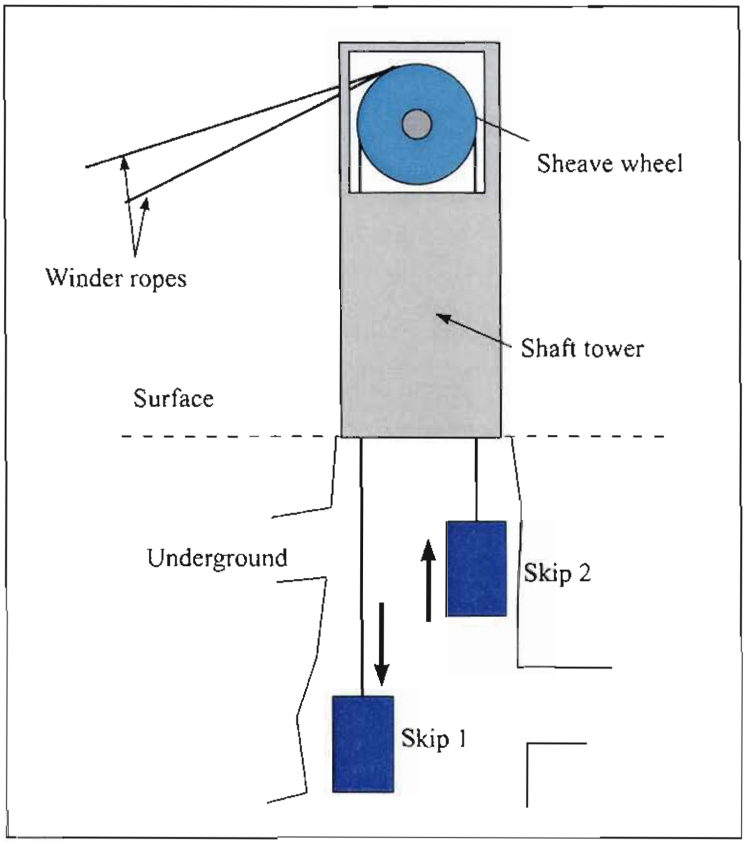


Figure 35: *Components of a winder system*

Mineral deposits are constantly exploited on deeper and deeper levels. Terms such as *deep level* and *deep shaft*, which are both relative definitions, came into use as mines had to extend deeper below the surface to extract minerals [27]. According to Hill and Mudd [28], a mine can be treated as a *deep level mine* if

- the depth is more than 2 300 m, or
- mineral deposit temperature is higher than 38°C.

It is a well known fact that most of the world's deep mines are in South Africa. Usually, these are gold or diamond mines. Large deposits of gold are known to exist at depths up to 5 000 m in a number of South African regions [27]. Due to the depth and structure of gold bearing reef in some areas, previous methods such as usage of sub-vertical shafts would not be economically viable. The local mining industry is therefore actively investigating new techniques for a single-lift shaft up to depths of 3 500 m, or even 5 000 m in the near future [27].

3.3 ROCK WINDERS AND MD CONTROL

3.3.1 The winding system

Vertical transport and mine hoisting used in the shaft is the most important feature in deep mines. Every deep mine must have the means to convey material in and out of the mine via a shaft.

The most important factors for a hoist, from an economic point of view, are:

- construction and parameters of winding ropes (mainly the safety factor)
- mine hoisting drum capacity
- low empty mass of the skip

All mine hoists manufactured today are driven electrically by motors that have an independent ventilation source. This results in lower power requirements due to more efficient cooling of the windings. Direct current (DC) drives were almost exclusively employed with solid state converters (thyristors). Lately, larger mine hoists are manufactured with alternating current (AC) drives that are frequency controlled [29].

3.3.2 Drum hoists

Drum hoists are the most commonly used type of hoisting system. Single drum hoists are acceptable for limited applications, but most drum hoists are double to facilitate balanced hoisting of two conveyances in the shaft.

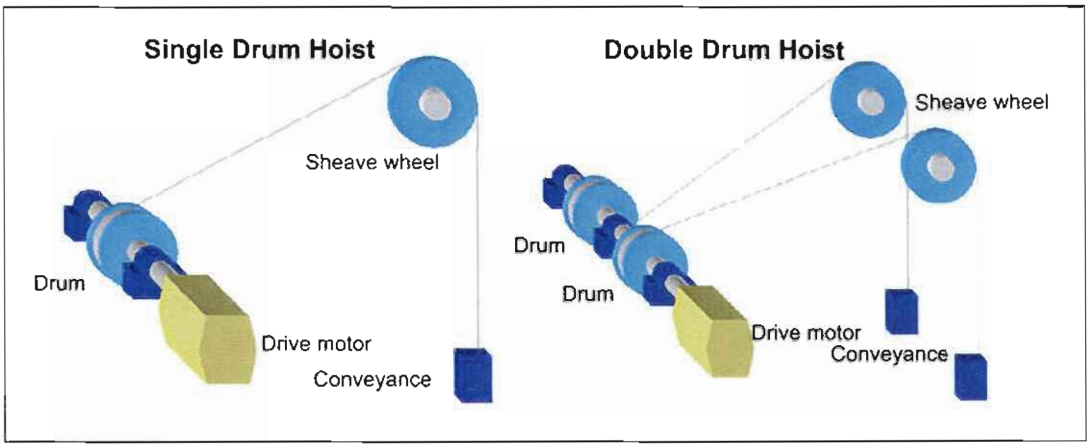


Figure 36: *Single drum and double drum hoists [30]*

3.3.3 *Blair multi-rope*

The conventional double drum hoist underwent a major development in 1957. Robert Blair introduced the concept of combining the load carrying capacity of the multiple ropes of the friction hoist system with the simplicity and flexibility of drum hoists [29]. This system is illustrated in Figure 37.

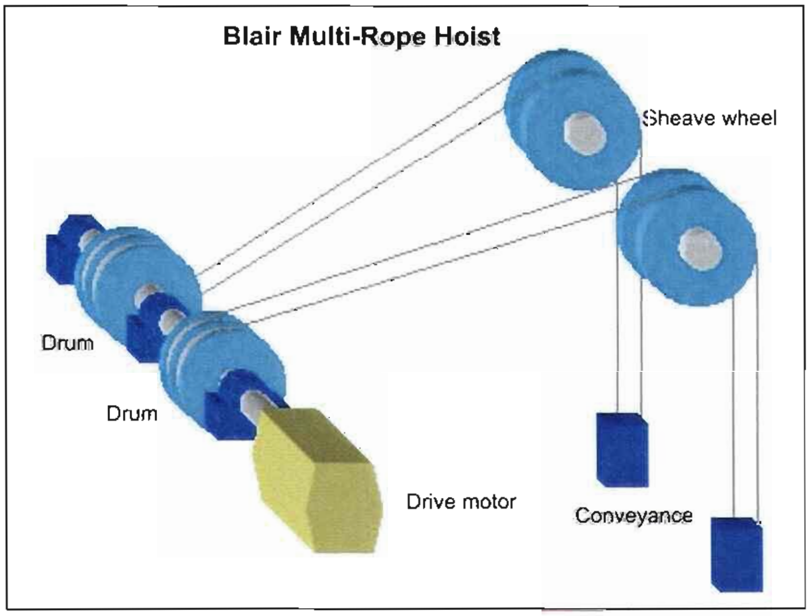


Figure 37: *Blair multi-rope hoist [30]*

Both drums of a double drum hoist are divided into two or more compartments with a single rope per compartment. Each rope on the drum is attached to a single conveyance.

The Blair multi-rope (BMR) system significantly increases the hoisting capacity of a drum hoist. Hoists with end loads of 32 t at depths of 2 500 m are currently in operation [29]. Because of their physical characteristics and a lower statutory safety factor, BMR hoists are mostly used for deep shaft mineral hoisting.

The drum diameters are less than that of equivalent conventional hoists, and are therefore more likely to be taken underground for sub-shaft installations [27]. In addition, two ropes are used to handle the load, both being narrower compared with a single drum rope.

Government mining regulations permits a 5% lower safety factor at the sheave when minerals are hoisted using a BMR hoist. This was incorporated after a demonstration by Robert Blair where one rope was severed at full speed, with the other rope still holding the load. The extra 5% allows the Blair hoists to descend a little deeper than other types [27].

3.3.4 Friction hoists

A friction (Koepe) hoist is a machine where one or more ropes pass over the drum from one conveyance to the other or from a conveyance to a counterweight. In both cases, separate tail ropes are looped in the shaft and connected to the bottom of each conveyance or counterweight [29].

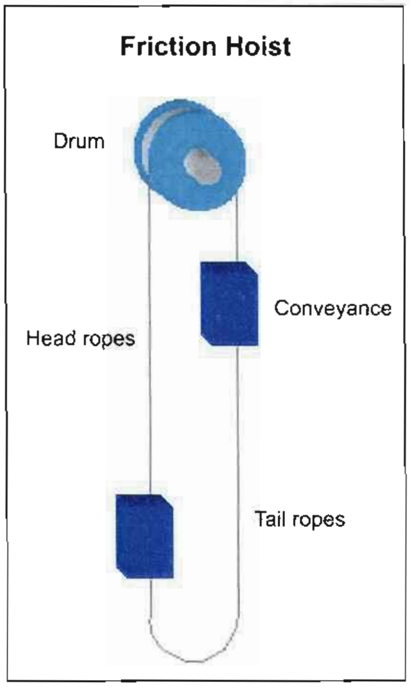


Figure 38: *Friction hoist [30]*

The tail ropes provide an economical solution for many hoisting applications, as they lessen the out-of-balance load and therefore the peak power required of the drive motor. Compared to a drum hoist of the same application, the tail rope reduces the required power rating of the motor by about 30%. The power consumption in kWh per cycle however remains virtually the same [29].

3.3.5 Comparison of different winding systems

The lowered power rating requirement induced by a tail rope system can be seen from the cycle graphs of two winder systems (Figure 39 and Figure 40). The one is a Koepe winder of Tau Tona (Figure 39), while the other is a BMR winder of Kopanang (Figure 40).

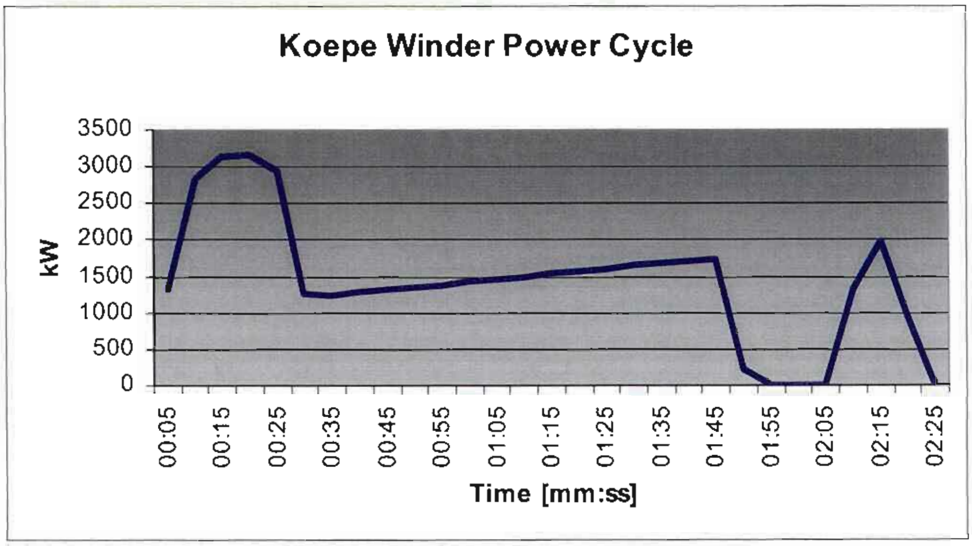


Figure 39: *Koepe winder cycle*

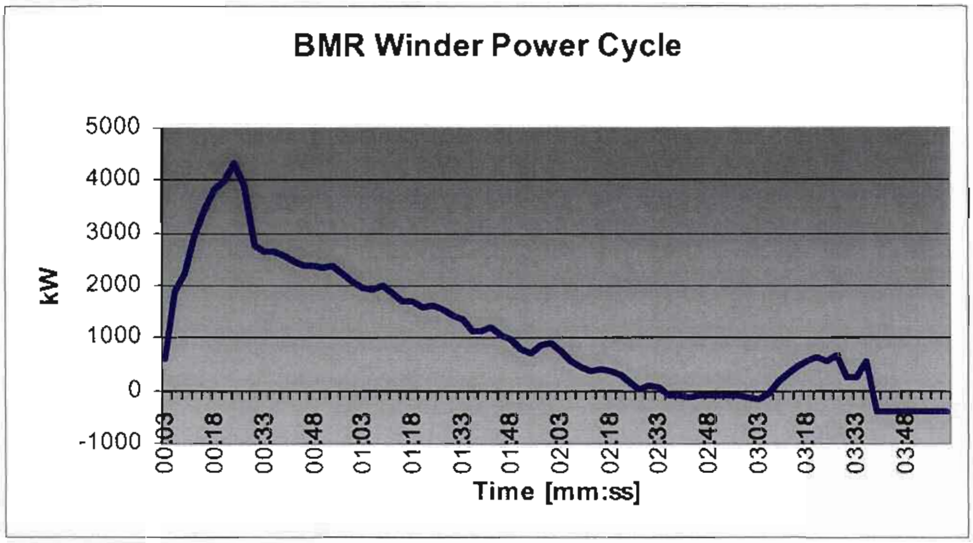


Figure 40: *BMR winder cycle*

The Koepe rock winder of Tau Tona has a lower and longer starting peak, compared to the higher, shorter starting peak of Kopanang's BMR rock winder. It is clear from these graphs that a lower power rating is required of a Koepe winder, but the total power consumption is practically the same – depending on the load and length of a cycle. Both winders can hoist around 20 ton per cycle.

Tail ropes have been used for a few double-drum hoists to gain the same effect, but the idea has not really gained acceptance by the mining industry. Koepe hoists normally use several hoisting ropes. The largest Koepe hoist can consequently handle heavier payloads than the largest drum hoist. Drum hoists are usually limited to the capacity of a single rope [29].

Carbogno concludes that Blair multi-rope hoists are preferred by South African deep level mines. [27]

3.3.6 Using winders for MD management

As explained in Section 1.3, the MD is calculated over a 30 minute integrated period. To successfully lower the MD during this period, it might be necessary to switch off certain equipment, such as pumps, for the last five minutes of the 30 minute period. As soon as the next 30 minute period starts, it might be necessary to start this equipment again. For example, in the case of pumps, the dam level might have risen too high.

Repeated cycling of motors incurs higher maintenance costs. In the case of pumps, the balancing disks grind against each other during start-up, increasing disk abrasion rate which results in higher repair costs.

Winder motors are designed for cycling. This can be seen from the short winding cycle of both the Koepe and BMR winders in the graphs of Figure 39 and Figure 40. Winders are therefore ideal for maximum demand control, as frequent power switching would not incur additional maintenance costs as in the case of pump motors.

3.4 POTENTIAL FOR MD MANAGEMENT

3.4.1 Calculation steps

Calculating the potential to manage the maximum demand using winders requires a few steps which are detailed on page 46. A few variables describing the situation and settings are required to understand the steps.

- Winder motor cycle (indicated in kVAh per cycle):
    - kVA usage
    - Duration of cycle
- Winder system's operational schedule:
    - Loading time
    - Hoisting time
    - Skip size
    - Production targets
- Notified maximum demand
- Demand interval
- Demand periods:
    - Off-peak
    - Peak
    - Standard

3.4.2 Average kVAh per cycle

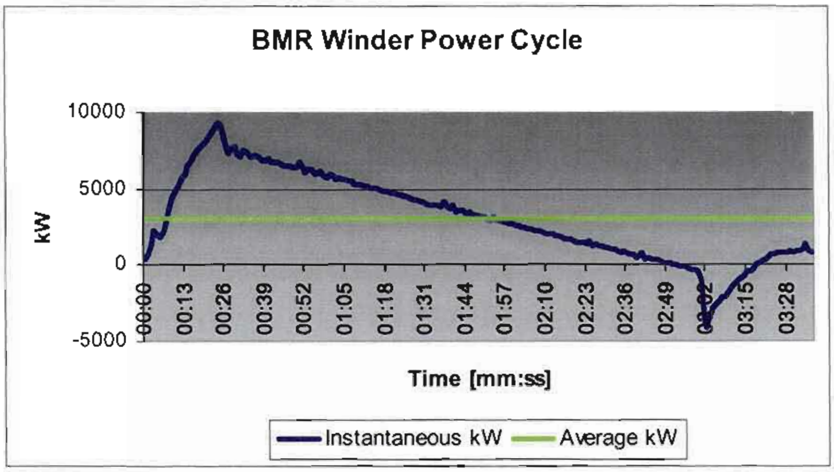


Figure 41: *Instantaneous and average kW of a winder's power cycle*

Instantaneous kW values are obtained by connecting a power meter logger to the winder's electrical panel. A kW reading is given every second. An average kW value is obtained by the sum of the instantaneous values divided by the number of values. In this example, 218 data points were obtained per cycle, giving an average value of ***3 112 kW per cycle***. The 218 values were acquired over a period of 218 seconds.

Example:

$$\frac{\text{kW/cycle} \times \text{time/cycle[sec]}}{\text{sec/hour}}$$
$$= \frac{3112 \times 218}{3600}$$
$$= 188.45 kWh / cycle$$

The conversion from kWh to kVAh depends on the power factor. This is the phase angle between the voltage and current. The kVAh value is calculated using the following formula [31]:

$$\overline{P} = \overline{VI} \cos(\theta)$$

with $\cos(\theta)$ the power factor and θ the phase angle

3.4.3 Operational schedule of winder system

The winder system's operational schedule must be ascertained to determine the possibility for MD control, of which the following variables need to be considered:

- loading time
- hoisting time
- skip size
- production targets

First, the loading and hoisting times are added to give the total cycle time:

$$t_T = t_L + t_H$$

Using the total cycle time, the maximum number of cycles, or skips, per hour can be calculated:

$$\text{Skips/hour} = S_H = \frac{60\,\text{min}}{t_T}$$

The production target (in tons) is then divided by the skip size (in tons) to give the number of possible skips per day:

$$\text{Skips/day} = S_D = \frac{\text{Production target}}{\text{Skip size}}$$

S_D (number of skips per day) is then divided by S_H (skips per hour) to give the number of hours per day that the winder *has* to operate to reach production targets:

$$\text{Hours per day to run} = H_R = \frac{S_D}{S_H}$$

The number of hours that the winder has to run (H_R) is subtracted from 24 to give the number of hours that the winder can stand (H_S) to enable us to intervene in the MD:

$$H_S = 24 - H_R$$

3.4.4 *Notified maximum demand*

The NMD is a natural requirement when considering the potential for MD management. The NMD must be supplied by the mine to enable calculation of the MD control capabilities.

3.4.5 *Demand interval*

The demand interval, as set by Eskom in their NMD Rules [21], is currently an integrated period of 30 minutes. This means that the average electricity demand over a 30 minute period should not exceed that of the NMD.

Figure 42 illustrates the integration period, where the average electrical energy usage over 30 minutes (green line) is below that of the notified maximum demand (red line).

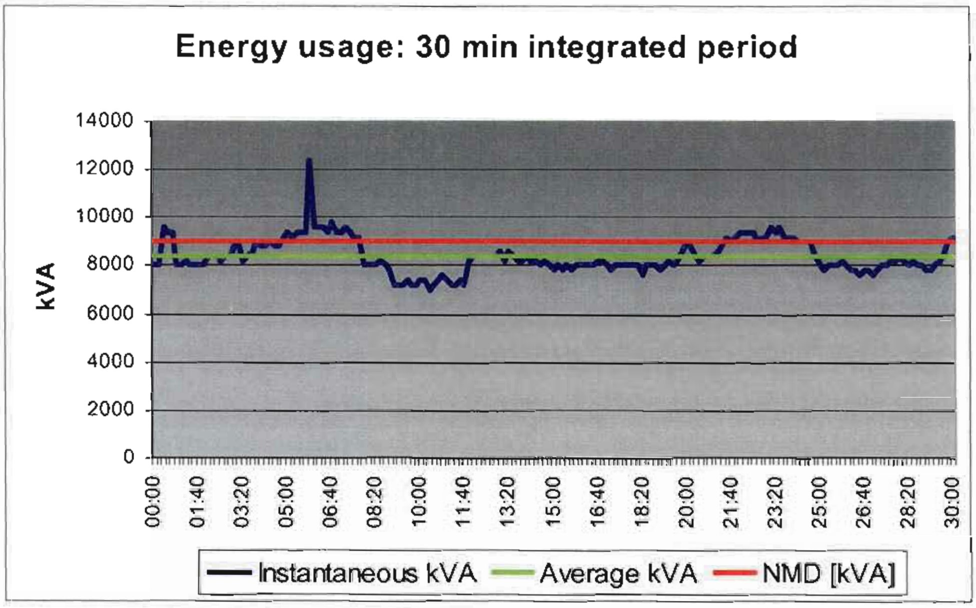


Figure 42: *Example of MD calculation over 30 min integrated period*

There were instances where the instantaneous electrical energy usage exceeded the NMD, but it was not sufficient to raise the average above the NMD for the 30 minute period.

A controller that manages the electricity demand would be able to successfully control the winders to lower the MD. This would be done if the demand is such that the timely control of the winders can influence the electrical energy usage over the integrated period.

Using the values from the previous example, it can be seen that the control of the winders will lower the MD successfully. This is possible if at least one winder is requested to stand for the last 8 minutes of the period, or at least two cycles.

Figure 43 illustrates what the effect would be if the average demand was 25 500 kVA for the first 22 minutes with at least one winder standing for the last 8 minutes. It is assumed that the demand for other equipment (such as pumps, fridge plants or fans) stays unchanged during the 30 minute integrated period.

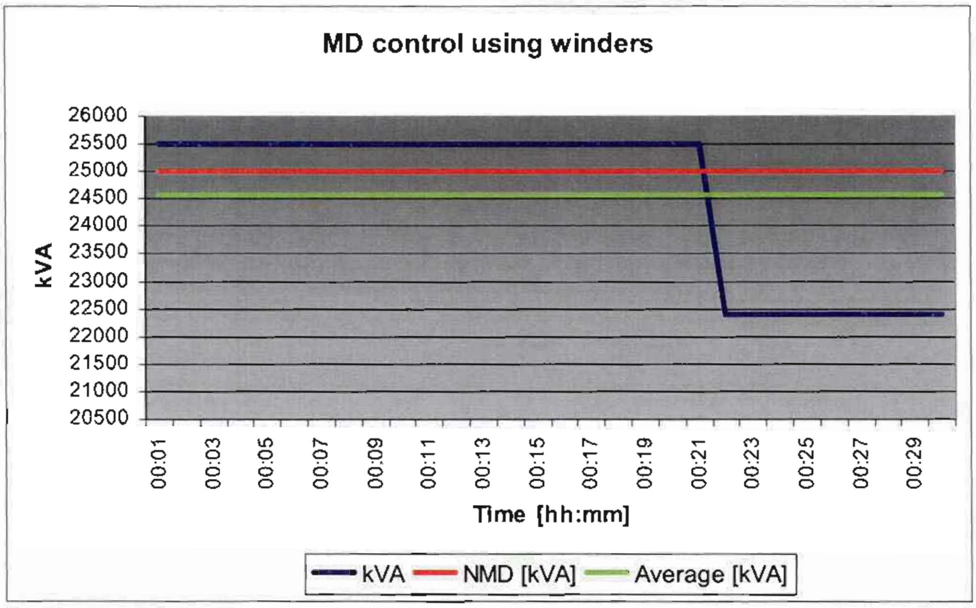


Figure 43: *Hypothetical example of MD control using winders*

The blue line is the instantaneous kVA value. The NMD is indicated with the red line at 25 000 kVA, with the average kVA value over the 30 minute period below that at around 24 500 kVA (green).

3.4.6 *Demand period*

The period of demand plays an integral role as well. During peak and standard periods, a network demand charge is applicable. A network access charge is billed during all time periods. This should be taken into account when the winders are used for MD management.

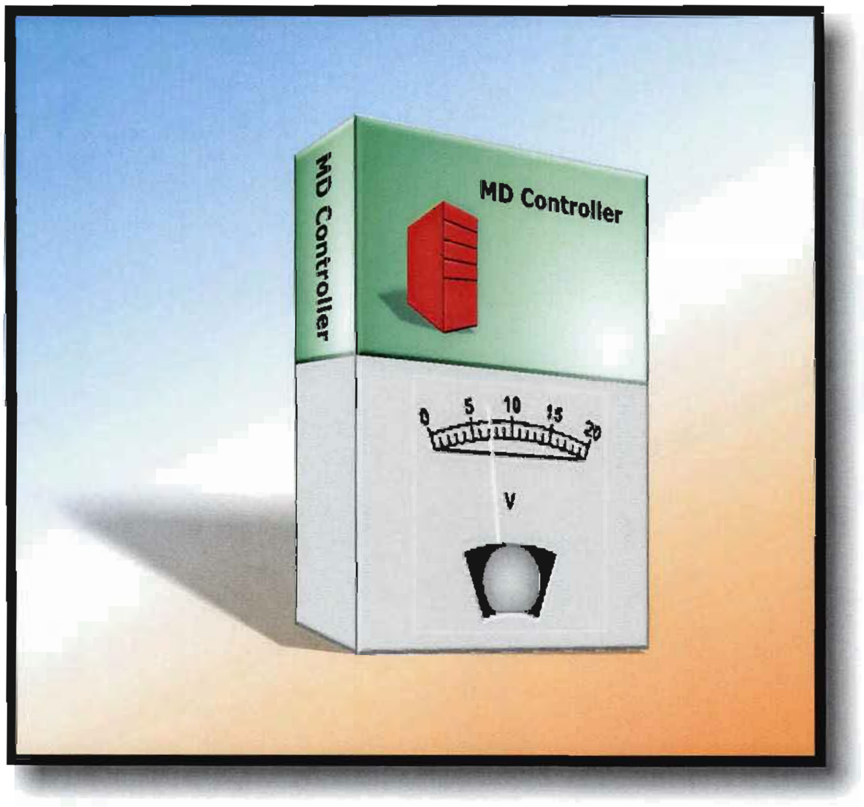
3.5 CONCLUSION

In this chapter, it was shown that winders form an integral part of the mining process. The vertical transport system is the only means of conveyance for a deep level mine.

