Research and implementation of a load reduction system for a mine refrigeration system

J Calitz

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Promoter: Dr. MF Geyser

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ABSTRACT

Title: Research and implementation of a load reduction system for a mine refrigeration system.

Author: Jan-Johan Calitz

Promoter: Dr. MF Geyser

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In this study, a system was developed to shift electrical load out of Eskom's peak period to the off-peak periods. This system was designed, based on research done for load shift philosophies of a refrigeration system of a mine. The investigation focussed on the mining industry, for it consumes a large percentage of the electrical energy generated in South Africa. The research results ensured a successful implementation of a Demand Side Management (DSM) program on the ventilation and cooling (VC) system of a mine, where large energy savings are possible.

Load management is required because a prediction, based on a study done by Eskom, shows that the electrical load demand may exceed South Africa's installed capacity, by as early as the beginning of 2007. To counter this phenomenon, a DSM program was then initiated by Eskom to decrease the load demand in South Africa, via load shifting.

New cooling plant controllers for the refrigeration system, which run in concurrence with the control philosophy of the entire mining system, are designed to ensure positive load shift results. These intermediate controllers operate within specified constraints for the refrigeration system.

A simulation and optimised model was first created to test the controllers, and to verify whether the achieved results adhered to the safety regulations. After the model was finalised, the new controller system (consisting of these controllers) was implemented at a specific mine's cooling system.

The installation of the new system's controllers and control philosophy, resulted in a successful load shift execution during the Eskom evening peak period. Additional to the load shift results, energy efficiency was also obtained through this implementation on the refrigeration system.

The success of the research can be determined by the actual energy savings achieved, compared to the predicted savings. The annual estimated load shift averaged around of 2.9 MW, with 3.5 MW during the nine summer months and 1.9 MW during the three winter months.

The actual results, however, show an over delivered load shift of 3.6 MW during three summer months, and 3.1 MW during the first two winter months, at Kopanang Mine. Consequently, a montbly energy cost saving of around R 46 000 for the summer months and R 217 000 for the winter months was achieved. These results indicated a projected annual saving of over R 1.4 million for Kopanang Mine.

These research results prove that DSM can be implemented on a mine's refrigeration system. Furthermore, the successful approach shown by this research can be applied on the cooling systems of other mines. Should this be done, a large contribution can be made concerning better financial savings, and more efficient power consumption of South African mines.

SAMEVATTING

Titel:	Die ondersoek en implementering van 'n las verminderingsprojek vir 'n myn se verkoelingsaanleg.
Outeur:	Jan-Johan Calitz
Promotor:	Dr. MF Geyser
Skool:	Meganiese Ingenieurswese
Fakulteit:	Ingenieurswese
Graad:	Magister in Ingenieurswese (Meganies)

'n Stelsel is tydens die verhandeling ontwerp om elektriese las uit Eskom se spitstye te verskuif. Die ontwerp is gebasseer op 'n ondersoek wat gedoen is om spesifiek lasbeheer op 'n myn se verkoelingsaanleg uit te voer. Die fokus van die ondersoek is hoofsaaklik gevestig op die mynindustrie, omdat dit een van die grootste energieverbruikers in Suid-Afrika is. Die uitkomste van die ondersoek verseker dat 'n suksesvolle aanvraagskant (DSM) bestuursprogram geïmplementeer kan word op die ventilasie- en verkoelingsaanleg (VV) van 'n myn, ten einde groot energiebesparing te lewer .

'n Vooruitskatting, gebasseer op 'n volledige studie wat deur Eskom gedoen is, het bepaal dat Suid-Afrika se geïnstalleerde energiekapasiteit bereik gaan word aan die begin van 2007. 'n Aanvraagskant bestuursprogram het in werking getree om die oormatige energieaanvraag te minimaliseer en om die probleem aan te spreek.

'n Detail ontwerp is gedoen op die beheerstelsel van 'n myn se verkoelingstelsel om lasskuif resultate te lewer. Dit is ontwerp om saam met gespesifiseerde beheerfilosofieë van al die afhanklike verkoelingstelsels op die myn gebruik te word.

Die tipe beheer moet altyd gebruik word binne beperkings soos gegee deur die spesifieke myn. Eers word 'n simulasie en 'n geoptimeerde model op gestel binne gegewe limiete. Nadat al die finaliseringsprosesse op die model gedoen is, word die nuwe stelsel geïnstalleer op 'n myn se verkoelingsaanleg.

Die bogenoemde implementering het tot 'n suksesvolle lasskuifprofiel gelei in Eskom se spitstye. Die totale energieverbruik het effektief ook verminder deur die nuwe stelsel op die verkoelingsaanleg te implementeer.

Die sukses van hierdie tipe ondersoek word hoofsaaklik bepaal deur die lasskuifresultate met vooruitgeskatte lasskuifuitslae te vergelyk. Die geskatte lasskuifresultate in aand spitstyd is 'n jaarlikse gemiddeld van 2.9 MW, wat bestaan uit 3.5 MW in die nege somermaande en 1.9 MW in die drie wintermaande.