Since the winder motors are designed to cycle, there will be no problems of increased maintenance due to frequent power switching of the winders. This regular power switching of a motor is critical to the success of a maximum demand controller.

It is proven that it is possible, and also beneficial to the mine, to manage maximum demand using the winder system.

CHAPTER 4: DEVELOPING A NEW MD CONTROLLER



4.1 PREAMBLE

Principles and specifications for a new MD controller will be determined in the course of this chapter. The development of MD control on winders will be discussed; and simulation software will be developed in accordance with the specifications.

Load prediction techniques will be examined and compared. These estimation methods will be used to forecast an MD value for the 30 minute integrated period, researched in Section 1.3 (see page 12).

A model of the mine will be simulated with the use of the newly developed software to ascertain the accuracy of the prediction methods. In addition, the possibility of automatic control of the winders will be established.

4.2 ESTABLISHING PRINCIPLES AND SPECIFICATIONS

4.2.1 Design principles

The purpose of the MD controller is to keep the MD charges, consisting of the network demand charge (NDC) and the network access charge (NAC), to a minimum. This implies maintaining the electricity demand throughout the day below the limits set for the current billing period. The demand can be managed by switching off large electricity users during high demand periods.

The control of these loads needs to be governed by the following:

- Safety of the mine and its personnel
- Switching of loads should not have adverse effects on production of the mine
- Switching should not compromise possible load shedding activities
- Diversity of load switching should be used to prevent repetitive switching

Calculation of maximum demand:

Maximum demand is the integrated kVA value over a specified interval. If the demand period is 30 minutes, the MD is calculated as follows:

$$\text{Total kVAh used} = [kVA] \times \frac{\text{time on [min]}}{60\text{ [min]}}$$

$$MD = \frac{\text{total } [kVAh] \text{ during demand period}}{\left(\frac{\text{demand period [min]}}{60\text{ [min]}}\right)}$$

$$\begin{aligned} \therefore MD &= \frac{\text{total } [kVAh] \text{ during 30 min}}{\left(\frac{30\text{ [min]}}{60\text{ [min]}}\right)} \\ &= \left(\text{total } [kVAh] \text{ during 30 min}\right) \times 2 \end{aligned}$$

The load contribution to the MD is thus directly related to the time the load was switched on.

Steps:

1. *The projected MD must be determined* to perform MD control. It has to be decided early on in the 30 min demand interval if control is required. A *predicted demand value* is therefore vital. This value will be available from the SCADA system on some mines, but this is not the norm. The predicted MD is calculated in the MD controller.
2. *Check if the predicted MD will compromise the demand targets*. The demand targets are the following:
    a. *Network access charge (NAC) demand*: This is the highest actual demand over a rolling 12 month period, or the notified maximum demand (NMD) for *all* time periods. The NAC is based on the annual utilised capacity (AUC) as explained in Section 1.3 (see page 12).

   b. *Network demand charge (NDC) demand*: This is the maximum demand recorded during the current billing period, *for standard and peak time periods.*

3. *Determine available loads that may be controlled.* Information should be available as to what the status of the individual loads is.

   Relevant Information is:

   1. On/off status
   2. kW rating of the load
   3. Estimated time period that the load can be switched off

4. *Switch loads off.* If the time off has exceeded the required limit, loads should be switched on again by controlling systems such as winders, pumps and fridge plants.

5. *Monitor the predicted demand.*

The following data inputs would be required for accurate calculations:

- Billing start and end day
- Demand interval (30 minutes)
- Percent of demand interval elapsed
- Demand periods:
  - Off-peak
  - Peak
  - Standard
- Notified maximum demand
- NAC demand
- NDC demand
- Predicted kVA for end-of-demand period

- kWh usage
- kVAh usage

4.2.2 Load prediction

4.2.2.1 Prediction techniques

The kVA for end-of-demand periods has to be predicted for timely MD intervention. Existing load profiles can be easily determined by measurements. In order to examine the effects of intervention on a load, a short-term model of that specific load is required to generate a controlled load profile.

Much research has been done in the area of accurate and efficient load forecasting methods for short, medium and long term estimations [32], [33], [34], [35], [36], [37] and [38]. These approaches range from trend extrapolation to more accurate techniques such as statistical and econometric methods and artificial neural networks (ANN). The forecasting technique tends to be more rigorous as the length of the forecasting term increases. Only short term forecasting techniques will be considered for direct load control as is used in MD management.

The prediction algorithms vary in complexity and data requirements. As more variables are used in an algorithm, adjustments can be traced more accurately. This comes at the expense of greater complexity [39].

Simpler prediction algorithms have the potential of being imprecise, but are much easier to implement. Their accuracy would be dependent on the change of electrical power demand over the 30 minute period.

4.2.2.2 Trend extrapolation

The half hourly demand is predicted using a number of data points from the start of the demand interval. These data points are used to generate an accumulated demand line. Trend extrapolation techniques are used on this demand line to forecast the end-of-period demand.

The accumulated demand line's data points are calculated as follows [39]:

$$\text{demand}_t = \frac{\int_0^t (\text{power}_t)dt}{30\,\text{min}} \tag{4.1}$$

where t is the time since the start of the demand interval.

The gradient of this demand line can be used to estimate the end-of-period demand. It can be shown that the gradient of equation 4.1 is given by:

$$\frac{d}{dt}(\text{demand})\Big|_t = \frac{\text{power}\big|_t}{30\,\text{min}} \approx \frac{\Delta(\text{power}_t)}{\Delta t \times 30\,\text{min}} \tag{4.2}$$

The gradient of the accumulated kVA can therefore be estimated by a time average of the apparent power (at a time t) divided by the interval duration (30 minutes). In this method it is assumed that the average power, taken over a certain time interval, remains constant until the end of the demand interval.

By means of the gradient obtained in equation 4.2, the MD at the end of the 30 minute interval can be estimated. This estimate is obtained as follows:

$$\text{MD} = (\text{demand})\Big|_t + (30\,\text{min} - t) \cdot \frac{d}{dt}(\text{demand})\Big|_t \tag{4.3}$$

Another, and in some instances more accurate, method is to find a function that fits the accumulated demand line. One mathematical operation to find such a function is the *least-squares polynomial fitting* (also known as a regression line) [40].

As the demand line would resemble a straight line, a linear function (or polynomial of the first order) would provide the most appropriate fit [41]. A straight line would be represented by a polynomial in the format of

$$p_1(x) = a_0 + a_1 x \tag{4.4}$$

from which the a_i are obtained from

$$\left.\begin{aligned} a_0(n+1) + a_1 \sum_i x_i &= \sum_i y_i \\ a_0 \sum_i x_i + a_1 \sum_i x_i^2 &= \sum_i y_i x_i \end{aligned}\right\} \tag{4.5}$$

Refer to Appendix A for a detailed explanation of these functions. The value of $p_1(x)$ for $x=30$ *minutes* will provide the estimated end-of-period demand value.

Parameters that can vary are the time into the demand interval (the *intervention time* – when the gradient of the accumulated kVA is calculated), as well as the interval between points. The intervention time can be specified by the user of the software (see Section 4.3, page 66).

Figure 44 and Figure 45 illustrate the steps needed to calculate the predicted demand after 5 minutes. Figure 46 and Figure 47 show the result of using this linear extrapolation technique after intervention times of 5 minutes and 15 minutes respectively.

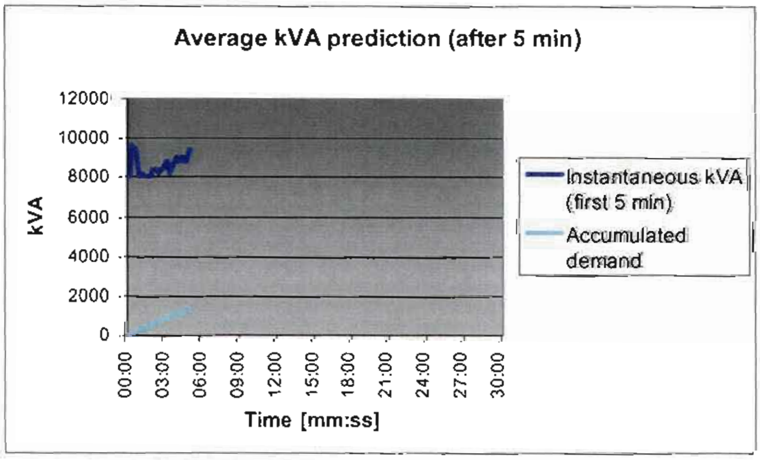


Figure 44: *First step in linear extrapolation: accumulated demand line*

The instantaneous kVA values are logged during the 5 minute interval (shown in the dark blue line of Figure 44). These values are used to plot an accumulated demand line (light blue).

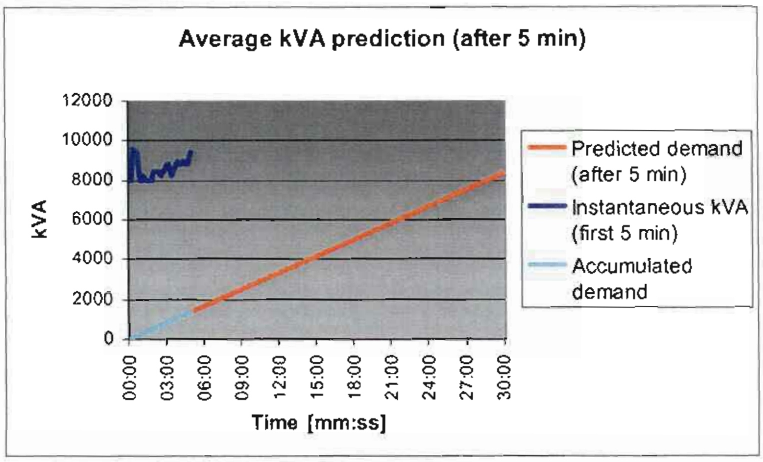


Figure 45: *Second step in linear extrapolation: predicted demand*

The values represented by the light blue line of Figure 44 are used to calculate a predicted demand using equations 3.4 and 3.5. The end-of-period demand value is used to plot the orange line of Figure 45.

Figure 46 and Figure 47 compare the predicted demand with the average over the 30 minute period. The instantaneous demand is shown for the entire 30 minute period to clarify how the average is calculated.

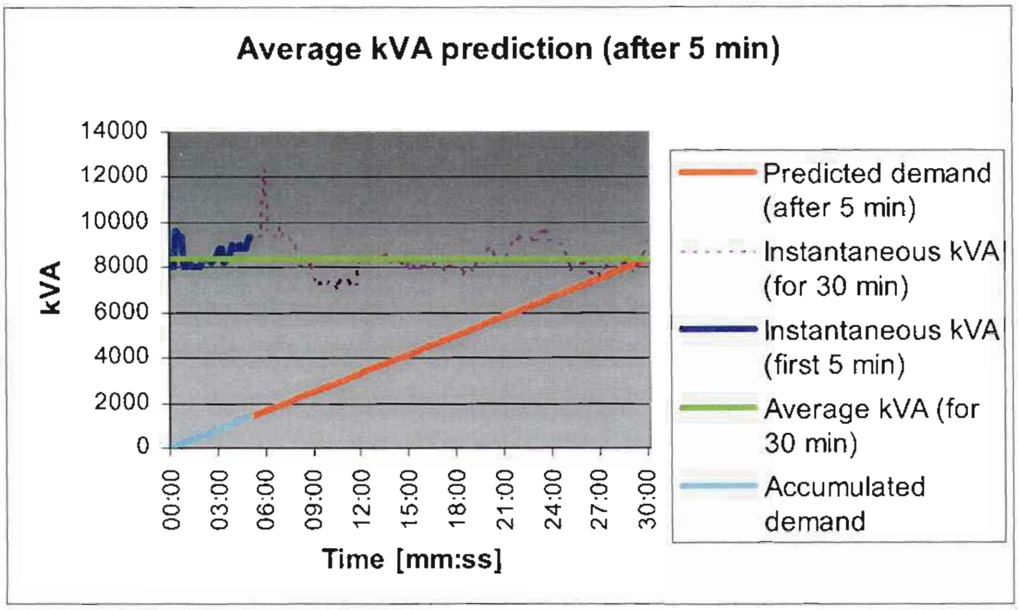


Figure 46: *Linear extrapolation kVA prediction after 5 minutes*

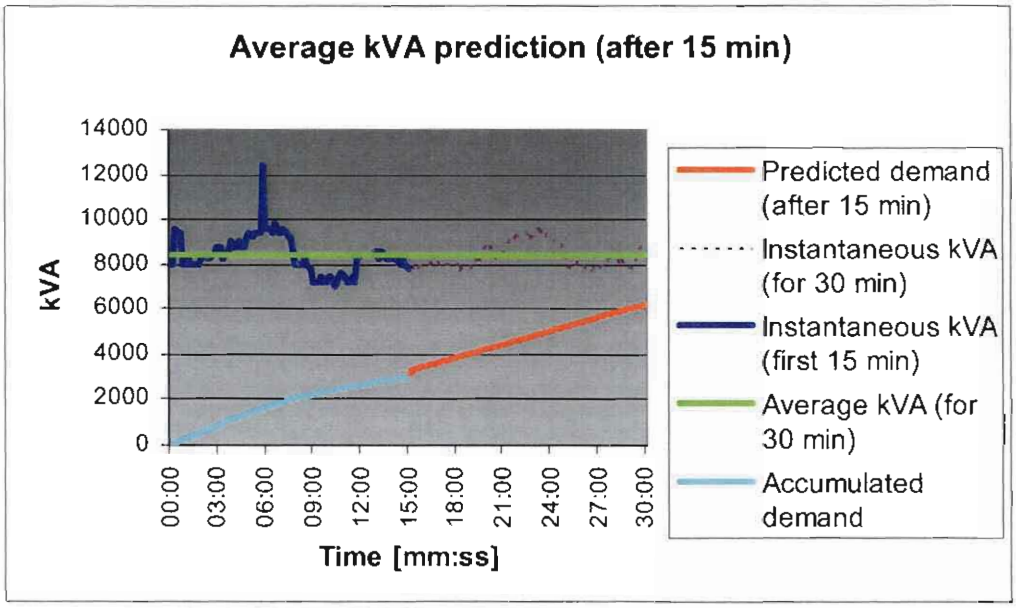


Figure 47: *Linear extrapolation kVA prediction after 15 minutes*

Figure 46 and Figure 47 show the electrical energy demand for the intervention period (dark blue). The electrical energy demand for the entire demand period (30 minutes) is shown (purple) to clarify the average demand for the 30 minute period (green).

The variation in results between different intervention periods can be seen from Figure 46 and Figure 47. The predicted demand of Figure 46, with an intervention period of 5 minutes, is close to the average of the 30 minute demand period. Figure 47's predicted demand, with an intervention period of 15 minutes, is much lower than the integration period's average. This clearly illustrates the effect that different intervention periods have on the predicted demand.

4.2.2.3 Statistical techniques

Several techniques exist for statistical estimation. [39] These include:

- Linear mean square estimation
- Exponential smoothing
- Kalman filter and state estimation
- Minimum mean square estimation
- Box Jenkins models and its variants:
    - Autoregressive (AR)
    - Moving average (MA)
    - Autoregressive moving average (ARMA)
    - Autoregressive integrated moving average (ARIMA)

Of the statistical techniques mentioned, *linear mean square* estimation is the easiest to implement [32]. This method is now described in more detail [42].

Consider the estimator $\hat{Y}$ of Y given by

$$\hat{Y} = g(X) = aX + b$$

The values of a and b must be such that the mean square error as defined by

$$\begin{aligned} e &= E\left[(Y - \hat{Y})^2\right] \\ &= E\left\{[Y - (aX + b)]^2\right\} \end{aligned}$$

are at a minimum. The values of a and b are given by

$$a = \frac{\sigma_{XY}}{\sigma_X{}^2} = \frac{\sigma_Y}{\sigma_X}\rho_{XY}$$

with

σ_Y = standard deviation of Y

σ_X = standard deviation of X

ρ_{XY} = correlation coefficient of X and Y

and

$$b = \mu_Y - a\mu_X$$

with

μ_Y = mean of Y

μ_X = mean of X

The mean of X is given by

$$\mu_X = E(X) = \begin{cases} \sum_k x_k p_X(x_k) & X : \text{discrete} \\ \int_{-\infty}^{\infty} x f_X(x) dx & X : \text{continuous} \end{cases}$$

The standard deviation of X is given by

$$\sigma_X = \sqrt{\sum X^2 - \frac{\left(\sum X\right)^2}{N}}$$

The covariance of X and Y (for discrete values of X) is given by

$$\begin{aligned} \text{Cov}(X,Y) = \sigma_{XY} &= E[(X - \mu_X)(Y - \mu_Y)] \\ &= \sum XY - \frac{\sum X \sum Y}{N} \end{aligned}$$

Therefore, the correlation coefficient of X and Y (for discrete values of X) is given by

$$\begin{aligned}\rho_{XY} &= \frac{\operatorname{Cov}(X,Y)}{\sigma_X \sigma_Y} \\ &= \frac{\sigma_{XY}}{\sigma_X \sigma_Y} \\ &= \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X^2 - \frac{\left(\sum X\right)^2}{N}\right)\left(\sum Y^2 - \frac{\left(\sum Y\right)^2}{N}\right)}}\end{aligned}$$

Figure 48, Figure 49 and Figure 50 show the result of using this linear mean square estimation on the same values as used during the linear extrapolation technique. In this case, Y would be the kVA values, in order to be able to calculate a predicted MD.

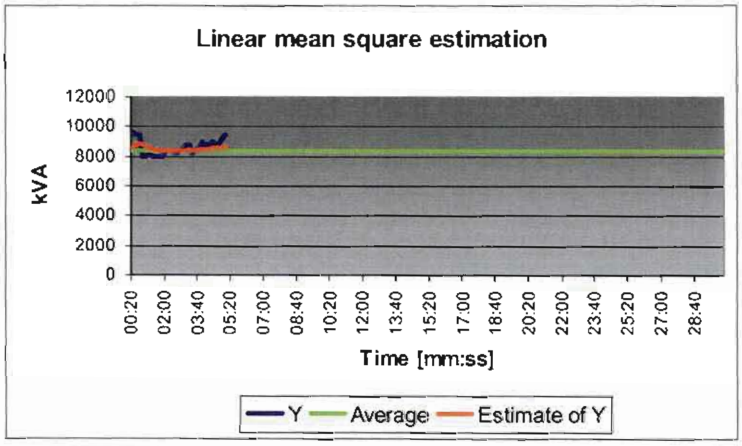


Figure 48: *Linear mean square estimation after 5 minutes*

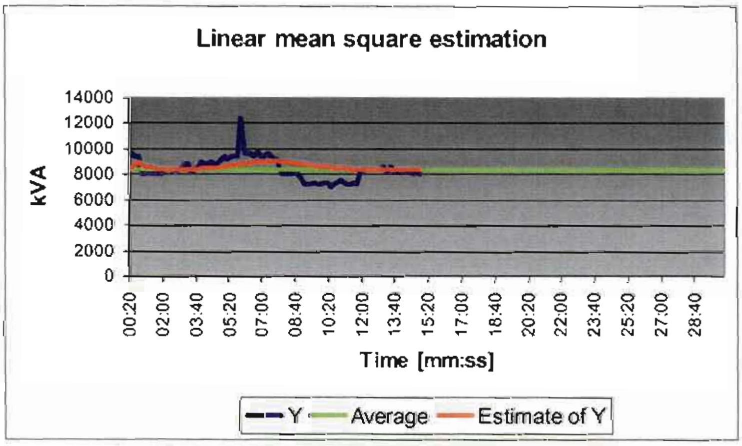


Figure 49: *Linear mean square estimation after 15 minutes*

Figure 48 and Figure 49 show the prediction after 5 and 10 minutes respectively. These prediction values are much more accurate than the linear extrapolation technique described earlier.

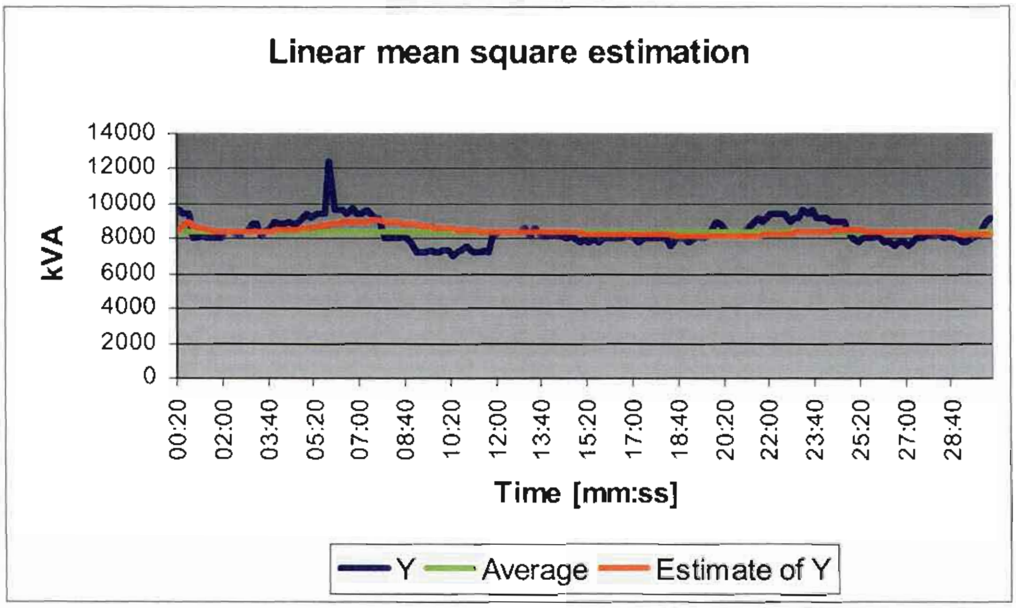


Figure 50: *Linear mean square estimation example*

It can be seen from Figure 50 that the estimation of Y (Y) follows the values of Y closely. There are exceptions when the kVA value of Y has sudden spikes (such as the one at 5:50), but the prediction value is still close to the average of the 30 minute period.

4.2.2.4 Artificial neural networks

An artificial neural network (ANN) is an interconnected group of artificial neurons that uses a mathematical model for information processing [43]. Predominantly an ANN changes its structure based on internal or external information that flows through the network.

In a more practical view, ANNs are non-linear statistical data modelling tools. They are used to model complex relationships between inputs and outputs, or to find patterns in data. The term ANN tends to refer mostly to neural networks employed in statistics and artificial intelligence.

An ANN consists of several layers [43]. One layer is an input layer; there is at least one hidden layer; last is the output layer. This is illustrated in Figure 51.

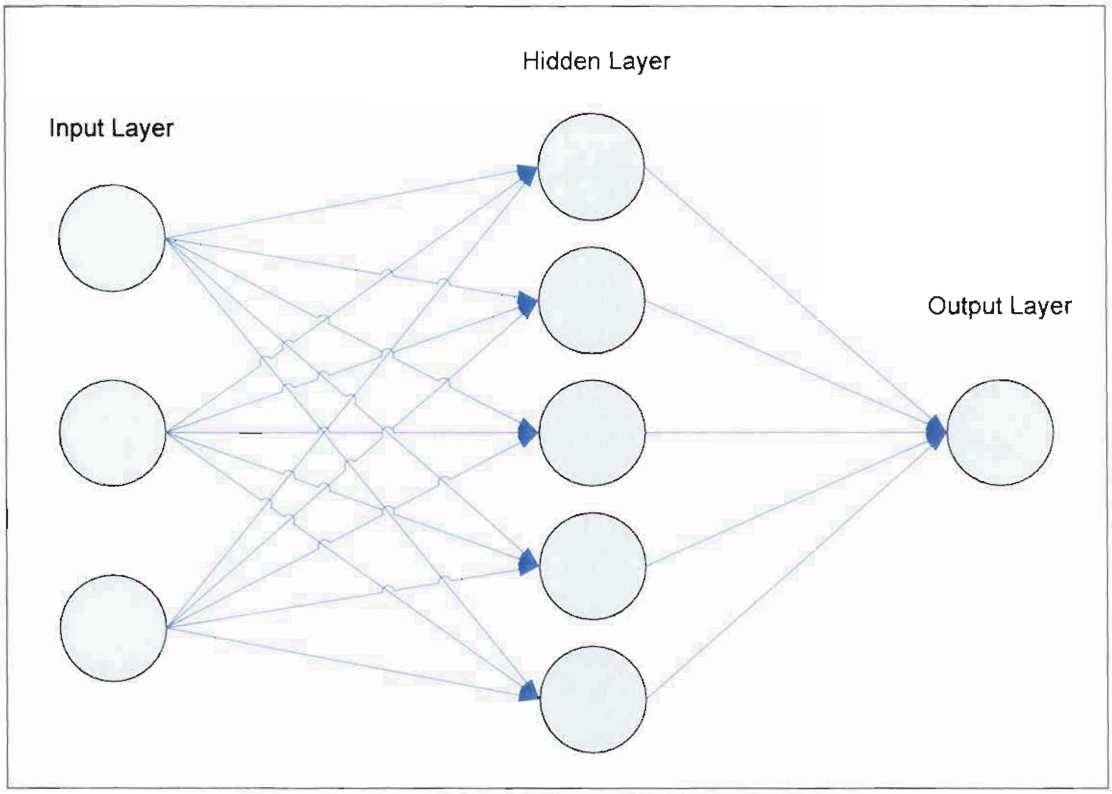


Figure 51: *Layers of an artificial neural network*

Each node in the layers of Figure 51 is connected to all the nodes of the previous layer. These connections are weights used in calculation. Every node sums the weighted inputs and calculates a non-linear function. The output of a layer is propagated to the next layer, or the output layer itself.

4.2.2.5 Fuzzy logic

Fuzzy logic deals with reasoning that is approximate rather than precisely deduced from classical predicate logic. Allowance is made for set values between and including 0 and 1 – shades of grey as well as black and white. In its linguistic form, these are imprecise concepts such as *slightly*, *quite* and *very* [44].

Each set of input variables are converted into a set of output variables using conditional logic. A predicted value is obtained by reversing the process. This process is known as *defuzzification* [45].

4.2.2.6 Conclusion

Only two of the four prediction techniques discussed in detail include mathematical procedures. Of these two, the linear extrapolation technique is much simpler to implement, but the linear mean square statistical estimation is more accurate.

The other two techniques include a sense of artificial intelligence. One method uses an artificial neural network and the other uses fuzzy logic. Compared with the mathematical procedures, these methods are much more complicated to implement and are therefore not investigated in detail. The other techniques proved to be successful.

The desired technique depends on the application. It is better to use a simpler, less processor intensive method if the prediction software is installed on the same computer as the SCADA system. If a separate system is installed, a more involved method can be used.

4.3 VERIFICATION OF THE SIMULATION MODEL

4.3.1 Introduction

The electricity usage of the mine was replicated using simulation software. All the software used had to be developed beforehand. Values for the electricity demand used during simulation, were obtained by installing electrical power loggers on the mine to monitor the load drawn from the Eskom incomers.

These actual values were then used as input to the simulation model to verify that the MD controller managed the winders in such a way as to prevent the NMD from being breached.

Simulation software had to be developed for the following components:

- Winder
- Winder controller
- Silo (used to store reef)
- MD meter
- MD controller

These components run in an environment known as the *Platform*, developed by HVAC International. The software was developed in such a way that the components used for the simulation could be reused for the control of the real system after installation on the mine. As the mine already has a SCADA system that communicates with the PLCs that controls the winders, the software was developed to communicate with the SCADA instead.

UML (Unified Modelling Language) is a visual language that provides a way for designers of object-oriented systems to visualize, construct and document the software system during development [42]. Many systems begin with use cases, as it provides a clear picture of what is planned in a new system. The use case diagram for the MD control system is illustrated in Figure 52.

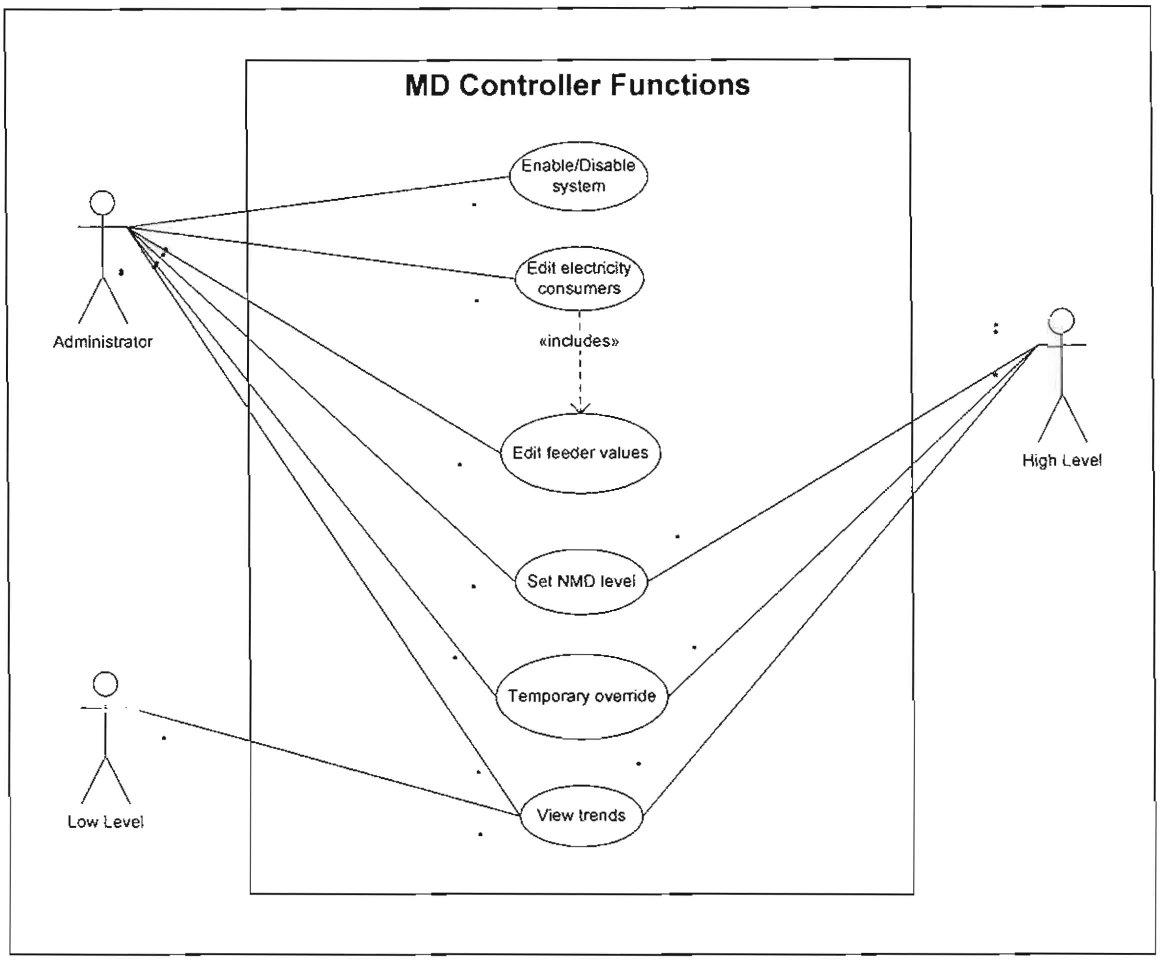


Figure 52: *Use case diagram*

The use case diagram shows *use cases* and *actors* and the associations among them. Use cases represent sequences of actions by the system; actors represent people (or other systems) that interact with the modelled system. In the diagram of Figure 52, the different user levels and the commands they can execute, are illustrated. The *«includes»* relationship indicates that when the *electricity consumers* are edited, that the *feeder values* are inherently edited as well.

A sequence diagram is used to model the interaction between object instances in the context of a relationship. Object instances are arranged horizontally, with the time running vertically from top to bottom.

The sequence diagram is shown in Figure 53.

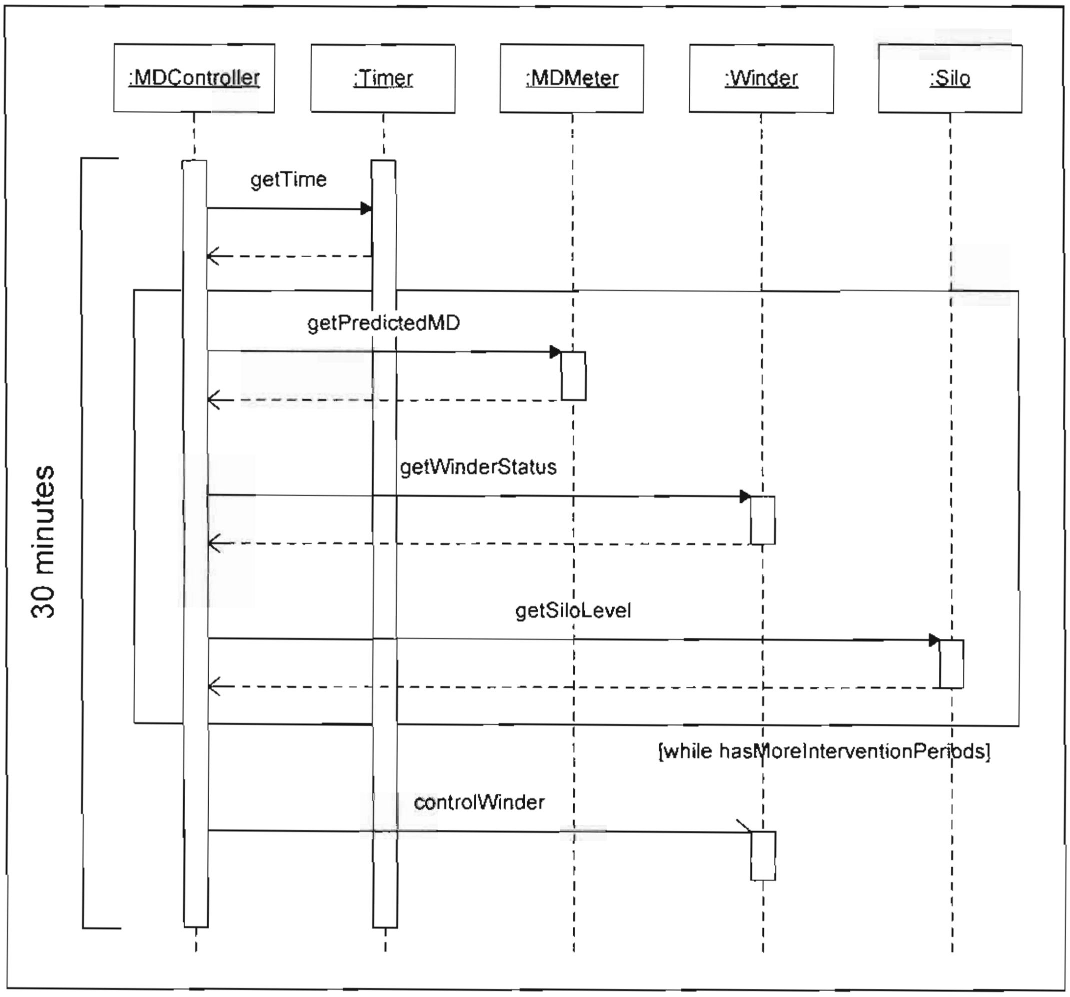


Figure 53: *Sequence diagram*

The sequence diagram indicates the order of progression of the MD controller. This cycle is executed on each intervention instance during the 30 minute period. Message flow is indicated with arrows. The notation used is explained in Table 5.

Table 5: *Sequence diagram message flow notation*

——►	Synchronous	Message sent from one object to another; the sending object waits for a result
——>	Asynchronous	Message sent from one object to another; the sending object does not wait for a result
- - - - ->	Return	Represent explicit return of control from the object to which the message was sent

Activity diagrams are used to describe workflows. At design level, they can be used to describe the detail flow within an operation. The activity diagram for the MD controller is shown in Figure 54.

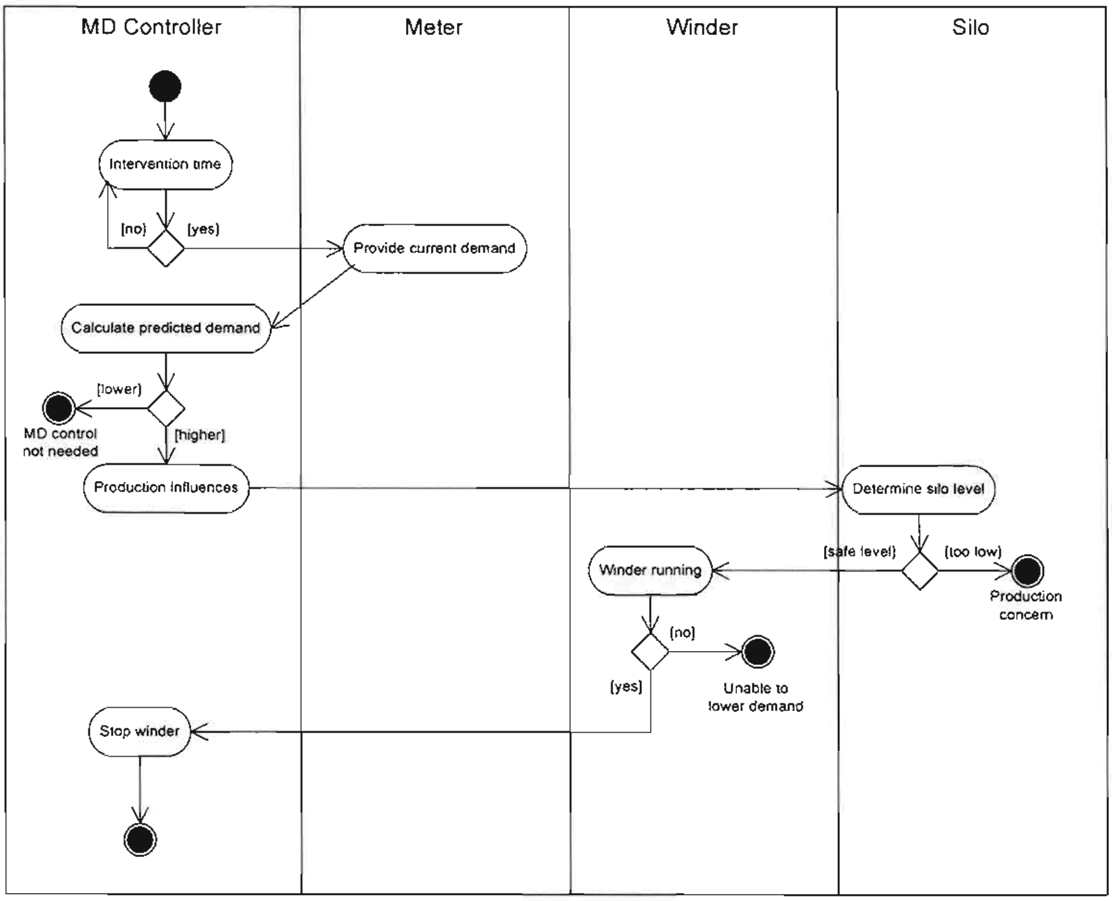


Figure 54: *Activity diagram*

The activity diagram in Figure 54 indicates the workflow of the MD controller. It first checks if the current time is an intervention stage. If it is, the meter component provides the current demand, which is used to calculate the predicted demand. The process ends if the predicted demand is lower than a specified threshold as no intervention is needed. If the predicted demand is higher than the threshold, a test is done for production influences. When the silo level is too low, the winder can not be stopped; the process ends. If the silo level is safe, the winder is stopped if it is running. The process repeats for each intervention time during the 30 minute period.

The communication process between the software, SCADA (Supervisory Control And Data Acquisition) and PLCs (Programmable Logic Controllers) is shown in Figure 55. A brief description of each component follows.

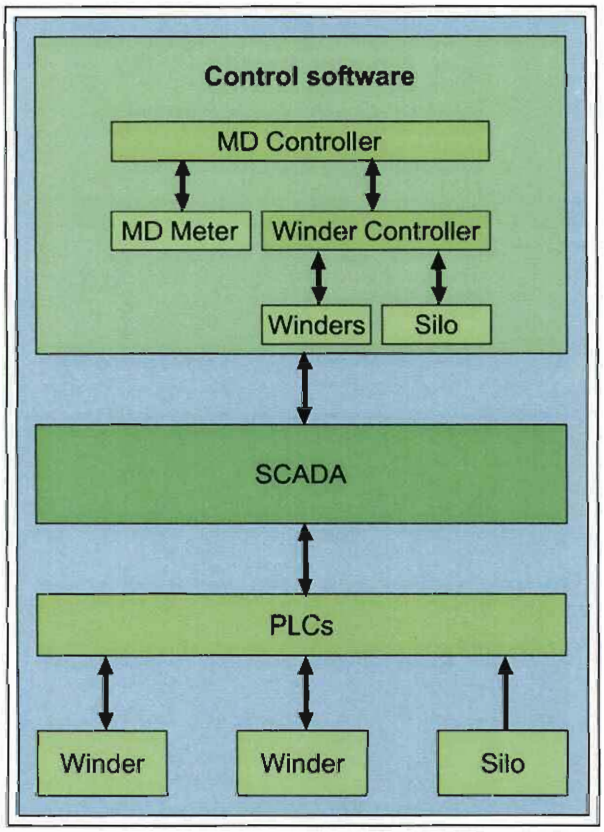


Figure 55: *Schematic diagram of information flow of the MD controller*

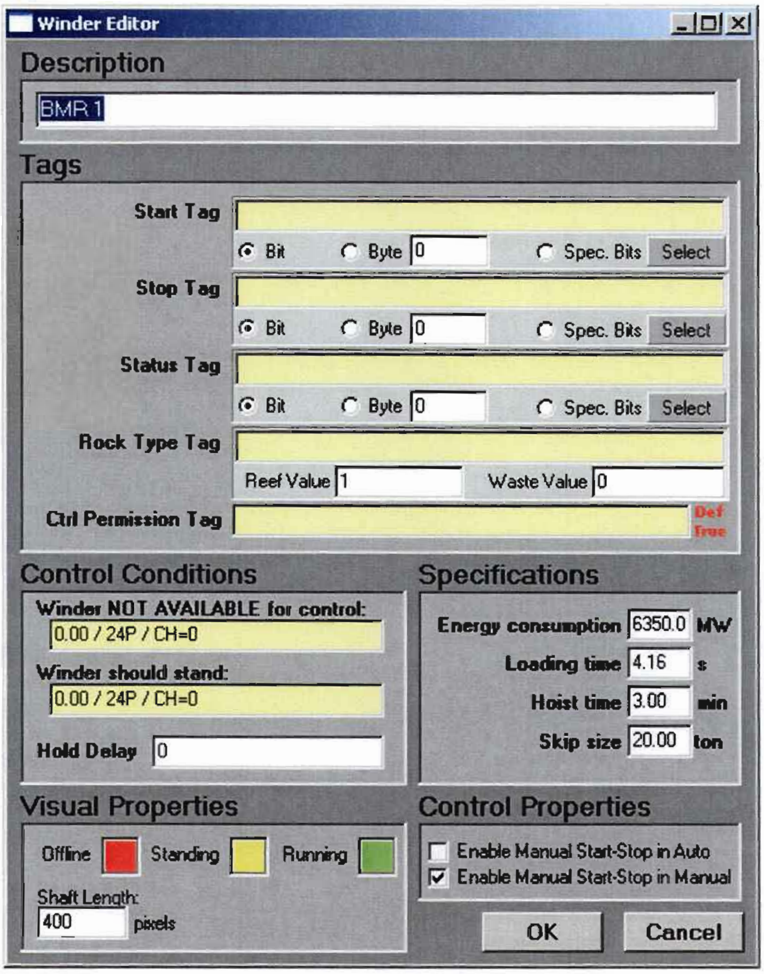
The control software communicates with the mine's SCADA system. Control signals are sent from the SCADA to the PLCs that control the winders. Information, such as the winders' statuses and the silo level are sent back to the PLCs. This data is then read by the SCADA, which in turn provides it to the control software.

Communication between the control software and the SCADA is realised with OPC (OLE for Process Control – OLE stands for Object Linking and Embedding). The OPC link provides tags that contain values from the PLCs. These values can be both read from and written to.

4.3.2 Winder

4.3.2.1 Settings

The winder component is used to simulate and control a winder on the mine. A snapshot of the possible settings is shown in Figure 56.



Description: BMR 1

Start Tag: ● Bit ○ Byte 0 ○ Spec. Bits

Stop Tag: ● Bit ○ Byte 0 ○ Spec. Bits

Status Tag: ● Bit ○ Byte 0 ○ Spec. Bits

Rock Type Tag: Reef Value 1 Waste Value 0

Ctrl Permission Tag

Winder NOT AVAILABLE for control: 0.00 / 24P / CH=0

Winder should stand: 0.00 / 24P / CH=0

Hold Delay 0

Energy consumption 6350.0 MW

Loading time 4.16 s

Hoist time 3.00 min

Skip size 20.00 ton

Offline 🟥 Standing 🟨 Running 🟩

Shaft Length: 400 pixels

☐ Enable Manual Start-Stop in Auto

☑ Enable Manual Start-Stop in Manual

Figure 56: *Winder component's settings*

4.3.2.2 Tags

- *Start* and *stop* control the winders
- *Status* checks if the winder is running
- *Rock type* specifies if the winder is hoisting waste or reef rock
- *Control permission* indicates if the winder may be controlled

4.3.2.3 Control conditions

Conditions can be specified when the winder is *not available* for control; or when the winder *should stand*. *Hold delay* indicates the length of a pulse to the SCADA. A hold delay of 0 seconds means the pulse is maintained for the duration of the condition. For example, a start command would be maintained until the winder has to stop again. A hold delay of x seconds (with $x > 0$), would result in the pulse returning to 0 after the x seconds. This setting's value depends on the SCADA connected to.

4.3.2.4 Specifications

With the exception of the *skip size*, the specification settings do not interfere with the control of the system. These settings are only used for logging purposes. During simulation mode, the silo reads the *skip size* to determine in or out flows in the course of level calculations.

4.3.2.5 Visual properties

The visual properties are used to change the display settings of the winder. Colours for *offline*, *standing* and *running* conditions can be specified. The height of the shaft can be changed as well. These settings do not interfere with the control of the system.

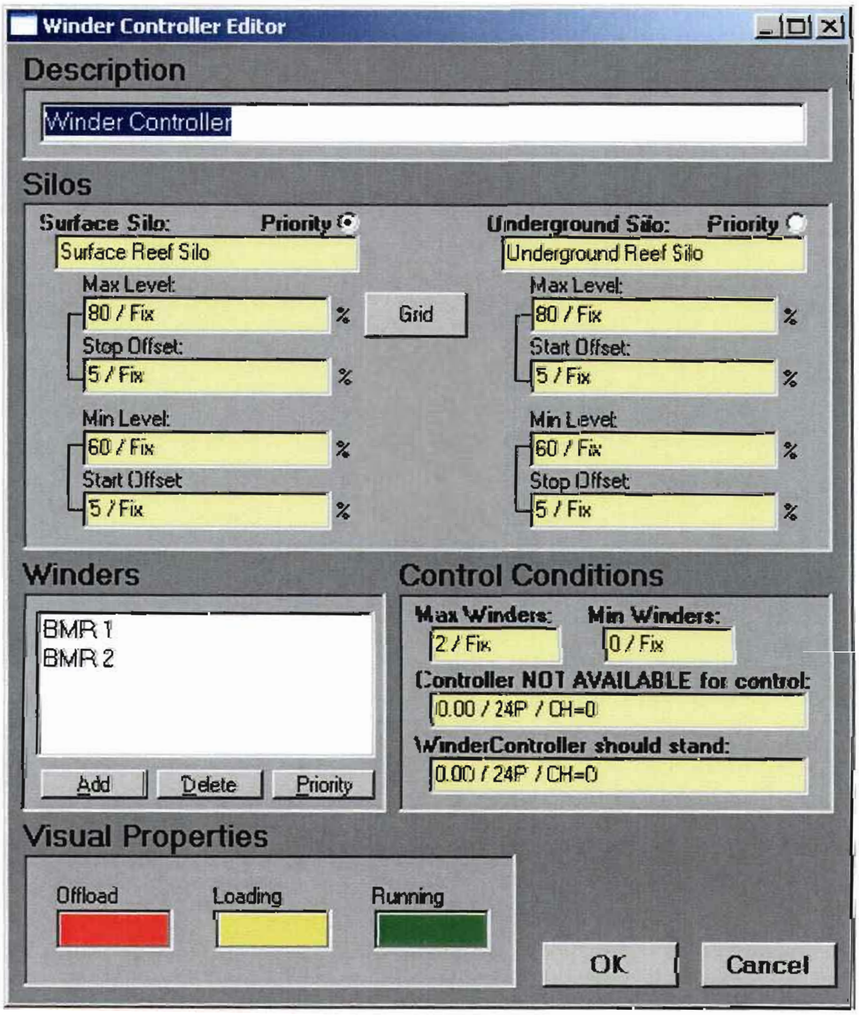
4.3.2.6 Control properties

The control properties specify whether the winder can be controlled by the control room operator under certain conditions. The two conditions are the *auto* and *manual* states of the Platform.