Uit die werklike resultate is gevind dat dit groter is as die verwagte waarde by Kopanang, met 'n gemiddeld van 3.6 MW lasskuif vir die eerste drie somermaande na implementering en 3.1 MW in twee wintermaande. Die kostebesparing vir die energieverbruik is bereken op 'n maandelikse gemiddeld van R 46 000 en R 217 000 vir die somer- en wintermaande onderskeidelik. Deur konstante maandelikse besparings kan 'n jaarlikse besparing van meer as R 1.4 miljoen vir die myn bereik word.

Die uitkoms van hierdie ondersoek is dat 'n DSM projek geïmplimenteer kan word op 'n verkoelingstelsel van 'n myn met behulp van die nodige historiese data en ondervinding. Die beheermetode kan dan ook suksesvol geïmplimenteer word op die verkoelingstelsels van die meeste ander myne.. Sodra dit gedoen word kan daar groot kostebesparings wees vir Suid-Afrikaanse myne.

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- My family and friends, for their full support during this study,

Most important, I want to thank my Lord Jesus Christ for His guidance, strength and everlasting love throughout my life, and especially throughout this study. I love You.

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LIST OF ABBREVIATIONS

°C	Celcius
BAC	Bulk Air Cooler
C	current available cold water dam capacity (l)
$C_{c\%}$	current cold-water dam level (%)
C_{max}	total cold-water dam capacity (l)
$C_{min\%}$	minimum cold water dam level (%)
COP	Coefficient of Performance
CP	Control Privelege
ct	current time
DL	dam Level
DME	Department of Minerals and Energy
DSM	Demand Side Management
EE	Energy Efficiency
EEDSM	Energy Efficiency Demand Side Management
ESCO	Energy Service Companies
HMI	Human Machine Interface
HVAC	Heating Ventilation and Air Conditioning
IEP	Intergrated Energy Plan
IO	Input Output
IRP	Intergrated Resource Planning
kW	kilo watt
L	Level
LM	load management
LS	load shift
Lt	minimum shut down time limit
M&V	Measurement and Verification
M_{ch}	flow per chiller (l/s)
M_{mine}	water flow to the mine (l/s)
MSt	minimum stop period for specific machine
M_{supply}	total supply flow through fridge plant
MW	Mega watt

N	number of available plants/chillers
NAESCO	National Association of Energy Service Companies
NERSA	National Energy Regulator of South Africa
NIRP	National Integrated Resource Plan
P	Pressure
PID	Proportional Intergral Derivative
PJ	Petajoule (10^{15} Joules) unit of energy
PLC	Programmable Logic Controller
ps	total peak seconds
s	Entropy
SCADA	Supervisory Control and Data Acquisition
SHE	Safety Health Environment
St	shut down time
T	time period before cold dam is empty (s)
T_{closed}	temperature where the valve must be totally closed
$T_{current}$	current temperature of the specific water in the system
T_{open}	temperature where the valve must be fully open
TOU	Time of Use
T_{wanted}	Set point inlet temperature
TWh	Terra Watt hour
v	specific volume
VC	Ventilation and Cooling
$V_{opening}$	proportional opening of the valve

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1. INTRODUCTION

This chapter gives an overview of the current electricity energy consumption in South Africa. It also emphasises the growth of energy demand, and the generated capacity that will be reached in the near future. Electrical load shifting and energy efficiency is a temporary solution initiated through Eskom Demand Side Management (DSM). It then focuses on the various sections of large energy consumers where the Eskom DSM program can be implemented.

1.1. BACKGROUND ON ENERGY DEMAND

1.1.1. Overview of South African energy consumption

There is a steady increase in the energy consumption of the world. In the past few decades, the energy consumption grew 11% in third world countries [1]. In South Africa (SA), it was predicted that the energy consumption would increase by 59% from 1990 over a period of 30 years [2].

In SA the growth of industry, residential areas and mining, increased rapidly over the past few years [3]. This increase in population and economic activities caused South Africa to become more energy intensive, as well as more energy sensitive [4]. With this steady increase of the factors mentioned above, energy becomes a more critical resource every day.

Electricity is the main energy resource used in SA [5]. Eskom is SA's main electricity supply utility and it supplies 95% of the electricity used in SA. Other suppliers are municipalities (1.5%) and privately owned generators (2.7%) [6]. Eskom is the fifth largest and second cheapest international supplier of electricity in the world [7]. This resulted in an incentive for consumers to save. The current licensed capacity for Eskom is around 39.8 GW, where the netto maximum operational capacity is around 35 GW [8].

By considering electricity as a main energy resource, the constant growth in energy consumption will result in the electricity demand reaching the energy supply capacity of Eskom in years to come. Figure 1-1 illustrates the daily average electricity demand over the past 10 years [3].