4.3.3 Winder controller

4.3.3.1 Settings

The winder controller is used to control each winder component. It requests the winder component to stand or run. Settings for the winder controller are shown in Figure 57.



Description

Winder Controller

Silos

Surface Silo: Priority ●
Surface Reef Silo
Max Level: 80 / Fix %
Stop Offset: 5 / Fix %
Min Level: 60 / Fix %
Start Offset: 5 / Fix %

Underground Silo: Priority ○
Underground Reef Silo
Max Level: 80 / Fix %
Start Offset: 5 / Fix %
Min Level: 60 / Fix %
Stop Offset: 5 / Fix %

Winders

BMR 1
BMR 2

Control Conditions

Max Winders: 2 / Fix
Min Winders: 0 / Fix
Controller NOT AVAILABLE for control: 0.00 / 24P / CH=0
WinderController should stand: 0.00 / 24P / CH=0

Visual Properties

Offload 🟥
Loading 🟨
Running 🟩

Figure 57: *Winder controller's settings*

4.3.3.2 Silos

The winder controller consists of two sections: the surface controller and the underground controller. The surface controller is responsible for the reef level of the surface silo, while the underground controller is responsible for the reef level of the underground silo.

The surface controller checks the boundaries of the surface silo. A winder will be stopped as soon as the surface silo reaches its specified maximum level. Should the silo level still be rising, following winders will be stopped at the stop offset added multiple times to the upper level (see Figure 58). The first winder will be started when the silo reaches its specified lower level. Subsequent winders will be started when the silo's level reaches its lower level minus the start offset.

The underground controller checks the boundaries of the underground silo. A winder will be started as soon as the surface silo reaches its specified upper level. Should the silo level still be rising, following winders will be started at the start offset added multiple times to the upper level (see Figure 58). The first winder will be stopped when the silo reaches its specified lower level. Subsequent winders will be stopped when the silo's level reaches its lower level minus the stop offset.

When the surface silo has priority, the controller's schedule is calculated using the surface silo's levels. The underground silo's levels will only be used during calculations if the surface silo's levels are inside the preferred zone as illustrated in Figure 58. The same conditions apply if the underground silo has priority.

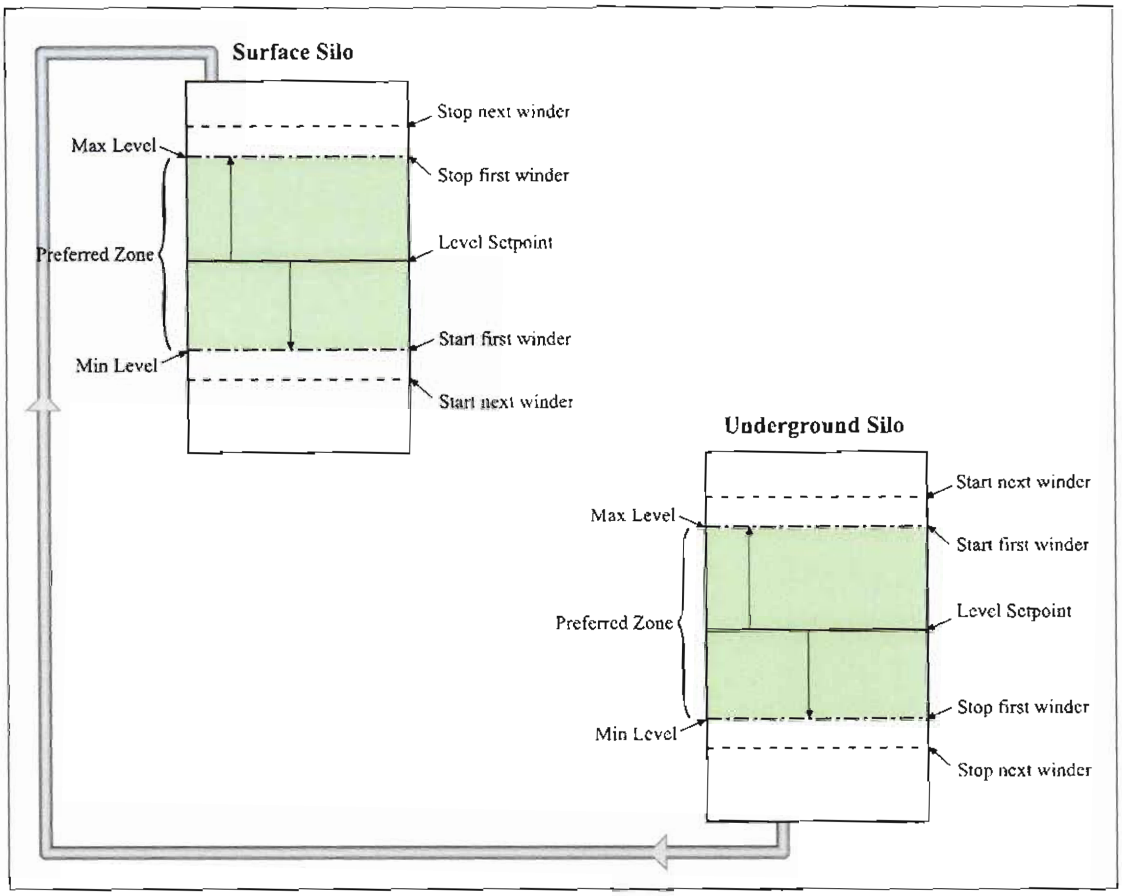


Figure 58: *Schematic of winder controller control philosophy*

In some instances, the mine does not have an underground silo per se. In these cases, the total ore underground is not available on the SCADA. Therefore, the controller will control the winders only according to the level of the surface silo.

4.3.3.3 Winders

The winders list is used to add and remove winders that will be controlled by the winder controller.

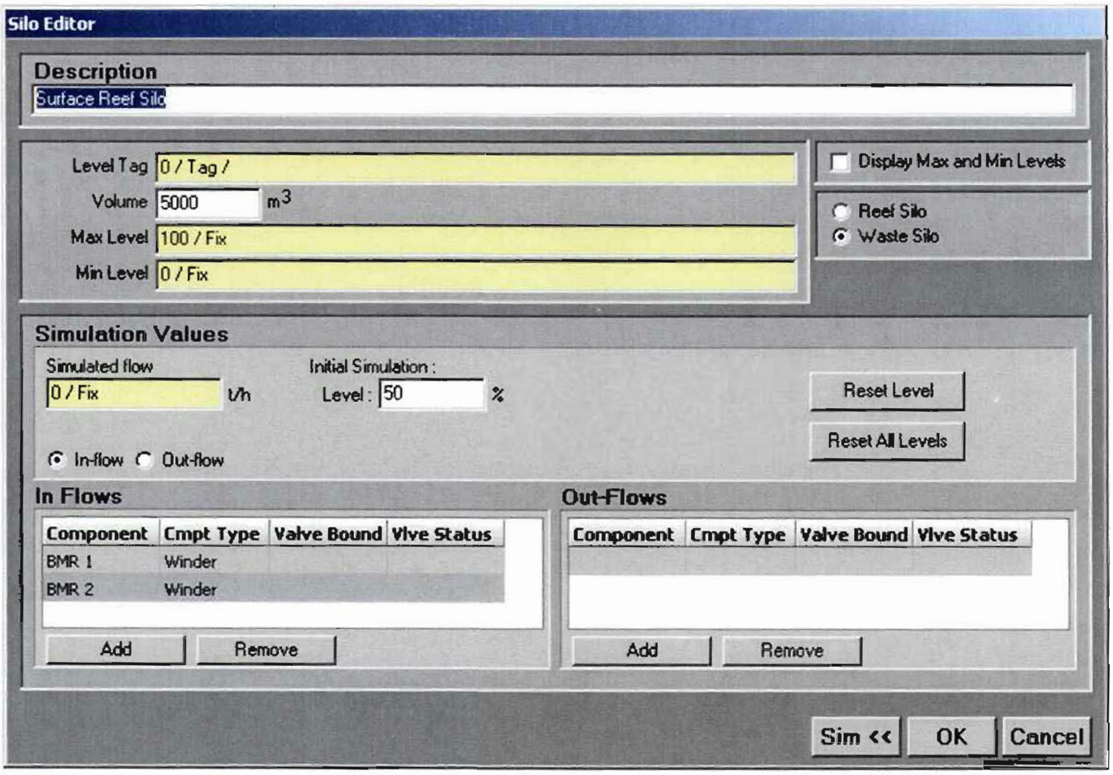
4.3.3.4 Control conditions

The *maximum* and *minimum* number of winders that can run at a specific time can be changed. As in the case of the winder component, the winder controller have settings to specify when the list of winders are *not available* for control; or when the winders should *stand*.

4.3.4 Silo

4.3.4.1 Settings

The silo component is used to read a value from the mine's SCADA, or to calculate a value during simulations. Figure 59 shows the settings for the silo component.



Description
Surface Reef Silo

Level Tag 0 / Tag /
Volume 5000 m^3
Max Level 100 / Fix
Min Level 0 / Fix

☐ Display Max and Min Levels

○ Reef Silo
● Waste Silo

Simulation Values
Simulated flow 0 / Fix t/h
Initial Simulation : Level : 50 %
● In-flow ○ Out-flow

In Flows

Component	Cmpt Type	Valve Bound	Vlve Status
BMR 1	Winder		
BMR 2	Winder		

Out-Flows

Component	Cmpt Type	Valve Bound	Vlve Status

Figure 59: *Silo component's settings*

The silo's *level* is read from a tag provided by the SCADA. The *volume* (in m^3), *maximum level* and *minimum level* (as percentage values) are entered by the user. Each silo can be specified as either containing *reef* or *waste*. The silo's maximum and minimum values are optionally displayed next to the silo.

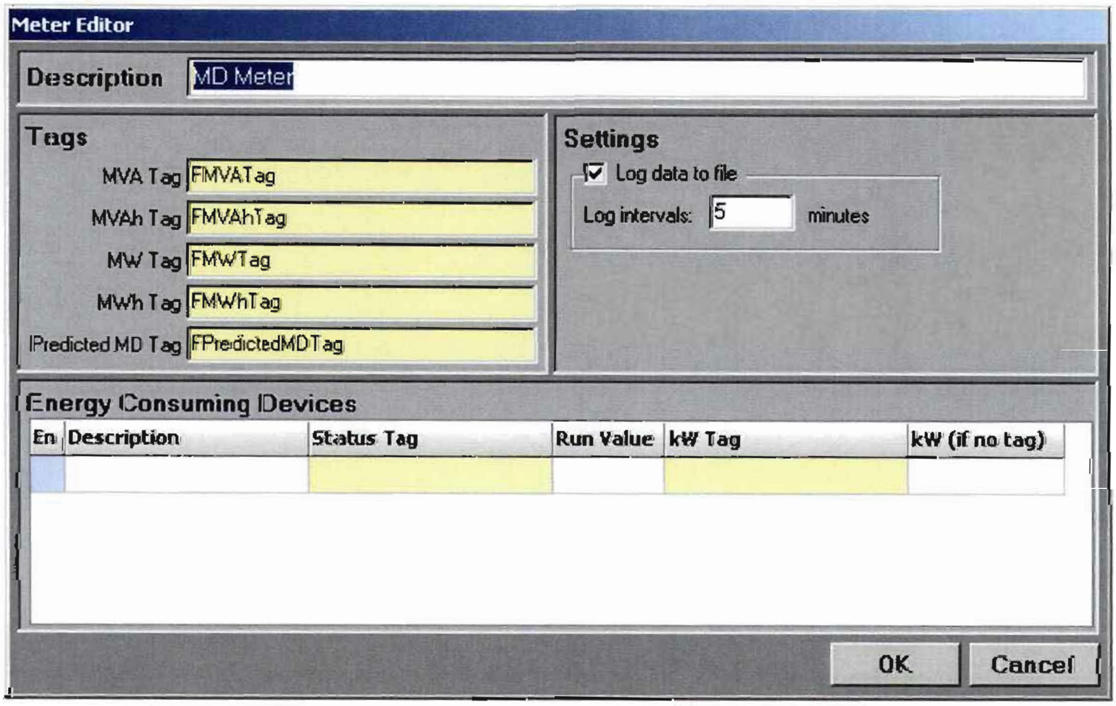
Unlike the other components, the silo is aware that the Platform is in simulation mode. A *simulated flow* value (in tons per hour) is used during calculations of the silo's level. This value is either an *in* or an *out flow*. An *initial* simulation level value should be specified as well.

States of winders can affect the silo level during simulation. A running winder can increase the level of a silo if it is selected as an *in flow*. Likewise, a running winder decreases the silo level if it is selected as an *out flow*.

4.3.5 MD meter

4.3.5.1 Settings

The MD meter is used to read electricity usage values from the mine's SCADA, or to calculate values during simulation. Settings for the MD meter are shown in Figure 60.



Description: MD Meter

MVA Tag: FMVATag
MVAh Tag: FMVAhTag
MW Tag: FMWTag
MWh Tag: FMWhTag
Predicted MD Tag: FPredictedMDTag

☑ Log data to file
Log intervals: 5 minutes

En	Description	Status Tag	Run Value	kW Tag	kW (if no tag)

Figure 60: *MD meter's settings*

The tags that can be read from the SCADA include *MVA*, *MVAh*, *MW*, *MWh* and *predicted MD* values. These tags will not necessarily be available on all mines – therefore, the list of *electrical energy consuming devices* was added. Devices added to this list will be monitored to check if they are running.

Each device has:

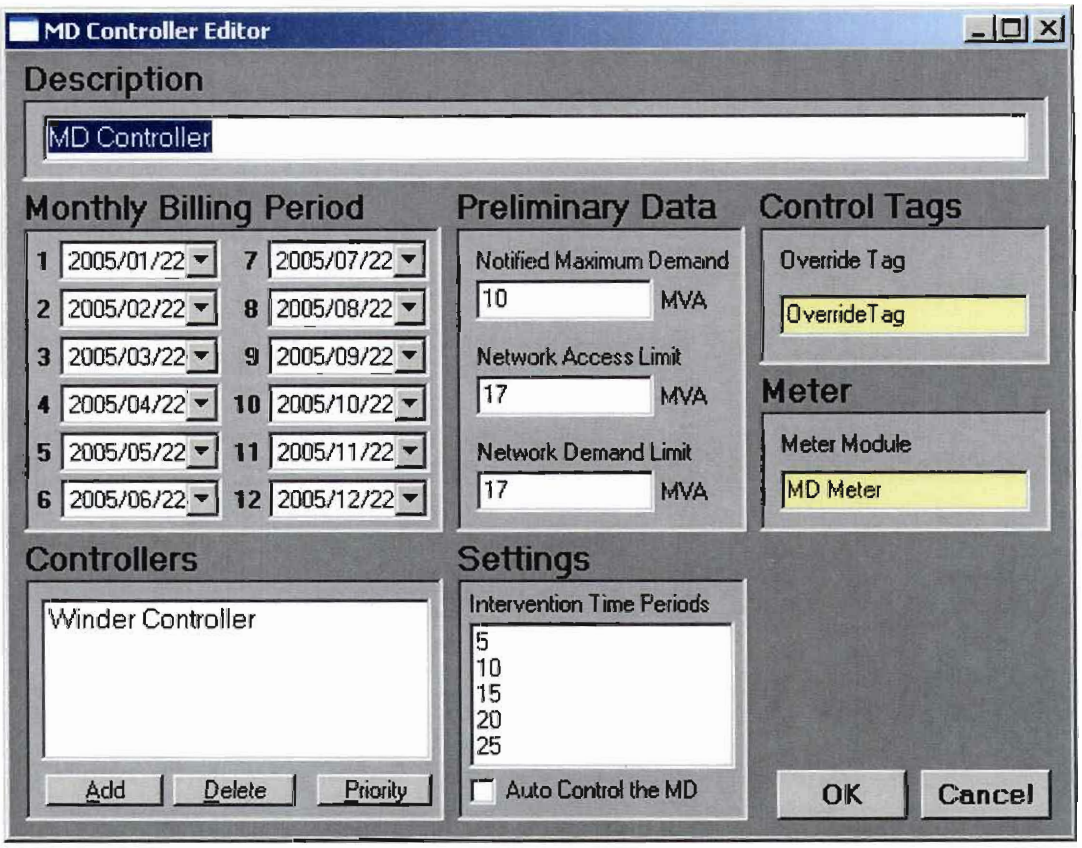
- a *description*,
- a *status tag* (to be read from the SCADA),
- a value that corresponds with the *running state* of the device (linked to the status tag),
- a *kW tag*,
- and an approximate *kW value* (if there isn't a kW tag available).

The kW values of all the running devices are summated to calculate the current electrical energy usage of the mine. These values are logged by the MD meter itself. The logging can optionally be disabled, or the interval can be changed.

4.3.6 MD controller

4.3.6.1 Settings

The MD controller is used to calculate the predicted MD during a certain time interval. Figure 61 shows the settings for the MD controller.



Description
MD Controller

Monthly Billing Period
1 2005/01/22
2 2005/02/22
3 2005/03/22
4 2005/04/22
5 2005/05/22
6 2005/06/22
7 2005/07/22
8 2005/08/22
9 2005/09/22
10 2005/10/22
11 2005/11/22
12 2005/12/22

Preliminary Data
Notified Maximum Demand 10 MVA
Network Access Limit 17 MVA
Network Demand Limit 17 MVA

Control Tags
Override Tag OverrideTag

Meter
Meter Module MD Meter

Controllers
Winder Controller

Settings
Intervention Time Periods
5
10
15
20
25
☐ Auto Control the MD

Figure 61: *MD controller's settings*

The *monthly billing period* determines when each billing month starts, used to resolve the start of a new month when calculating the AUC or MUC. Preliminary limits for the *NMD*, the *NAC* (all time periods) and the *NDC* (standard and peak periods) are specified for initial calculations. An optional tag can be added for *override* purposes to enable the control room operator to disable the MD controller from the SCADA.

Controllers that can help with MD intervention are added to a list in the MD controller. The *meter module* that supplies the current electricity demand must be selected for the MD controller to be able to function. *Intervention time periods* must be selected as well. These are the times when the controller checks that the demand does not exceed the specified thresholds (NMD, NAC and NDC).

4.3.7 Platform

The components listed in 4.3.2 to 4.3.6 run in an environment known as the Platform. Any number of combinations of components can be added to the Platform. These components are then set up to interact with each other. Figure 62 illustrates the interaction between the components.

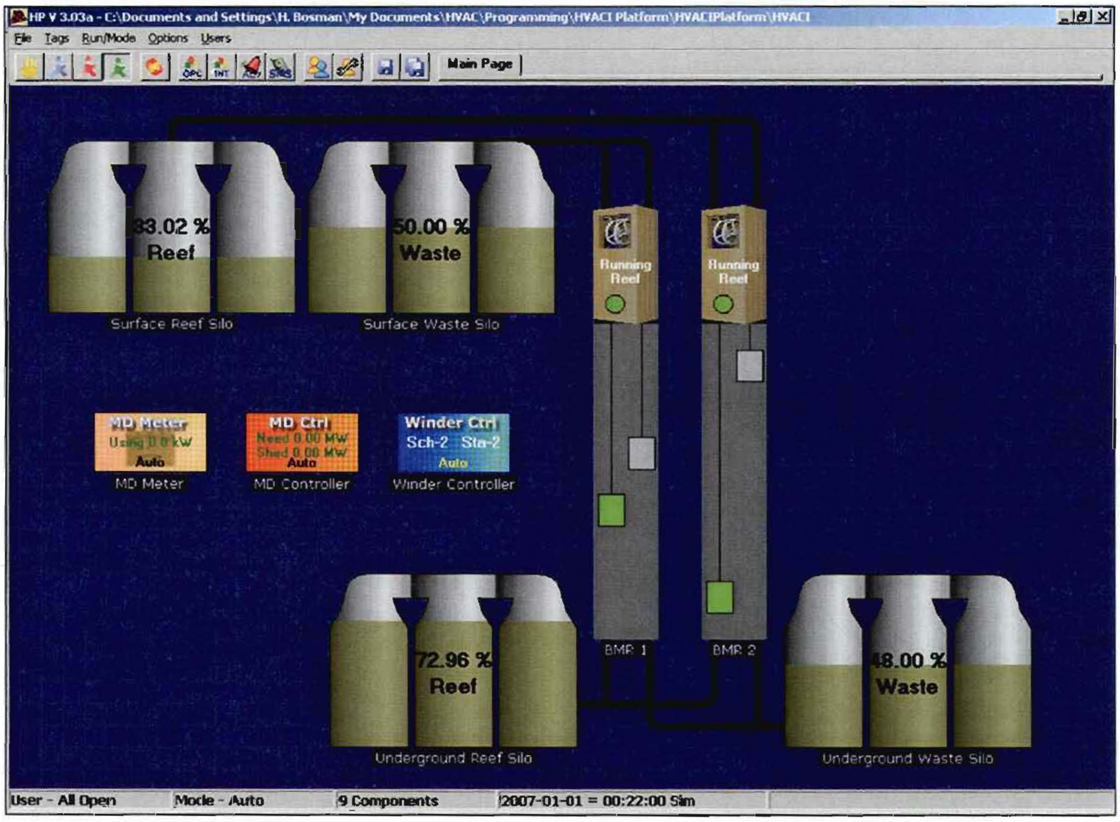


Figure 62: *The Platform with winders, silos, an MD meter, MD controller and a winder controller*

The Platform has four operating modes: edit, idle, manual and auto. Operating modes are selected by the four icons on the left of the toolbar (respectively the yellow hand, the blue, red and green figures), shown in Figure 63.

Figure 63: *Platform settings and options*

Other settings of the Platform include:

- run mode (real time or simulation),
- OPC options,
- internal tags (used for advanced calculations),
- alarms,
- SMS notifications (in case of for example alarms)
- and user management.

These settings are not discussed in detail, as the Platform is only an environment for the other components to run in.

4.3.8 Simulation results

A simulation was performed to test the prediction algorithms and effects of switching the winders, using the software developed. The clear water pumping system and the rock winders are linked to the MD meter for calculation purposes.

Pump status is obtained from controllers installed at the mine. These controllers form part of an automation system that controls the pumps in accordance with DSM principles [49]. Figure 64 displays the layout of this pumping system.

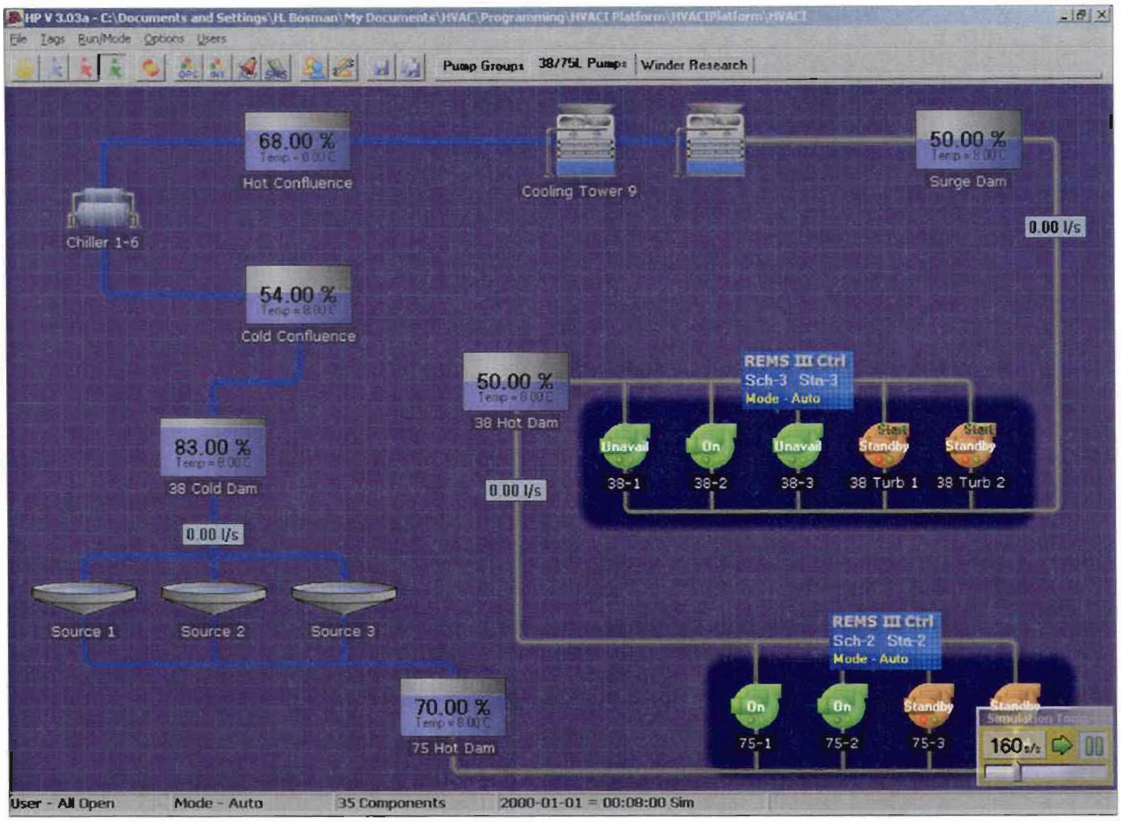


Figure 64: *Layout of the pumping system used for simulations*

Figure 64 shows the seven pumps logged in the MD meter. There are three pumps and two turbines on 38 Level. Turbine status is not monitored by the MD meter, as turbines use the kinetic energy of descending water to pump water from the hot dam on 38 Level. The four pumps on 75 Level are monitored.

It can be seen in Figure 64 that the Platform is in simulation mode. This is evident from the time and date displayed in the status bar, as well as the yellow *Simulation Tools* window in the bottom right corner.

The winders, winder controller, silo, MD meter and MD controller are shown in Figure 65. These components are used during simulations to calculate the silo levels, current electricity demand and winder schedules.

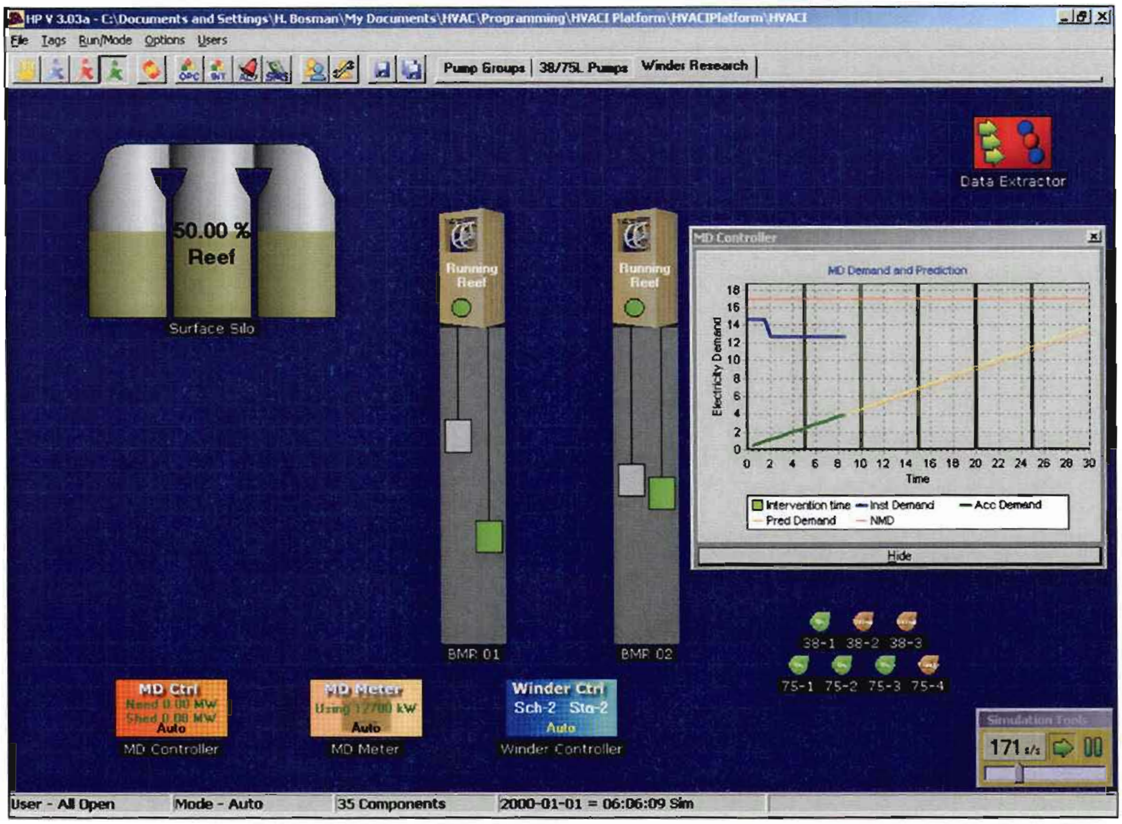
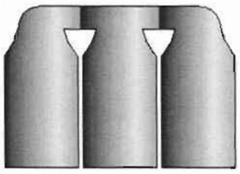


Figure 65: *Simulation of the MD controller and its components*

Two tool windows are displayed as well. The simulation control window (Figure 65, bottom right) enables the user to set the simulation speed, or start/stop the simulation. The graph window (Figure 65, middle right) indicates the instantaneous demand, compared with the predicted demand. This window is described in detail in Figure 66. The components simulated in Figure 65 are described in Table 6.

Table 6: *Components used in simulations*

	Silo	The silo image displays the level of the silo and provides it to the winder controller for scheduling calculations
	Winder	The winder component simulates winder status
	Pump	The pump component displays pump status
 MD Ctrl Need 0.00 MW Shed 0.00 MW Auto	MD controller	The MD controller calculates the MWs to be shed
 MD Meter Using 12700 kW Auto	MD meter	The MD meter provides the kW value of running components
 Winder Ctrl Sch-2 Sta-2 Auto	Winder controller	The winder controller calculates the schedule for the winders according to the silo level

The MD controller's graph window displays the MD demand and prediction, while the instantaneous demand is provided by the MD meter. Figure 66 displays this window.

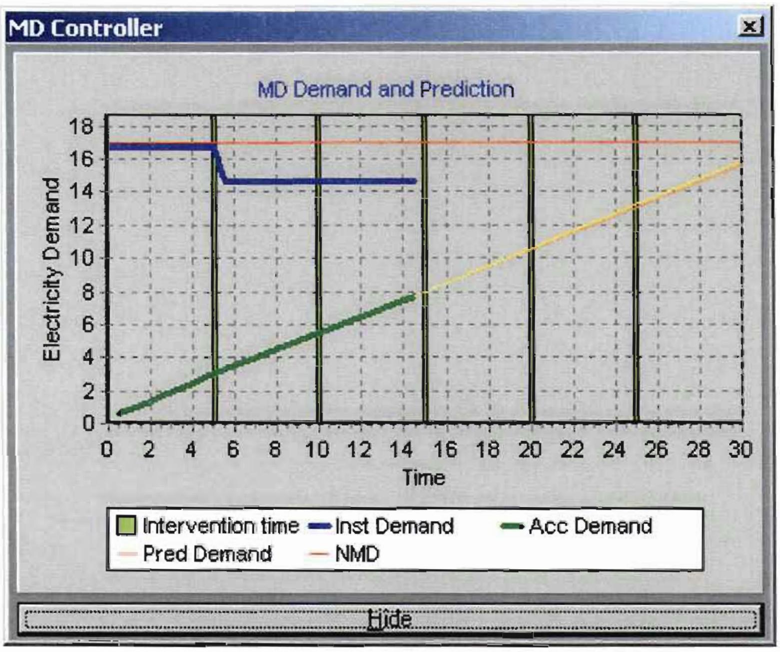


Figure 66: *MD controller graph*

Figure 66's graph contains the following data:

- NMD for the current 30 minute integrated period: horizontal red line.
- Instantaneous demand: blue line.
- Accumulated demand as described in Section 4.2.2: green line starting at point (0, 0). This line is extended using techniques explained in Section 4.2.2 (indicated with the yellow and orange lines).
- Intervention times, as described in Section 4.3.6, are indicated by vertical lines that extend over the height of the graph at 5 minute intervals.

Figure 67 shows simulation results for one day. The simulation results are obtained by summing the pumps' and winders' kW values. The MD controller then calculates a winder schedule according to the total electricity consumption. An NMD of 17 MVA was chosen. This means that the NMD will be breached if both winders and seven pumps are running during standard and peak times. Each pump consumes an estimated 2 000 kVA, BMR 1 consumes 2 700 kVA and BMR 2 consumes 2 000 kVA.

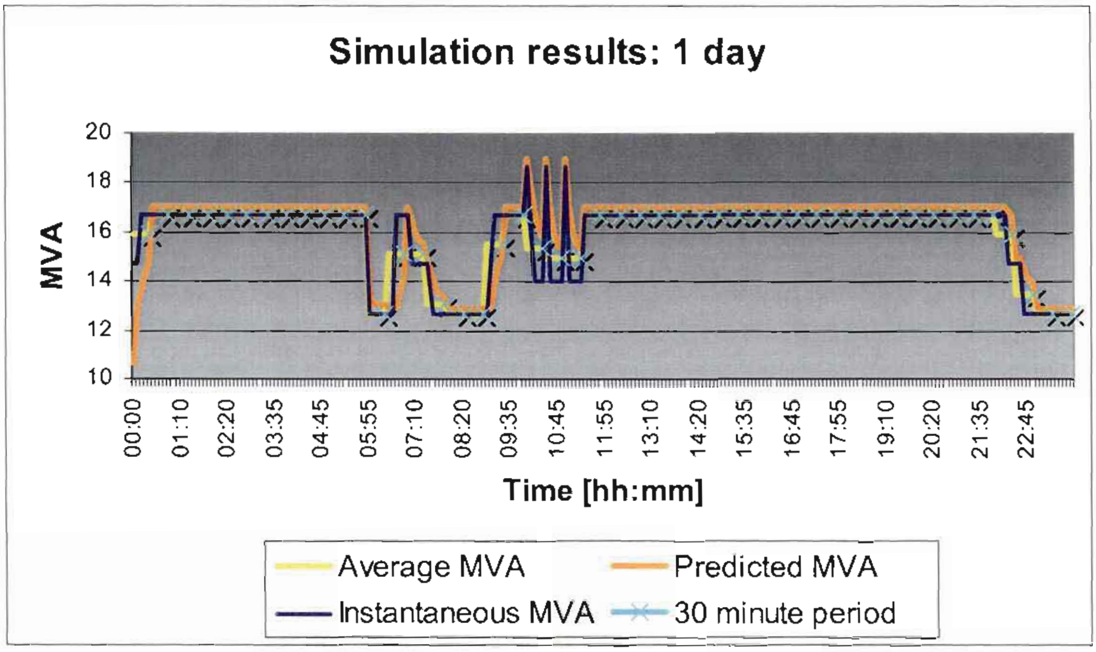


Figure 67: *Simulation results for one day*

The dark blue line in Figure 68 displays the instantaneous MVA demand. Using these values, the MD controller calculates a predicted MVA value, shown in orange. The average electricity demand for the 30 minute integrated period is shown in yellow. The light blue crosses indicate the end-of-demand periods on the average line.

Figure 68 shows the same results for a nine hour period. It can be seen in this graph where the winders were requested to shed some load.

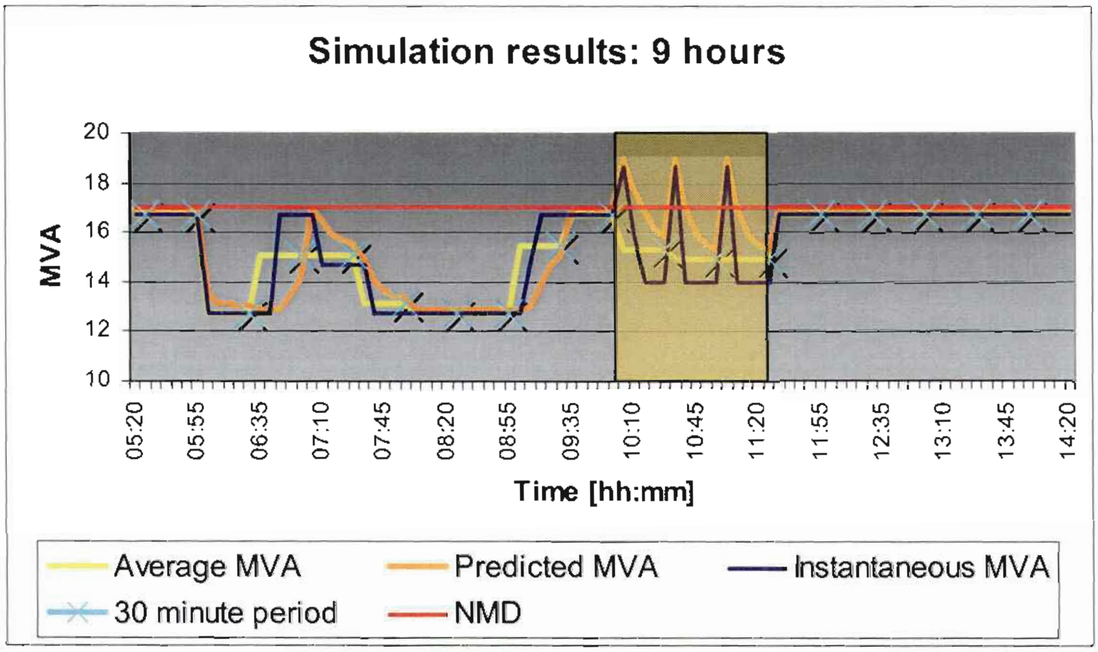


Figure 68: *Simulation results for nine hours*

The spikes in Figure 68 (from 10:00 to 11:20) display the times where the winders were cycled to control the MD. It can be seen that the 30 minute average would have breached the NMD (red line), if the winders were not requested to stand for the remainder of the 30 minute period. BMR 1 stood for a total of 60 minutes to manage the MD and BMR 2 for 55 minutes.

It is important to note that the MD controller did not influence production (Figure 69). The winders have already shed the maximum possible for the day. Therefore they can not be used for any further MD management for the remainder of the day. Using the equations in Section 4.2.2 it can be calculated that a maximum of two hours can be shed per day. This is for a daily production target of 6 000 t and winder cycle times of 3.6 minutes. A two hour period is provided for load shifting activities during the evening peak:

$$\begin{aligned} t_T &= t_L + t_H \\ &= 0.6 + 3 \qquad \text{where } t_L = 0.6 \text{ and } t_H = 3 \text{ min} \\ &= 3.6 \min \end{aligned}$$

$$\begin{aligned} S_H &= \frac{60\,\text{min}}{t_T} \\ &= \frac{60}{3.6} \\ &= 16.67\ \text{skips/hour} \end{aligned}$$

$$\begin{aligned} S_D &= \frac{\text{Production target}}{\text{Skip size}} \\ &= \frac{6000}{18} \qquad\qquad \text{with a skip size of 18 ton} \\ &= 333.33\ \text{skips/day} \end{aligned}$$

$$\begin{aligned} H_R &= \frac{S_D}{S_H} \\ &= \frac{333.33}{16.67} \\ &= 20\ \text{hours} \end{aligned}$$

$$\begin{aligned} H_S &= 24 - H_R \\ &= 24 - 20 \\ &= 4\ \text{hours to shed} \end{aligned}$$

Two hours are subtracted from H_S to calculate the number of hours that can be exploited for MD management. This allows the MD controller 2 hours to stop the winders.

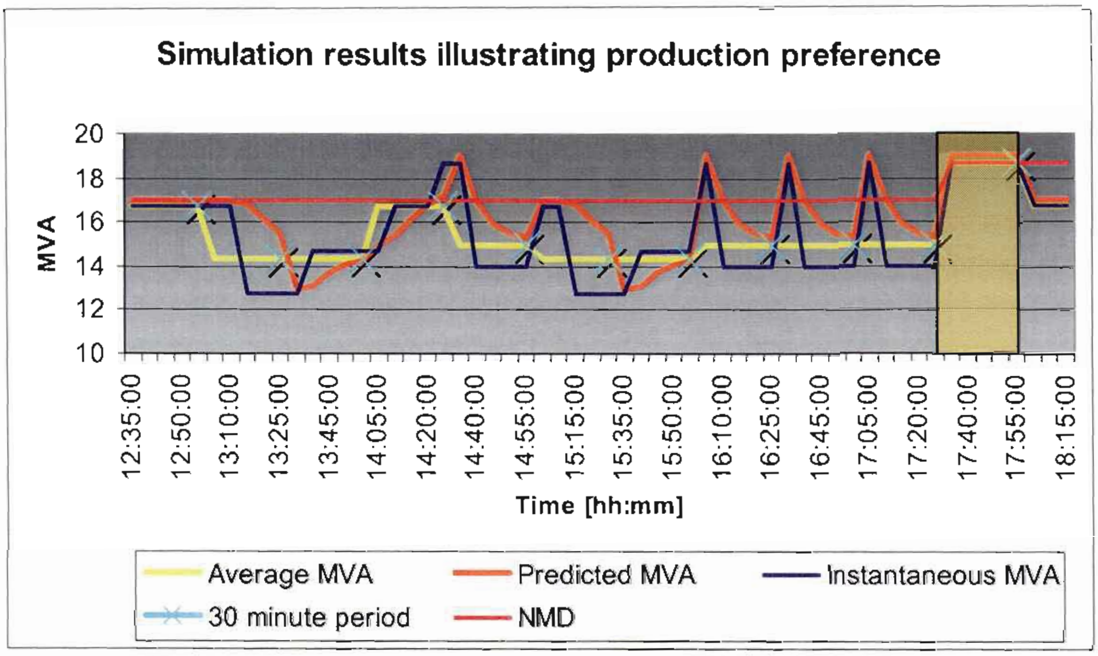


Figure 69: *Simulation illustrating production preference*

The highlighted area of Figure 69 shows where the winders could not prevent the MD from being breached. In the time period from 14:30 to 17:30 the winders were controlled to lower the MD. However the number of pumps running caused the MD to rise again after 17:30. As the winders were already stopped for a total of two hours by 17:30, they could not be stopped again. The MD was therefore breached, as production has privilege over MD control.

It can be seen that the software additionally adjusted the NMD to the new higher value (at 17:30). There is no point in trying to keep the MD below a level that was breached earlier – the mine would already be penalised for a higher MD than the one notified to Eskom (see Section 1.3).

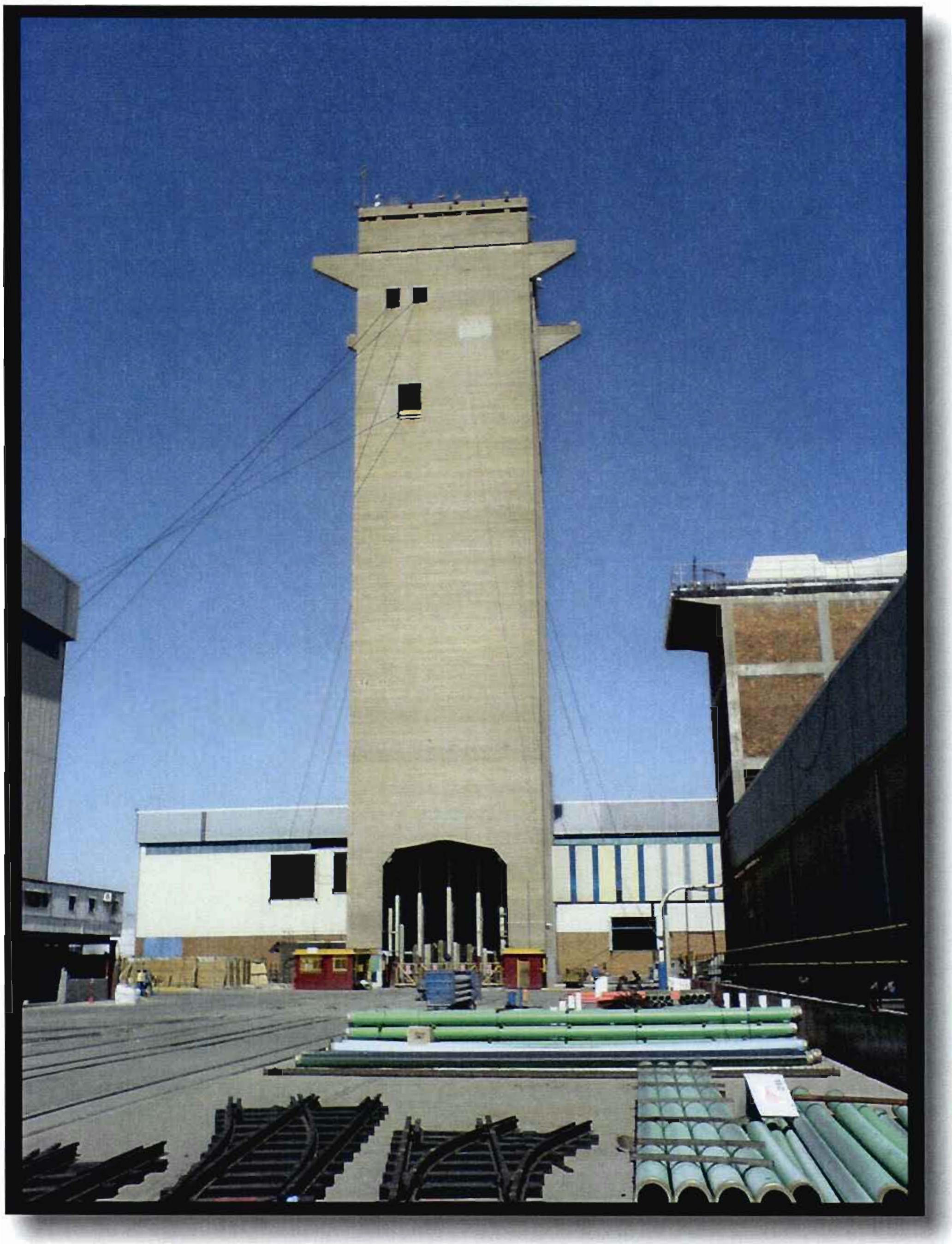
4.4 CONCLUSION

The simulation software developed, using the mathematical procedures described in this chapter, proved to be successful in maintaining the MD below that of a specified NMD. Although the simulations were only performed using the clear water pumping system together with the rock winding system, results attained proved that the winders could be used to manage the MD.

Production will not be affected by the use of the software, as was proved during the simulation. Results obtained demonstrated that the MD controller will not interfere with the winding operation if it is determined that production will be influenced.

Other DSM ventures, such as load shifting, would not be affected either. The MD controller works in conjunction with these controllers. This was proved by the pump controller that managed the pumps in unison with the MD controller.

CHAPTER 5: CASE STUDY – KOPANANG GOLD MINE



5.1 BACKGROUND ON KOPANANG MINE

Kopanang, owned by AngloGold Ashanti, is situated on the Free State side of the Vaal River, close to Orkney. It forms part of AngloGold Ashanti's Vaal River Operations together with Great Noligwa, Tau Lekoa and Moab Khotsong. The Vaal River and West Wits Operations are the only active AngloGold Ashanti operations in South Africa.

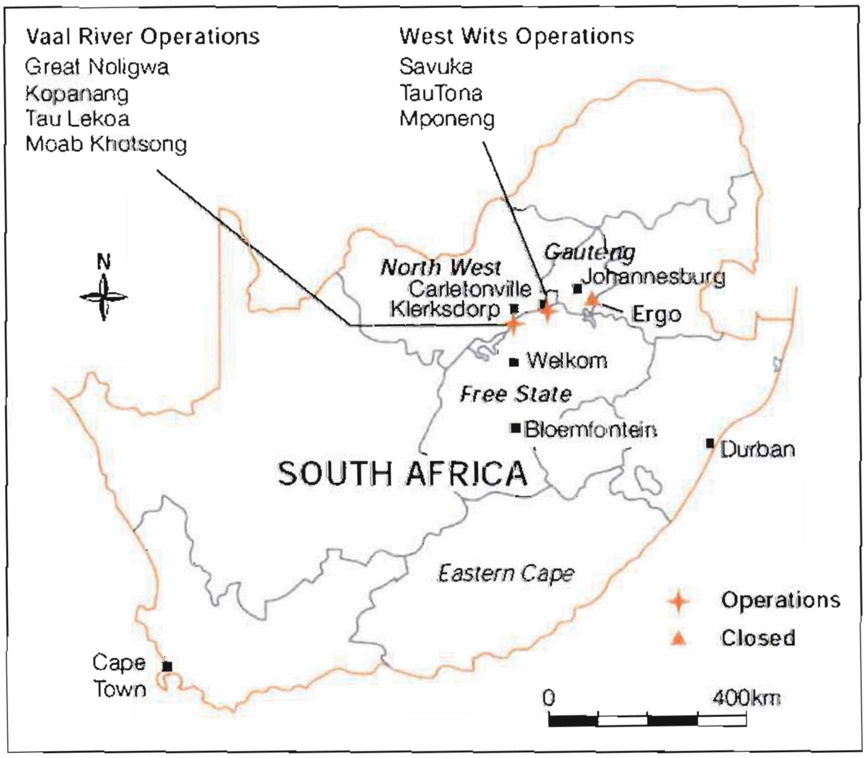


Figure 70: *AngloGold Ashanti's South African operations [22]*

The sinking of the mine's shaft started in 1978, with first gold produced during 1984. The shaft has a depth of 2 240 m and hoists 226 000 tons of material, including waste, per month. Currently, there are 6 300 employees, including contractors. The mine is expected to last another 15 to 20 years [22].

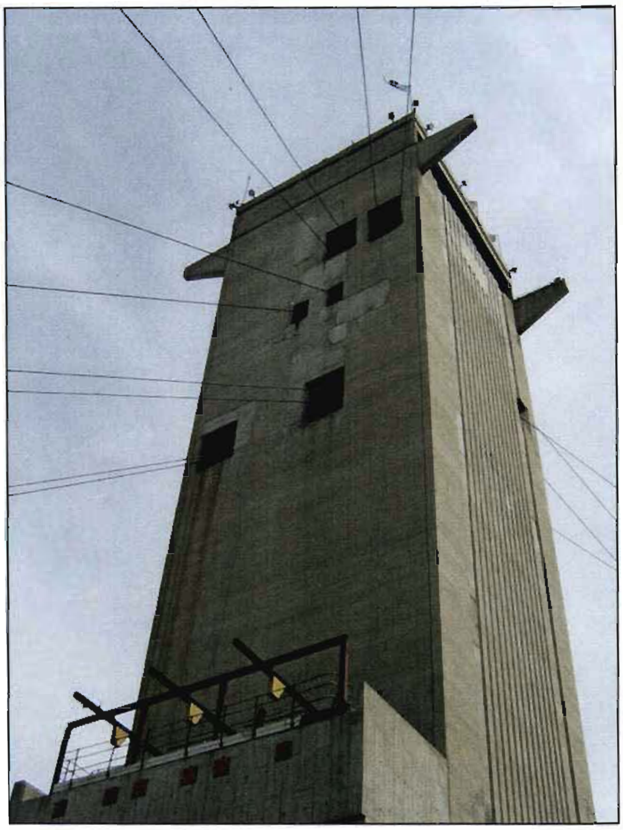


Figure 71: *Kopanang's shaft tower*

The Vaal Reef is the principal reef mined at Kopanang. A secondary C Reef, which is mined on a smaller scale, lies 200 m above the Vaal Reef. Due to the complex geological units and lateral variations in the character of the Vaal Reef, several distinct facies have been identified. Each of these facies has its own unique gold distribution and grade characteristics. At Kopanang in particular, gold is associated with narrow, discontinuous bands of pyrobitumen which are present in the Stilfontein facies of the Vaal Reef.

Ore from Kopanang is fed to the Vaal River No 9 plant, which has a milling and treatment process. This plant receives two feeds: one from Kopanang's Vaal Reef ore and the other from neighbouring Tau Lekoa's ore from the Ventersdorp Contact Reef. Both these streams are augmented by low-grade ore from the waste dumps.

Kopanang's performance in 2005 was in line with that of 2004 at 482 000 ounces of gold. Total cash costs declined by 3% to R 56 427 per kg of gold produced. Gross profit was $8 million higher in 2005. The capital expenditure was 8% higher than the previous year and was spent mostly on ore reserve development. Gold production is expected to decrease in 2006 to between 457 000 and 475 000 ounces.

5.2 IMPLEMENTATION OF THE MD CONTROLLER AT THE MINE

No hardware was required to control the winders, as Kopanang's winders were fully automated before the start of the study. This simplified the implementation of the MD controller.

The MD controller uses this data to calculate when MD will be reached. Appropriate action is taken when the MD controller finds that the NMD will be breached before the end of the current time period. Either one or both winders will be stopped, depending on the rate of change of electrical energy usage.

The mine must be able to override the auto control option. This will mostly occur during periods of high production demands. A username, password and reason to override must be supplied to discourage excessive use of the override function.

5.3 PRACTICAL PROBLEMS ENCOUNTERED

5.3.1 Surface silo level

Some problems were encountered in the course of the installation of the MD controller. Solutions for some of the problems resulted in other dilemmas. One such a problem was that the surface silo level was not available on the mine's SCADA system.

The lack of a silo level resulted in the mine having to override the controller. This meant that the controller could not control the winders under certain conditions – such as periods of high reef extraction. Despite the fact that the operator has to enter a name, password and reason for the override, the system is overridden on a regular basis. This limits the effectiveness of the MD controller.

Once the problem with the silo level was fixed, it was found that the instrumentation did not report an accurate value (Figure 72). As seen in the graph, the level is fixed at 59%, with spikes throughout the day. The system therefore still has an override function, which is used excessively.

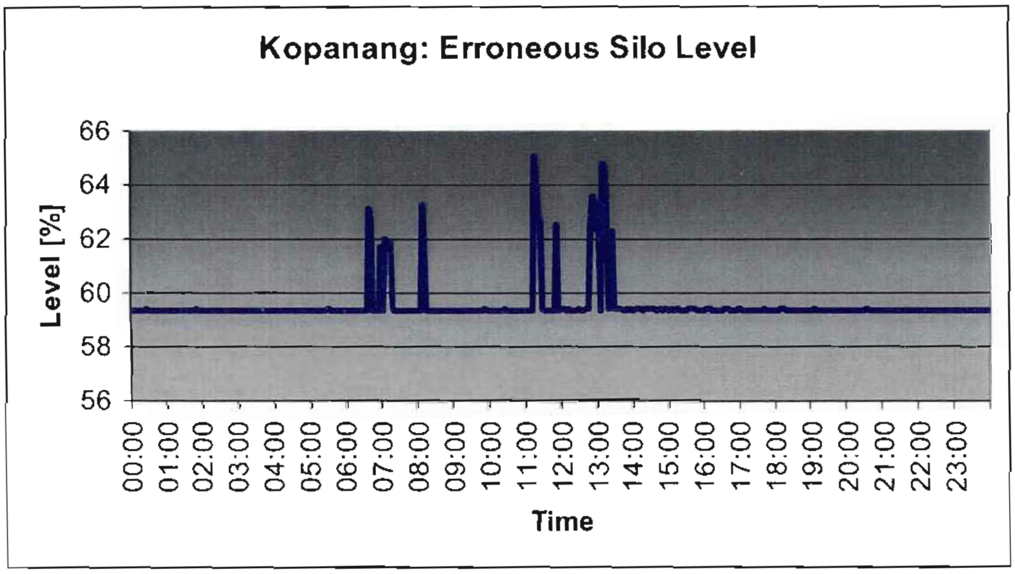


Figure 72: *Erroneous silo level reading*

5.3.2 Underground silo level

Another problem is the fact that there is no underground silo per se. The MD controller therefore has no way of determining underground rock levels and is not able to automatically control the winders according to such a level. This results in the system being overridden to extract rock when the underground storage is running out of space.

5.3.3 The human factor

Control of the winders is limited as well. The only possible command on the system is to stop the winders. Consequently the winders cannot be commanded to start hoisting during periods of low electricity demand. As a result, the system still depends on the human factor to prepare silo levels for conditions where the electrical demand nears the NMD of the mine.

5.3.4 Electrical demand data

In order for the MD controller to work as intended, real-time electrical demand data is required. This data is not available on the mine's SCADA system. Loggers are installed on Eskom's feeders, but this data is only available at AngloGold Ashanti's Vaal River control room. Due to limitations on the Vaal River SCADA this data currently cannot be sent back to Kopanang's SCADA system.

A solution to this problem would be to calculate a base load for the mine using data supplied by the Vaal River system. This base load will not be monitored in real-time for MD management. The mine's NMD is therefore scaled down to compensate for the base load that will not be monitored. Some loads' electric current values are measured and logged on Kopanang's SCADA system. These ampere values are used to calculate the kVA values, which in turn is used for instantaneous demand calculations.

Kopanang's loads consist of the following:

- Business services: residential
- Compressed air ring: compressors
- Main fans
- Man winding
- General mining activities
- Pumping
- Refrigeration
- Rock winding
- Gold plant: CIP (Carbon In Pulp) treatment
- Gold plant: Residue pumps
- Gold plant: ROM (Run Of Mine) milling
- Miscellaneous services

The base load is determined by plotting graphs for each separate load. These graphs are shown in Appendix B. It can be deduced from the graphs that the following factors do not form part of the base load:

- Pumping
- Refrigeration
- Rock winding

Fortunately, the electrical current values of the pumps, fridge plants and rock winders are logged on Kopanang's SCADA system. These values are then used to calculate a predicted demand value for the three systems.

A base load is established by summating the kVA values of systems that are not logged on Kopanang's SCADA, but supplied by the Vaal River control room. This base load is shown in Figure 73.

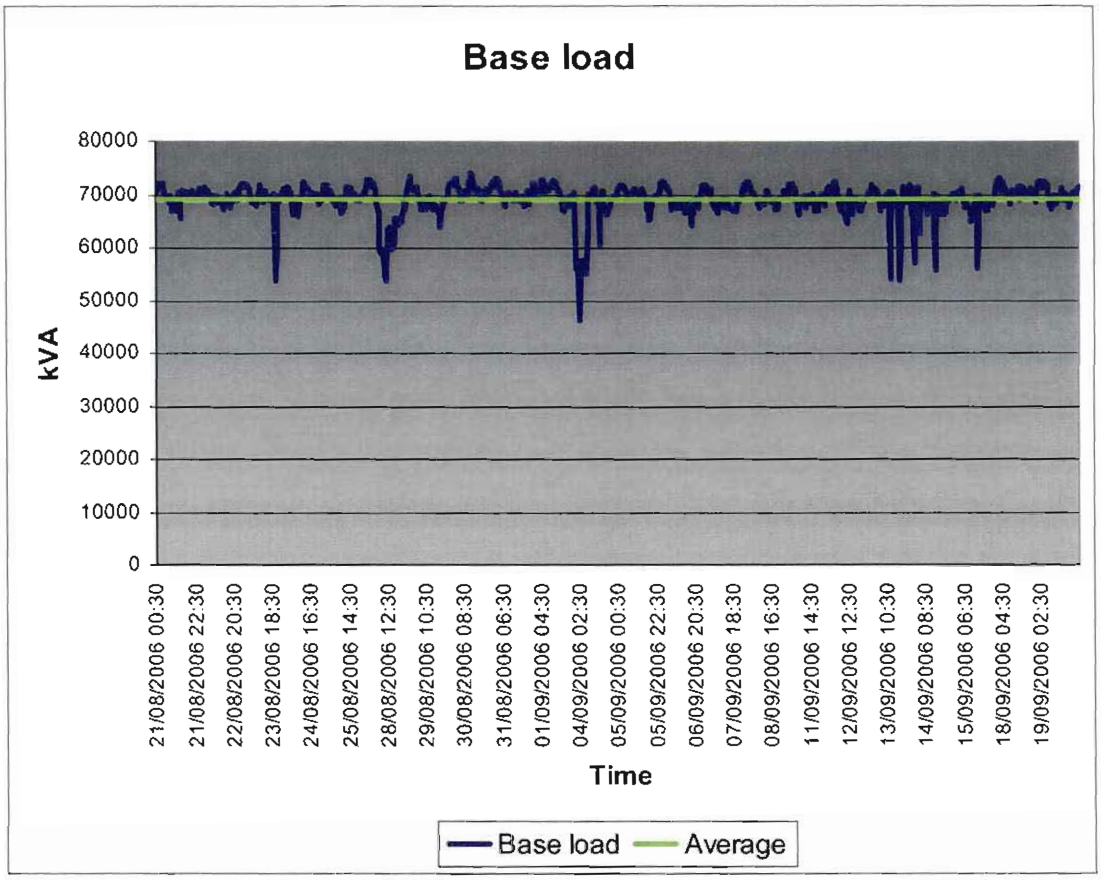


Figure 73: *Kopanang's base load*

In Figure 73, Kopanang's base load and its average are shown for a period of one month. The average value ranged from 67 MVA to 69 MVA over a three month period. The NMD was therefore scaled down with 70 MVA in order for the MD controller to calculate estimations using values from Kopanang's SCADA system.

The pumping, refrigeration and rock winding profiles are shown in Figure 74. Data used to plot this graph was supplied by AngloGold Ashanti's Vaal River control room.

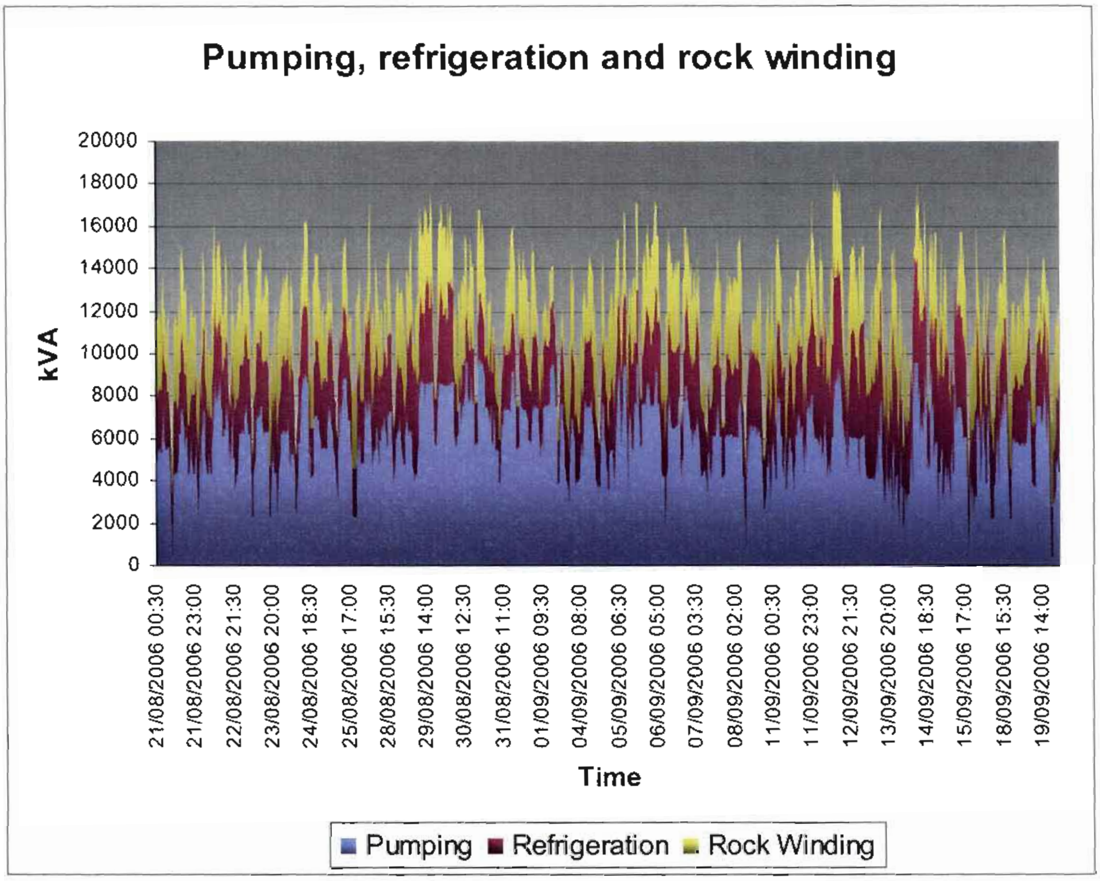


Figure 74: *Kopanang's pumping, refrigeration and rock winding profiles*

Figure 74 shows the erratic electrical energy profiles of the pumps, fridge plants and rock winders in contrast with the systems that comprise the base load (see Figure 73). It is therefore crucial to log these values for MD control purposes. The time period is the same as for Figure 73.

5.4 RESULTS ATTAINED WITH THE USE OF THE MD CONTROLLER

The MD controller currently installed on the mine does not control the winders automatically. Rather than switching the winders, the controller makes suggestions to the control room operator. The operator can switch the rock winders at own discretion. After a test period, the MD controller will be converted to a fully automatic controller. The winders will be controlled in accordance with the predicted demand, keeping production in consideration.

Results attained with the manual control of the winders are illustrated in Figure 75. The layout used for the graphs is the same as those of the simulations (see Figure 67, Figure 68 and Figure 69), as the simulation and control software are integrated. The results are therefore logged in the same format.

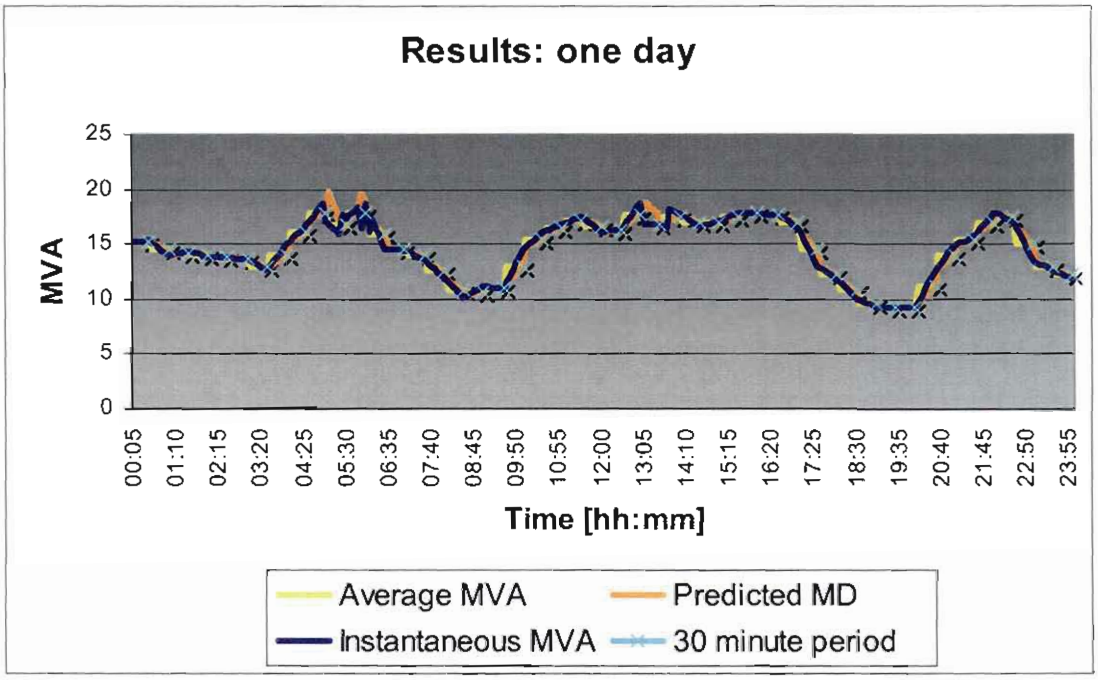


Figure 75: *MD controller results for a period of one day*

The dark blue line in Figure 75 displays the instantaneous MVA demand. These values are calculated by logging the electricity usage of the pumps, fridge plants and rock winders. Using these values, the MD controller calculates a predicted MVA value, shown in orange. The average electricity demand for the 30 minute integrated period is shown in yellow. The light blue crosses indicate the end-of-demand periods on the average line.

Figure 76 shows the total electricity demand of the pumps, fridge plants and rock winders. The time period is the same as that of Figure 75. There was decided on a scaled MD of 18 MVA (see Section 5.3.4) in agreement with the mine. This is much lower than their NMD as reported to Eskom, but a decreased value is used for testing purposes.

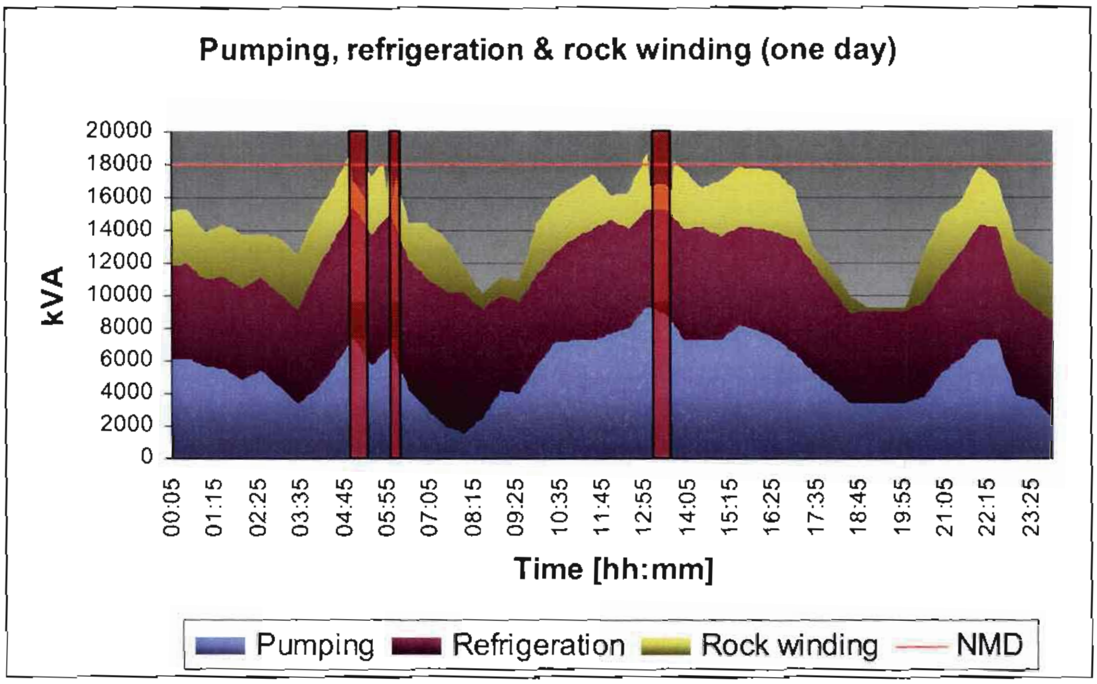


Figure 76: *Electricity usage of pumps, fridge plants and rock winders for a period of one day*

The highlighted areas of Figure 76 indicate where the winders were controlled to prevent the NMD (red line) from being breached. The sudden drop in the rock winders' electricity usage (yellow graph) can be seen right at the start of the highlighted times. There were instances where the summation of the pumps, fridge plants and rock winders were higher than the NMD, but the 30 minute average is still lower.

The first highlighted time is shown at a larger scale in Figure 77. It can be clearly seen in this graph where the total electricity usage is higher than the NMD.

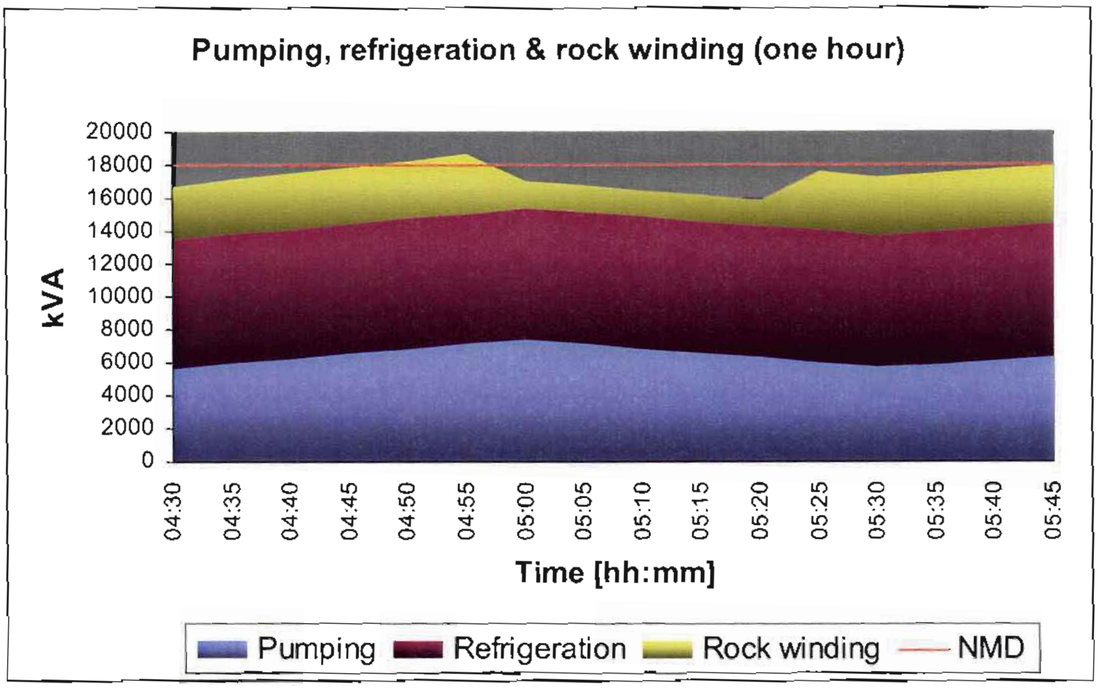


Figure 77: *Electricity usage of pumps, fridge plants and rock winders for a period of one hour*

Figure 77 shows a clear indication of one of the instances where the rock winders were stopped to prevent the NMD from being breached. This graph is for a period of one hour and fifteen minutes.

Without the MD controller, the mine's MD would have reached a value that is 1 770 kVA higher than their notified MD. The timely intervention and control of the winders saved the mine approximately R 137 000 (excluding VAT) over a rolling twelve month period. The calculations are shown in the following equations:

$$\begin{aligned}\text{NDC} &= \text{R}\ 6.69 \times 1\,770\ \text{kVA}\\ &= \text{R}\ 11\,841.30\end{aligned}$$

$$\begin{aligned}\text{NAC} &= \text{R}\ 5.91 \times 1\,770\ \text{kVA}\\ &= \text{R}\ 10\,460.70\end{aligned}$$

As the NAC is based on the AUC, this higher kVA value is used as the AUC for a rolling twelve month period starting from the month where the higher MD occurred. The raise of 1 770 kVA in MD would therefore be accumulated over twelve months:

$$\begin{aligned}\text{Total savings} &= (\text{NAC} \times 12) + \text{NDC} \\ &= (\text{R } 10\,460.70 \times 12) + \text{R } 11\,841.30 \\ &= \text{R } 125\,528.40 + \text{R } 11\,841.30 \\ &= \text{R } 137\,369.70\end{aligned}$$

The average kVA value would rise with 4 500 kVA in the extreme case. This would happen when both rock winders have to be switched off for the entire 30 minute period to manage the MD. The maximum possible savings achieved would then be around R 349 000. Calculations are shown:

$$\begin{aligned}\text{NDC} &= \text{R } 6.69 \times 4\,500\text{ kVA} \\ &= \text{R } 30\,105.00\end{aligned}$$

$$\begin{aligned}\text{NAC} &= \text{R } 5.91 \times 4\,500\text{ kVA} \\ &= \text{R } 26\,595.00\end{aligned}$$

$$\begin{aligned}\text{Total savings} &= (\text{NAC} \times 12) + \text{NDC} \\ &= (\text{R } 26\,595.00 \times 12) + \text{R } 30\,105.00 \\ &= \text{R } 319\,140.00 + \text{R } 30\,105.00 \\ &= \text{R } 349\,245.00\end{aligned}$$

Even though the rock winders are not yet controlled automatically by the MD controller, the success of the recommendations made to the Mimic operator can be seen from the results in Figure 75 to Figure 77. It can therefore be concluded that the installation of the MD controller at Kopanang effectively managed the MD. The full automatic control of the rock winders would therefore be viable after the test period.

5.5 IMPACT ON SOUTH AFRICA

The MD controller developed in this study, will obviously only benefit South Africa as a whole if it is implemented on a large scale. Installing the controller on multiple sites could potentially lower the country's MD to such a level that the need for new power stations could be delayed. This will clearly only be possible if there were hundreds of sites available to install a winder MD controller. Unfortunately, there are currently not enough mines in South Africa with winders large enough to make this a realistic goal.

The MD controller however can potentially lower a mine's NMD. This reduction in NMD will enable Eskom to free capacity demand that can be used by other customers. An extra benefit to the mine (if the NMD is lowered) will be a reduced electricity bill.

A pilot study done at AngloGold Ashanti's Mponeng gold mine shows a potential 4 200 kVA load that could be shed by the winders to manage the mine's MD. Neighbouring Tau Tona gold mine has a potential of 5 500 kVA. Annual savings achievable with implementation of the MD controller is R 325 000 for Mponeng and R 426 000 for Tau Tona. Calculations are shown in Table 7.

Table 7: *Possible annual savings for Mponeng and Tau Tona*

Mponeng	**Tau Tona**
$\text{NDC} = \text{R } 6.69 \times 4\ 200 \text{ kVA}$ $= \text{R } 28\ 098.00$	$\text{NDC} = \text{R } 6.69 \times 5\ 500 \text{ kVA}$ $= \text{R } 36\ 795.00$
$\text{NAC} = \text{R } 5.91 \times 4\ 200 \text{ kVA}$ $= \text{R } 24\ 822.00$	$\text{NAC} = \text{R } 5.91 \times 5\ 500 \text{ kVA}$ $= \text{R } 32\ 505.00$
$\text{Total savings} = (\text{NAC} \times 12) + \text{NDC}$ $= (\text{R } 24\ 822.00 \times 12) + \text{R } 28\ 098.00$ $= \text{R } 297\ 864.00 + \text{R } 28\ 098.00$ $= \text{R } 325\ 962.00$	$\text{Total savings} = (\text{NAC} \times 12) + \text{NDC}$ $= (\text{R } 32\ 505.00 \times 12) + \text{R } 36\ 795.00$ $= \text{R } 390\ 060.00 + \text{R } 36\ 795.00$ $= \text{R } 426\ 855.00$

5.6 CONCLUSION

Although some problems were encountered during the installation of the MD controller, it was shown that the controller does manage the MD to acceptable levels. The winders proved to be an effective and instant remedy for a high electricity demand. As was demonstrated earlier, production is not influenced by the use of the controller.

Compared with other systems at the mine, such as the pumps and fridge plants, the winders are ideal for MD management. The inherent cyclic operation of the winders makes them the preferred system to control the mine's MD.

CHAPTER 6: CONCLUSION

6.1 SUMMARY

Eskom's peak generating capacity is running low as the demand for electricity increases. Projections show the peak demand will be higher than Eskom's current generating capacity by as early as 2007.

Eskom launched a DSM programme to control this growth in electricity demand. The main purpose of this programme is to reduce electrical energy usage during evening peak demand times. One method to realise this evening peak reduction is to shift load to other times of the day. An inherent problem with this method is the possible increase of an electricity user's maximum demand.

In order to limit this maximum demand, certain systems could be shut down when the electricity usage is on the verge of reaching a high level. It was shown that rock winders are the most suitable of all of the systems used on a mine to manage the maximum demand.

In the course of this study, software was developed to simulate and manage the MD of a mine. The software logged electrical demand data of certain systems in order to calculate a predicted demand value. The rock winders would be stopped in order to lower the MD, should the estimated demand be higher than a certain threshold.

A study done at AngloGold Ashanti's Kopanang gold mine proved the feasibility of such a controller. The MD controller developed in this study was installed at the mine in order to control their maximum demand. Results attained from the installation proved the success of such a controller. It is important to note that the system developed in this study does not interfere with production.

6.2 RECOMMENDATION FOR FURTHER WORK

This study could be extended to control other large electricity consumers on a mine. Some of the systems used on a mine were investigated in Section 1.3. The systems and the feasibility for MD management are shown in Table 8.

Table 8: *Feasibility of MD control on certain systems*

System	MD management possibility
Lighting	Impractical to switch off lights for MD management
Pumping	Cannot stop in certain instances – dams might be overflowing
Fridge plants	Critical to keep mine cool and in workable condition
Compressed air	Needed for drills – production would slow down
Winders	Instant reduction in electricity use

It can be seen in Table 8 that systems such as pumps, fridge plants and compressors are not really suited for MD control or frequent switching. These systems could however be controlled together for MD management.

As an example, cycling of pumps could be prevented by switching off only one pump for a longer period. Switching off only one pump would prevent the dam levels from rising too fast, compared with the stopping of for example two pumps. In conjunction with switching off the pump, the veins of a compressor can be controlled as well to lower its electricity demand. The combination of the two different systems would result in a lowered MD, but with a smaller influence on one particular system.

The influences on the control of particular systems would have to be investigated before they are manipulated to manage a mine's MD. Their effect on production would have to be considered beforehand, as was done for the rock winders in the course of this study. Mechanical limitations need to be examined as well. As an example, it was shown in Section 2.3 that balancing disks on pumps wear much more during start-up than during normal running operations.

REFERENCES

[1] Department of Minerals and Energy: *Energy Efficiency Strategy of the Republic of South Africa*, March 2005, Department of Minerals and Energy, Private Bag X59, Pretoria, 0001, South Africa, Tel: (+27) 12 317 8000, Fax: (+27) 12 322 3416.

[2] National Energy Regulator: *Lighting up South Africa*, 2000, National Energy Regulator of South Africa, PO Box 40343, Arcadia, 0007, South Africa, Tel: (+27) 12 401 4600, Fax: (+27) 12 401 4700.

[3] Surtees, RM: *Electricity Demand Growth in South Africa and the Role of Demand Side Management*, Eskom, PO Box 1091, Johannesburg, 2001, South Africa.

[4] Engineering News: *SA to run short of peak power capacity by 2007,* 16 July 2003, Engineering News, PO Box 75316, Garden View, 2047, South Africa, Tel: (+27) 11 622 3744, Fax: (+27) 11 622 9350.

[5] News 24: *Power failure hits Cape Town*, 20 January 2006, News24, PO Box 2271, Cape Town, 8000, South Africa, Tel: (+27) 21 406 2134, Fax: (+27) 21 406 3459.

[6] Mail & Guardian: *Power failure affects entire Western Cape*, 19 February 2006, Mail & Guardian, PO Box 91667, Auckland Park, Johannesburg, 2006, South Africa, Tel: (+27) 11 250 7300, Fax: (+27) 11 250 7503.

[7] Nortje, T: *South Africa's Demand Side Management Program: A Savings Opportunity*, 2005, Eskom, PO Box 1091, Johannesburg, 2001, South Africa.

[8] Engineering News: *SA to run short of peak power capacity by 2007*, 16 July 2003, Engineering News, PO Box 75316, Garden View, 2047, South Africa, Tel: (+27) 11 622 3744, Fax: (+27) 11 622 9350.

[9] Chamber of Mines of South Africa: *Facts and Figures of 2004*, 2005, 5 Hollard Street, Marshalltown, Johannesburg, Tel: (+27) 11 498 7100, Fax: (+27) 11 834 1884.

[10] Engineering News: *31 SA firms in energy-conservation pledge*, 1 September 2006, Engineering News, PO Box 75316, Garden View, 2047, South Africa, Tel: (+27) 11 622 3744, Fax: (+27) 11 622 9350.

[11] Sowetan Supplement: *Big business shows its commitment to energy efficiency*, 24 June 2005, 61 Commando Road, Industria West, Johannesburg, 2142, South Africa, Tel: (+27) 11 471 4093.

[12] ESI Africa: *Demand Side Management in South Africa*, Issue 1, 2003, Spintelligent (Pty) Ltd, PO Box 321, Steenberg, 7947, South Africa, Phone: (+27) 21 700 3500, Fax: (+27) 21 700 3501.

[13] ISEP – Eskom (Resources and Strategy), Energy Research Institute – University of Cape Town, National Energy Regulator: *National Integrated Resource Plan 2003/4 Reference Case*, 27 February 2004, Eskom, PO Box 1091, Johannesburg, 2001, South Africa.

[14] NER: *Electricity supply statistics for South Africa*, 2001, National Energy Regulator of South Africa, PO Box 40343, Arcadia, 0007, South Africa, Tel: (+27) 12 401 4600, Fax: (+27) 12 401 4700.

[15] Department of Minerals and Energy: *White Paper on Energy Policy*, 1998, Department of Minerals and Energy, Private Bag X59, Pretoria, 0001, South Africa, Tel: (+27) 12 317 8000, Fax: (+27) 12 322 3416.

[16] Department of Minerals and Energy: *Energy Efficiency Strategy*, 2004, Department of Minerals and Energy, Private Bag X59, Pretoria, 0001, South Africa, Tel: (+27) 12 317 8000, Fax: (+27) 12 322 3416.

[17] National Energy Regulator: *Energy Efficiency and Demand Side Management Policy*, 2004, National Energy Regulator of South Africa, PO Box 40343, Arcadia, 0007, South Africa, Tel: (+27) 12 401 4600, Fax: (+27) 12 401 4700.

[18] Department of Minerals and Energy: *Integrated Energy plan for the Republic of South Africa*, 19 March 2003, Department of Minerals and Energy, Private Bag X59, Pretoria, 0001, South Africa, Tel: (+27) 12 317 8000, Fax: (+27) 12 322 3416.

[19] Eskom: *Western Cape Newspaper Insert*, April 2006, Eskom, PO Box 1091, Johannesburg, 2001, South Africa.

[20] Eskom: *Tariffs and Charges Effective from 1 April 2006 – 31 March 2007*, August 2005, Eskom, PO Box 1091, Johannesburg, 2001, South Africa.

[21] Eskom: *Notification of Demand or Changes to Notified Maximum Demand (NMD) Rules for Application to Network Charges*, August 2005, Eskom, PO Box 1091, Johannesburg, 2001, South Africa.

[22] AngloGold Ashanti: *AngloGold Ashanti Country Report: Vaal River*, 2006, PO Box 62117, Marshalltown, South Africa, 2107, Tel: (+ 27) 11 637 6000.

[23] AngloGold Ashanti: *AngloGold Ashanti Country Report: West Wits*, 2006, PO Box 62117, Marshalltown, South Africa, 2107, Tel: (+ 27) 11 637 6000.

[24] AngloGold Ashanti: *AngloGold Ahanti Virtual Mine Tour*, www.anglogold.com, accessed 17 August 2006, PO Box 62117, Marshalltown, South Africa, 2107, Tel: (+ 27) 11 637 6000.

[25] GoldFields: *South African Operations Overview*, www.goldfields.co.za, accessed 20 September 2006, Tel: (+27) 11 644 2522, Fax: (+27) 11 484 0550.

[26] Harmony: *Gearing for Growth: A review of operations and projects*, Harmony Annual Report 2006, Tel: (+27) 11 411 2000.

[27] Carbogno, A: *Mine hoisting in deep shafts in the 1st half of 21st Century*, August 2002, Silesian Technical University, Mining Mechanization Institute, Akademicka 2, PL 44-101 Gliwice, Poland.

[28] Hill, FG; Mudd, JB: *Deep Level Mining in South African Gold Mines*, 5th International Mining Congress, 1967, Moscow.

[29] De La Vergne, J: *Hard Rock Miner's Handbook*, McIntosh Engineering, 2003, McIntosh Engineering Limited, 710 McKeon Avenue, North Bay, Ontario, Canada, Tel: (+1) 705 494 8255, Fax: (+1) 705 474 2652.

[30] FFE Minerals: *Mine Hoist for FFE Minerals*, www.flsmidth.com, accessed 18 July 2006, PO Box 5221, Weltevredenpark 1715, South Africa, Tel: (+27) 11 679 2593, Fax: (+27) 11 679 2611.

[31] Saadat, H: *Power System Analysis*, McGraw-Hill, 1999, The McGraw-Hill Companies, PO Box 182604, Columbus, OH 43272, Tel: (+1) 877 833 5524, Fax: (+1) 614 759 3749.

[32] Boake, IG: *A strategy for electrical load management in the South African mining industry*, Doctoral thesis, Rand Afrikaans University, December 2003, University of Johannesburg, PO Box 524, Auckland Park, 2006, South Africa, Tel: (+27) 11 489 2637, Fax: (+27) 11 489 2191.

[33] Box, GEP; Jenkins, GM; Reinsel, GC: *Time series analysis forecasting and control*, Prentice Hall, 1994, Pearson Education, One Lake Street, Upper Saddle River, NJ 07458.

[34] Bonnville Power Administration, US Department of the Interior, prepared by Ernest & Ernest: *Review of energy forecast methodologies and assumptions*, Portland Oregan, 1976.

[35] Gellings, CW; et al: *Demand forecasting for electric utilities*, The Fairmont Press, 1992, The Fairmont Press, Inc, 700 Indian Trail, Lilburn, Georgia 30047, Tel: (+1) 770 925 9388, Fax: (+1) 770 381 9865.

[36] CIGRE Working Group 39-0s: *Present practices on load forecasting and load management: a survey*, Electra no 145, December 1992, 21 rue d'Artois, 75 008 Paris, France, Tel: (+33) 15 389 1290, Fax: (+33) 15 389 1299.

[37] Kim, HS; et al: *Electric load forecasting and classification using neural networks for the EMS*, Proceedings of IASTED Conference, Power and Energy Systems, September 2000, IASTED Secretariat, Building B6, Suite #101, 2509 Dieppe Avenue SW, Calgary, Alberta, Canada, T3E 7J9, Tel: (+1) 403 288 1195, Fax: (+1) 403 247 6851.

[38] Riquelme, J; et al: *Possibilities of artificial neural networks in short-term load forecasting*, Proceedings of IASTED Conference, Power and Energy Systems, September 2000, IASTED Secretariat, Building B6, Suite #101, 2509 Dieppe Avenue SW, Calgary, Alberta, Canada, T3E 7J9, Tel: (+1) 403 288 1195, Fax: (+1) 403 247 6851.

[39] Janse van Rensburg, JF: *A maximum demand control system and energy saving study for a diamond mine*, Mini-dissertation, University of Johannesburg, November 2005, University of Johannesburg, PO Box 524, Auckland Park, 2006, South Africa, Tel: (+27) 11 489 2637, Fax: (+27) 11 489 2191.

[40] Villet, CM; Prentice, JSC: *Numerical analysis*, Applied Mathematics 2B, Rand Afrikaans University, June 2000, University of Johannesburg, PO Box 524, Auckland Park, 2006, South Africa, Tel: (+27) 11 489 2637, Fax: (+27) 11 489 2191.

[41] Zill, DG; Cullen, MR: *Differential Equations with Boundary-Value Problems*, Brooks/Cole, 2001, Thomson Higher Education, 10 Davis Drive, Belmont, CA 94002, Tel: (+1) 800 354 9706, Fax: (+1) 800 487 8488.

[42] Hsu, H: *Schaum's Outlines of probability, random variables & random processes*, McGraw-Hill, 1997, The McGraw-Hill Companies, PO Box 182604, Columbus, OH 43272, Tel: (+1) 877 833 5524, Fax: (+1) 614 759 3749.

[43] Wikipedia: *Artificial neural networks*, Wikipedia, en.wikipedia.org/wiki/Artificial_neural_networks, accessed 24 October 2006.

[44] Wikipedia: *Fuzzy logic*, Wikipedia, en.wikipedia.org/wiki/Fuzzy_logic, accessed 24 October 2006.

[45] Wikipedia: *Defuzzification*, Wikipedia, en.wikipedia.org/wiki/Defuzzification, accessed 24 October 2006.

[46] Rautenbach JW, *Engineering a novel automated pump control system for the mining environment*, 2006, Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Mechanical Engineering at the North West University, Faculty of Engineering, Tel: (+27) 18 299 4020, Fax: (+27) 18 299 4450.

[47] Tschaggelar, R: *Neural networks*, Ing.Büro R. Tschaggelar, 17 November 2000, Spilchbüel 1, 8342 Wernetshausen, Switzerland, Tel: (+41) 44 937 23 67, Fax: (+41) 44 937 15 41.

[48] Bennett, S; Skelton, J; Lunn, K: *Schaum's Outlines of UML*, McGraw-Hill, 2001, The McGraw-Hill Companies, PO Box 182604, Columbus, OH 43272, Tel: (+1) 877 833 5524, Fax: (+1) 614 759 3749.

[49] Le Roux, DF: *A new approach to ensure successful implementation and sustainable DSM in RSA mines*, 2006, Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Electrical Engineering at the

North West University, Faculty of Engineering, Tel: (+27) 18 299 4020, Fax: (+27) 18 299 4450.

APPENDIX A: LEAST-SQUARES POLYNOMIAL FITTING

A wide variety of functions can be used in least-squares curve fitting [1]. The use of polynomial fitting functions is discussed in this Appendix.

Consider a set of points (x_i, y_i); $i = 0, 1, \ldots, n$ obtained from an experiment. The function $y = y(x)$ can be approximated by a polynomial of the degree n. This polynomial passes through each data point.

If we however believe that the relationship $y = y(x)$ is linear, then it would make more sense to find the best straight line that approximates the function. A criterion is needed that allows us to determine the fitting function such that its deviation from the given points is minimised.

The deviation at point x_i is the difference between the fit $f(x)$ and the actual function $y(x)$:

$$\Delta_i = f(x_i) - y_i$$

The function $f(x)$ is chosen so that

$$S = \sum_{i=0}^{n} [f(x_i) - y_i]^2 \quad \textbf{(A1)}$$

is a minimum. S is the sum of the differences between the approximation points $f(x_i)$ and the data points y_i.

Consider the case where $f(x)$ in (A1) is an m^{th} degree polynomial $p_m(x)$, with $m = n$. The function $p_m(x)$ must be chosen such that

$$S = \sum_{i=0}^{n} \left[p_m(x_i) - y_i\right]^2 \qquad \textbf{(A2)}$$

is a **minimum**. Since

$$p_m(x) = a_0 + a_1 x + \ldots + a_m x^m \qquad \textbf{(A3)}$$

we must have

$$\frac{\partial S}{\partial a_k} = 0 \quad ; \quad k = 0, 1, \ldots, m$$

From (A2) we have

$$\frac{\partial S}{\partial a_k} = 2\sum_{i=0}^{n} \left[p_m(x_i) - y_i\right] \frac{\partial p_m}{\partial a_k}(x_i) \quad ; \quad k = 0, 1, \ldots, m$$

But from (A3) we have that

$$\frac{\partial p_m}{\partial a_k}(x_i) = x_i^k$$

and therefore

$$\frac{\partial S}{\partial a_k} = 2\sum_{i=0}^{n} \left[p_m(x_i) - y_i\right] x_i^k \quad ; \quad k = 0, 1, \ldots, m \qquad \textbf{(A4)}$$

Furthermore,

$$\frac{\partial^2 S}{\partial a_k^2} = 2\sum_{i=0}^{n} x_i^k x_i^k \geq 0 \quad ; \quad k = 0, 1, \ldots, m$$

So that the requirement of (A2) does indeed give a minimum for S. This value is obtained from (A4):

$$\sum_{i=0}^{n} p_m(x_i) x_i^k = \sum_{i=0}^{n} y_i x_i^k \quad ; \quad k = 0, 1, \ldots, m \qquad \textbf{(A5)}$$

The system in (A5) consists of $m + 1$ equations in $m + 1$ unknowns a_j. The a_j are therefore determined uniquely.

From (A3) we obtain a more explicit form for (A5):

$$
\begin{aligned}
k=0:&\quad a_0(n+1)+a_1\sum_i x_i+\ldots+a_m\sum_i x_i^m=\sum_i y_i\\
k=1:&\quad a_0\sum_i x_i+a_1\sum_i x_i^2+\ldots+a_m\sum_i x_i^{m+1}=\sum_i y_i x_i\\
&\;\vdots\\
k=m:&\quad a_0\sum_i x_i^m+a_1\sum_i x_i^{m+1}+\ldots+a_m\sum_i x^{2m}=\sum_i y_i
\end{aligned}
$$

To fit a straight line (m = 1), for example, we have

$$p_1(x)=a_0+a_1x$$

from which the a_i are obtained from

$$
\begin{aligned}
&a_0(n+1)+a_1\sum_i x_i=\sum_i y_i\\
&a_0\sum_i x_i+a_i\sum_i x_i^2=\sum_i y_i x_i
\end{aligned}
$$

[1] Villet, CM; Prentice, JSC: *Numerical analysis*, Applied Mathematics 2B, Rand Afrikaans University, June 2000, University of Johannesburg, PO Box 524, Auckland Park, 2006, South Africa, Tel: (+27) 11 489 2637, Fax: (+27) 11 489 2191.

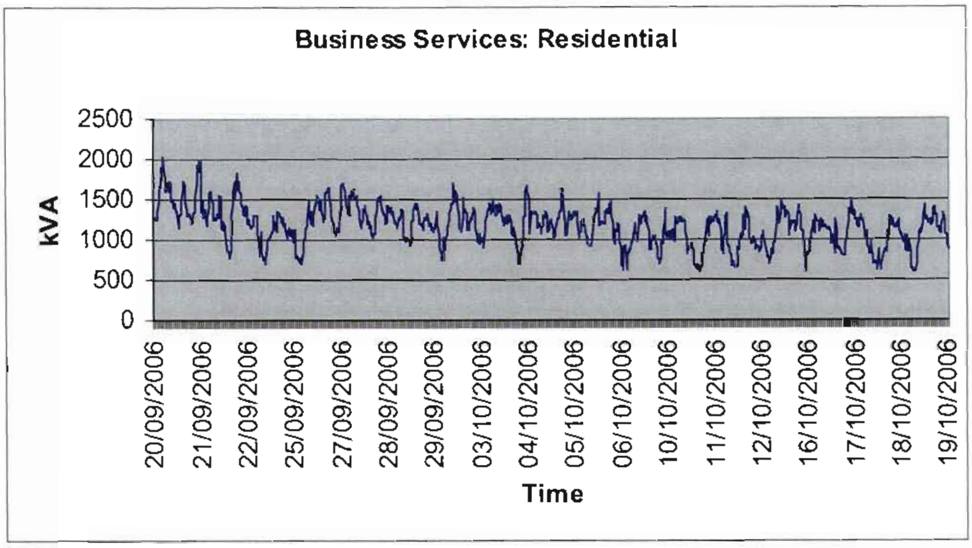
APPENDIX B: DETERMINING THE BASE LOAD

Kopanang's base load is determined by using data supplied by AngloGold Ashanti's Vaal River control room. The data examined is for a period of three months, from September 2006 to November 2006.

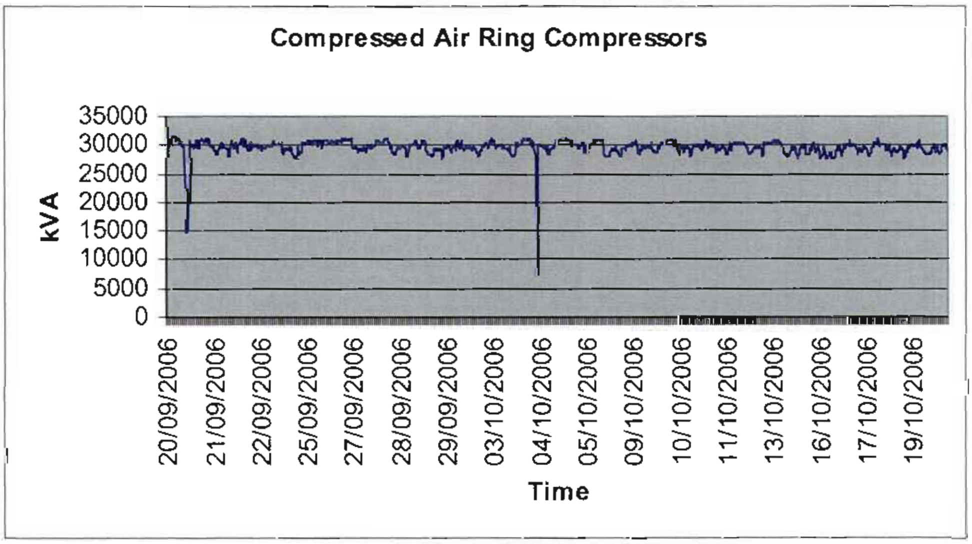
Kopanang's loads consist of the following:

- Business services: residential
- Compressed air ring: compressors
- Main fans
- Man winding
- General mining activities
- Pumping
- Refrigeration
- Rock winding
- Gold plant: CIP (Carbon In Pulp) treatment
- Gold plant: Residue pumps
- Gold plant: ROM (Run Of Mine) milling
- Miscellaneous services

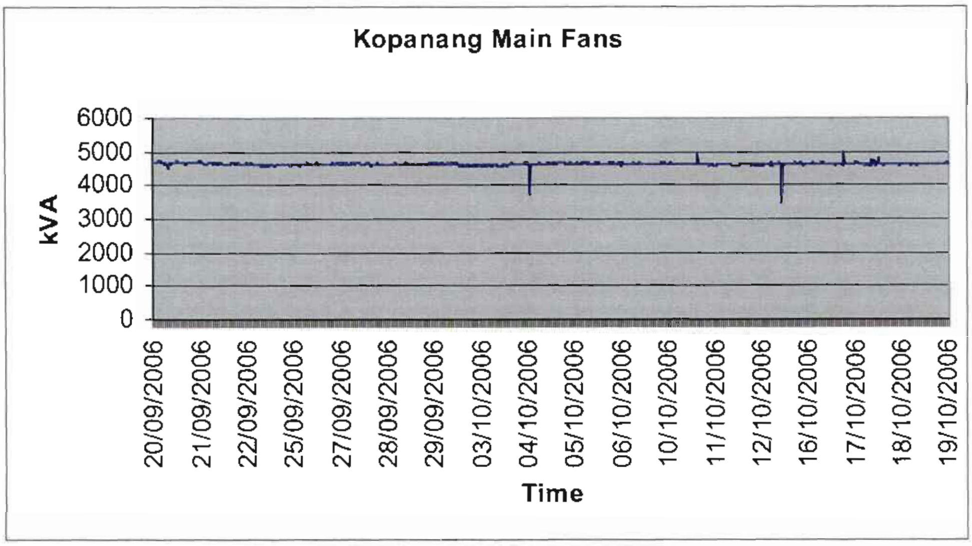
The base load is determined by plotting graphs for each separate load. These graphs are shown in Appendix B - Figure 1 to Appendix B - Figure 14.



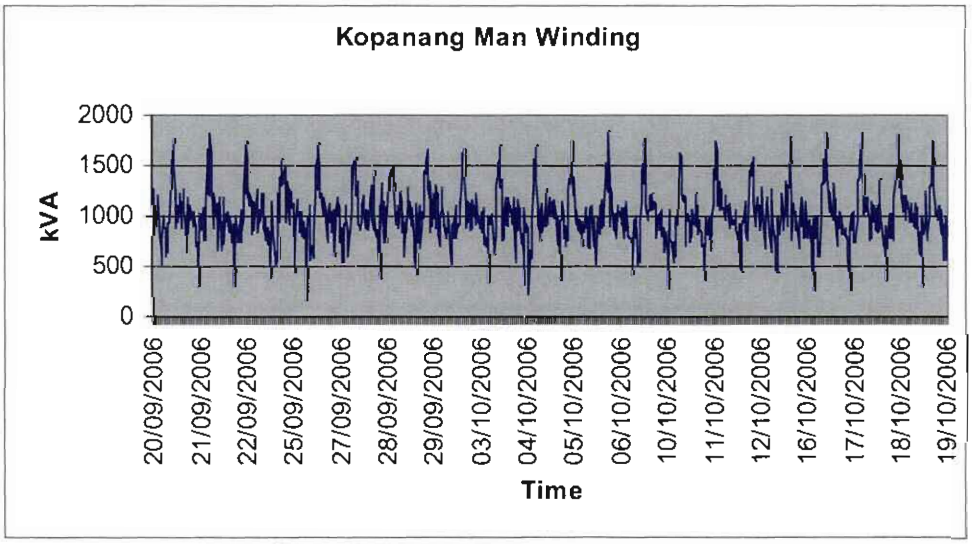
Appendix B - Figure 1: *Business services: residential*



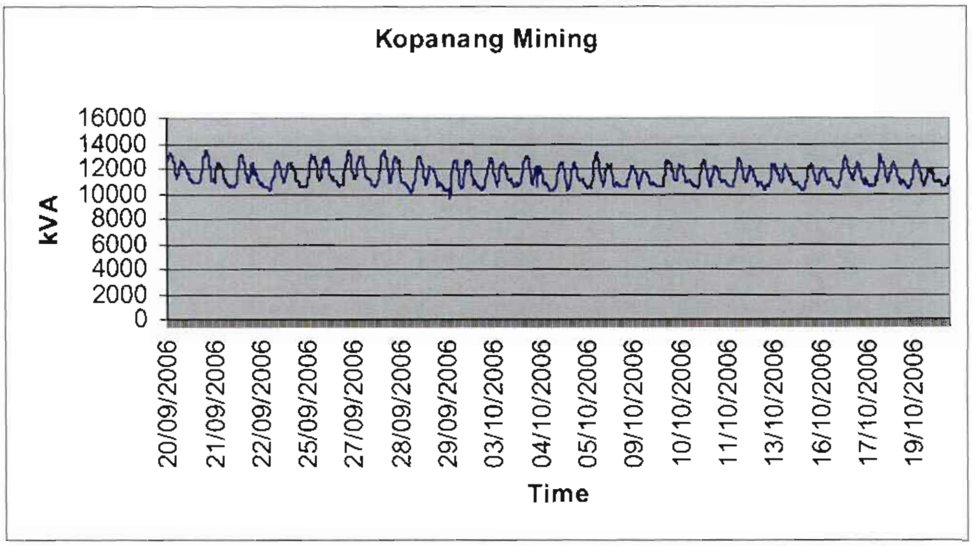
Appendix B - Figure 2: *Compressed air ring: compressors*



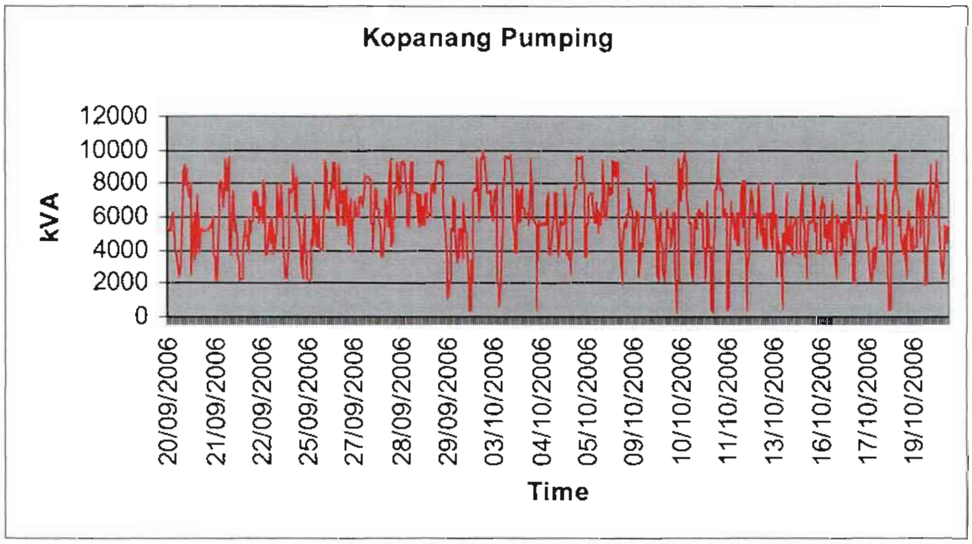
Appendix B - Figure 3: *Main fans*



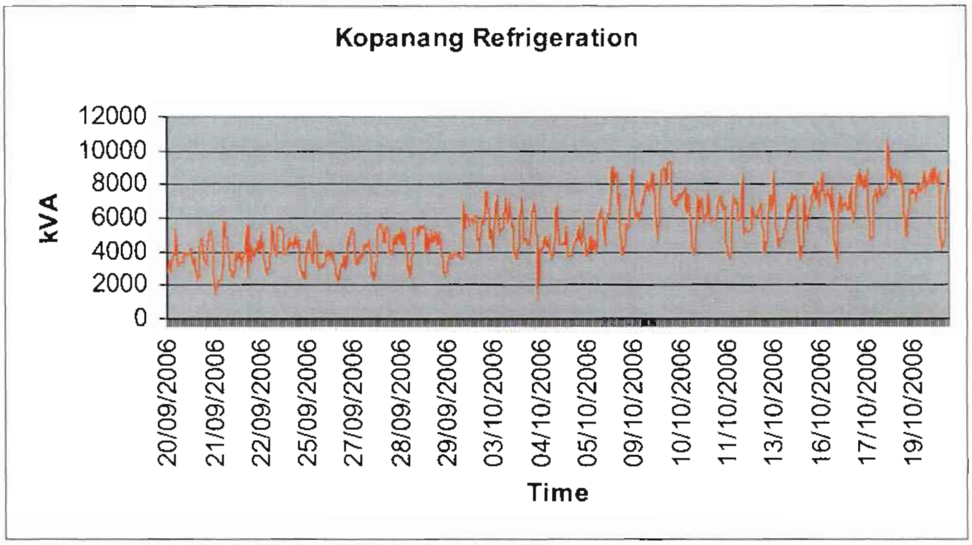
Appendix B - Figure 4: *Man winding*



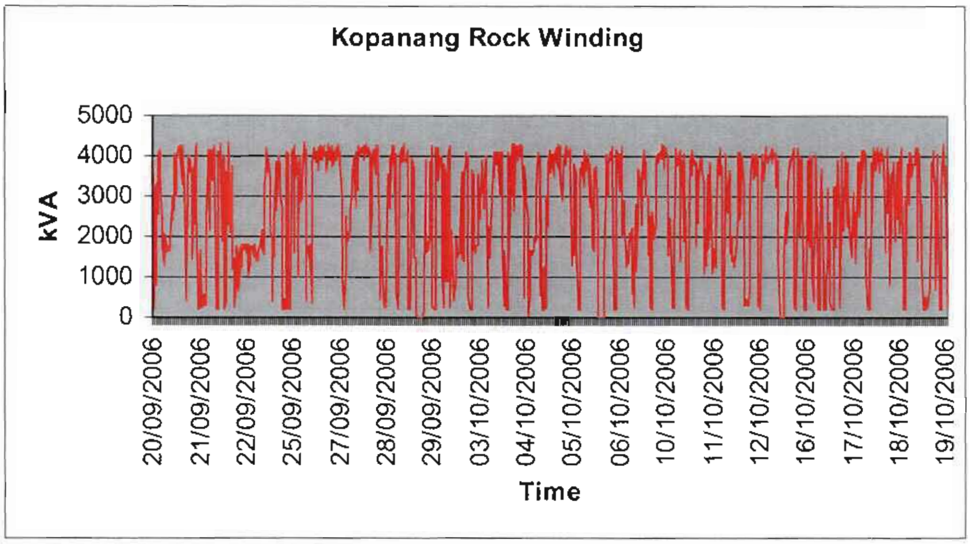
Appendix B - Figure 5: *General mining*



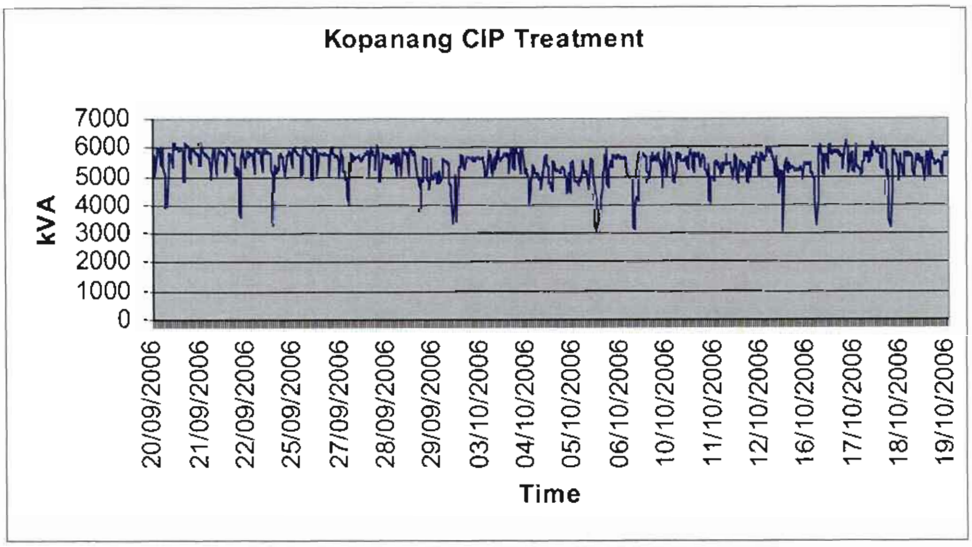
Appendix B - Figure 6: *Pumping*



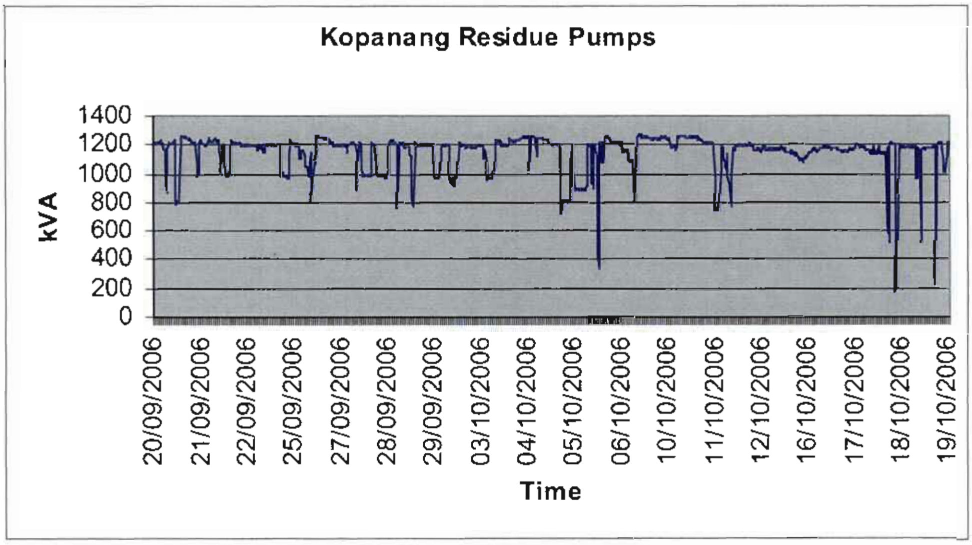
Appendix B - Figure 7: *Refrigeration*



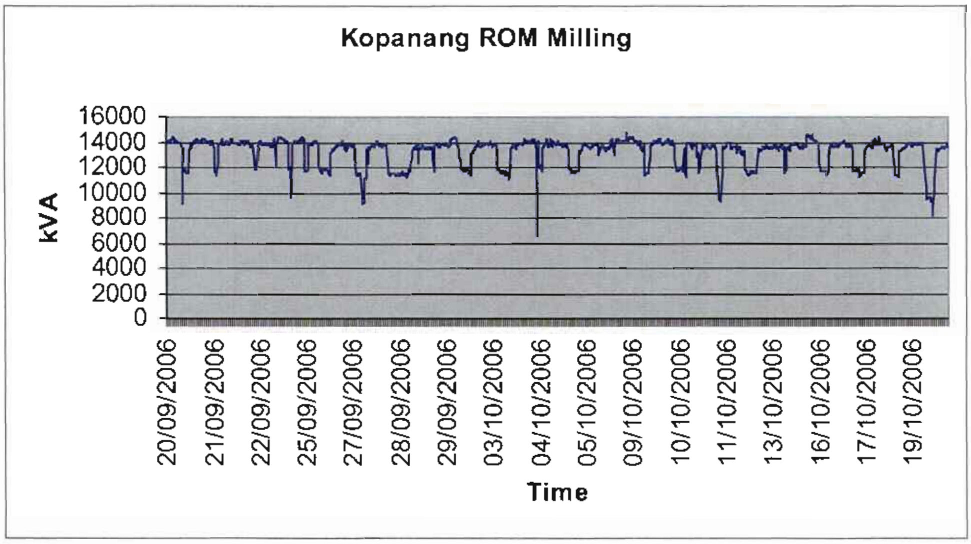
Appendix B - Figure 8: *Rock winding*



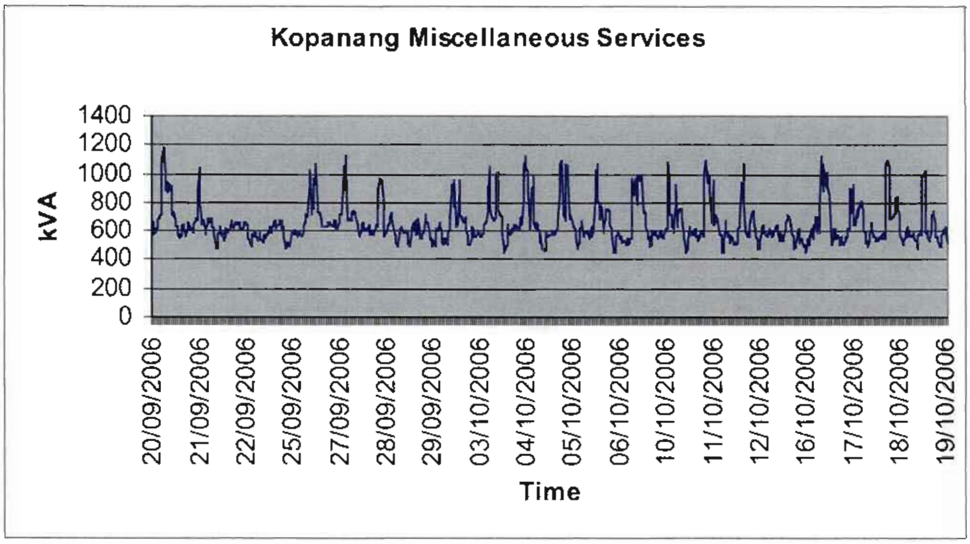
Appendix B - Figure 9: *Carbon in pulp treatment*



Appendix B - Figure 10: *Residue pumps*



Appendix B - Figure 11: *Run of mine milling*

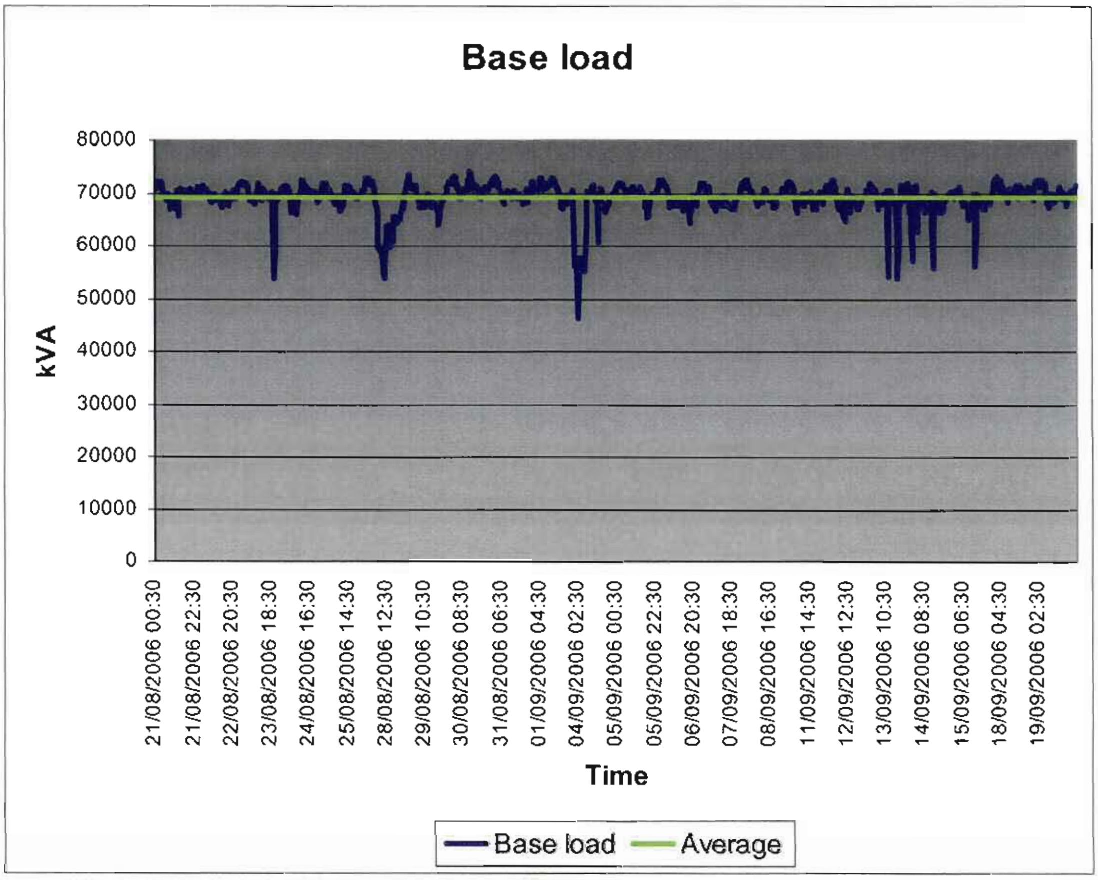


Appendix B - Figure 12: *Miscellaneous services*

It can be deduced from the graphs that the following factors do not form part of the base load:

- Pumping (Appendix B - Figure 6)
- Refrigeration (Appendix B - Figure 7)
- Rock winding (Appendix B - Figure 8)

By summating the values of the other graphs, the base load can be determined. This base load is shown in Appendix B - Figure 13.

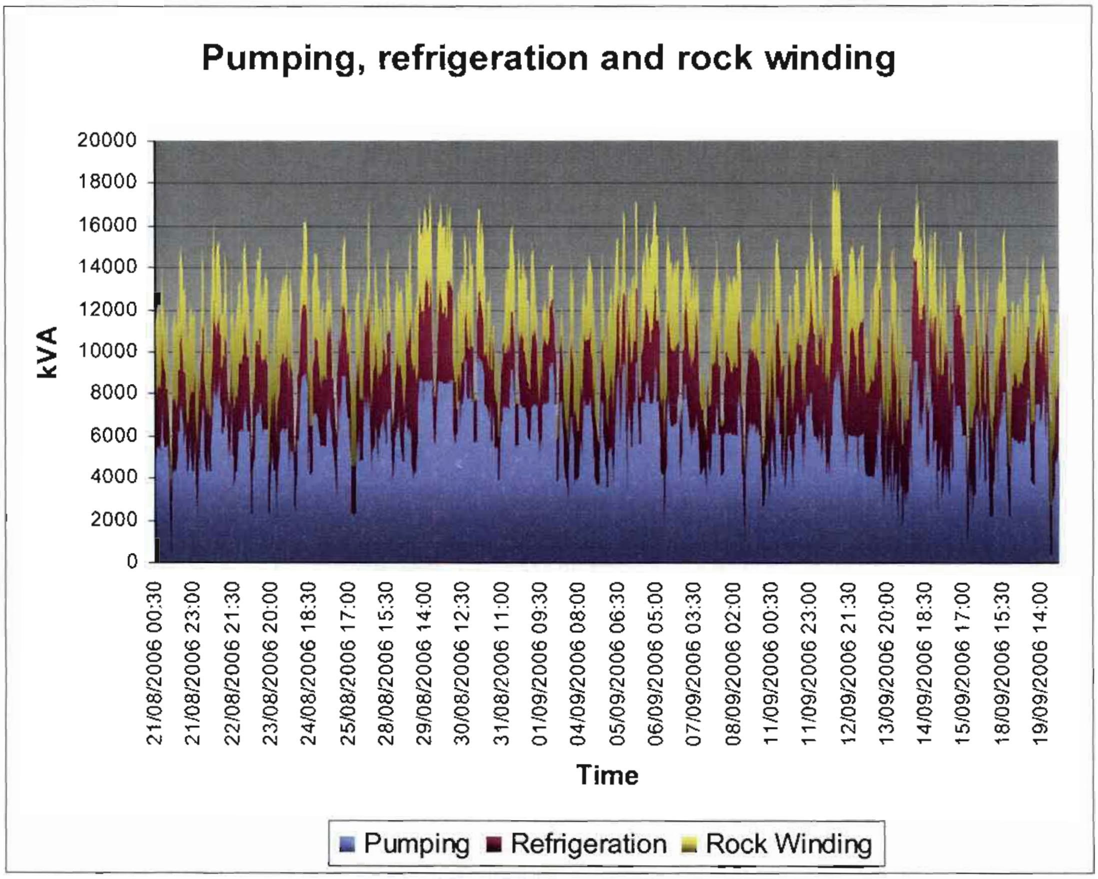


Appendix B - Figure 13: *Kopanang's base load*

In Appendix B - Figure 13, Kopanang's base load and its average are shown for a period of one month. The process is repeated for values of September, October and November to provide an average. This average value ranged from 67 MVA to 69 MVA over the three month period. The NMD was therefore scaled down with

70 MVA in order for the MD controller to calculate estimations using values from Kopanang's SCADA system. A small safety factor is catered for.

The pumping, refrigeration and rock winding profiles are shown in Appendix B - Figure 14. Data used to plot this graph was supplied by AngloGold Ashanti's Vaal River control room.



Appendix B - Figure 14: *Summation of pumping, refrigeration and rock winding electricity demands*

Appendix B - Figure 14 shows the erratic electrical energy profiles of the pumps, fridge plants and rock winders in contrast with the systems that comprise the base load of Appendix B - Figure 13. It is therefore vital to log these values for MD control purposes.