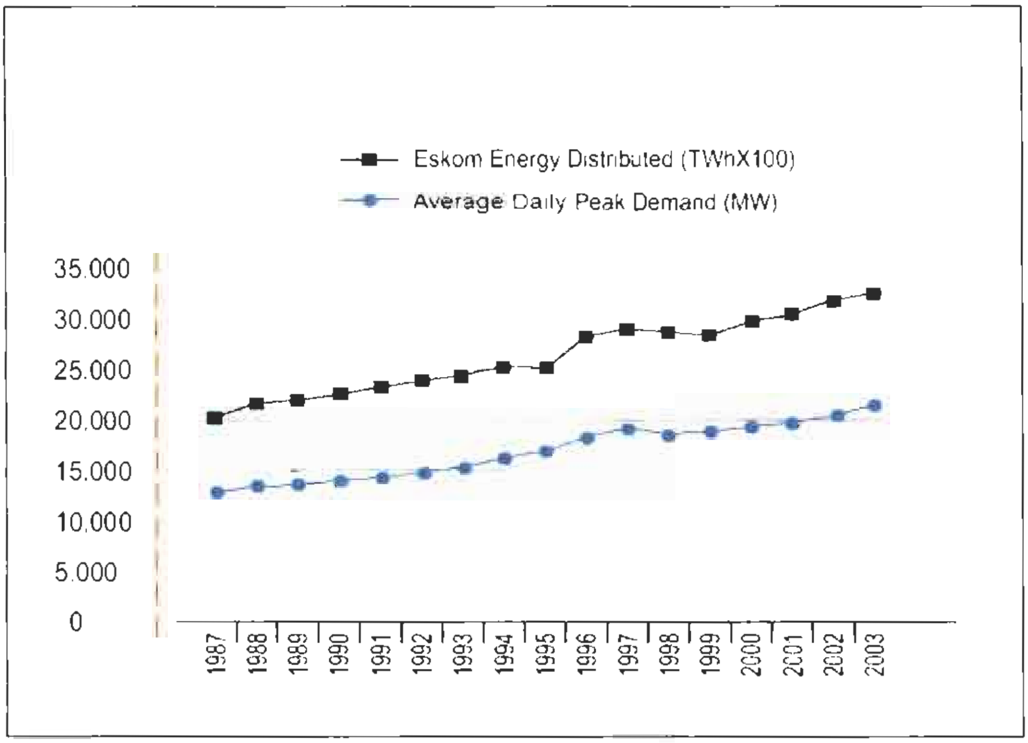


Figure 1-1: Eskom energy distributed in daily average peak demand

Its stated that there has been a constant year-on-year average growth of 3% for the economical activities in SA since 1970 [9]. Due to the relation between the economical and energy growth in SA, as mentioned earlier, it is obvious that there will be an increase in the energy demand as the economy grows. This increase in growth of energy demand is illustrated in the above figure. Therefore, it can be expected to have the same average energy demand growth in the future.

1.1.2. Peak electricity demand problem

The current electricity demand, experienced by Eskom, is dominated by two peak intervals during the day. This load shape mainly results from the power consumption of the residential sector. A maximum daily load demand profile for SA can be seen in Figure 1-2.

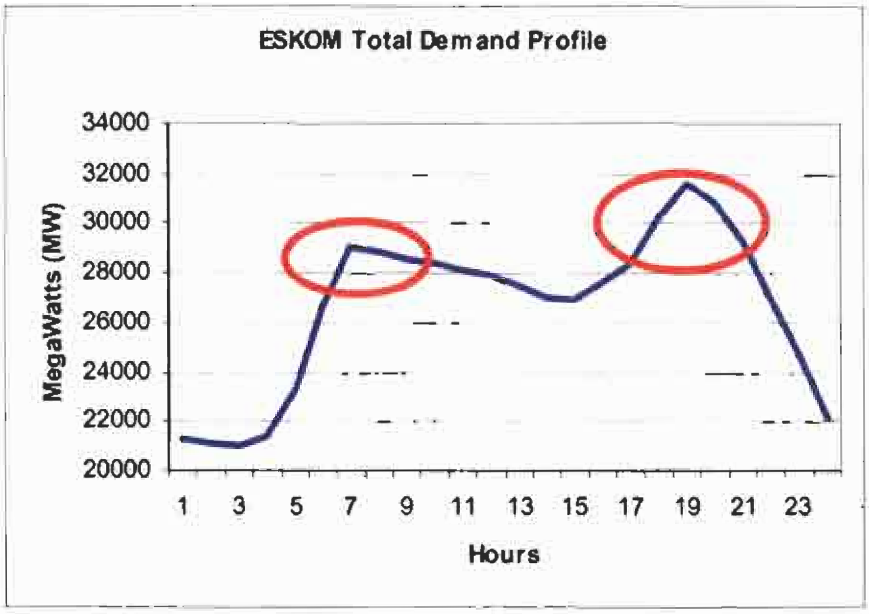


Figure 1-2: Daily profile of Eskom's total demand

From the figure, one can see that these peak periods fall between 7:00 and 10:00, and between 18:00 and 20:00. The daily consumption also varies relative to the season. The peak demand experienced in winter is more pronounced than in summer. Figure 1-3 illustrates this [10].

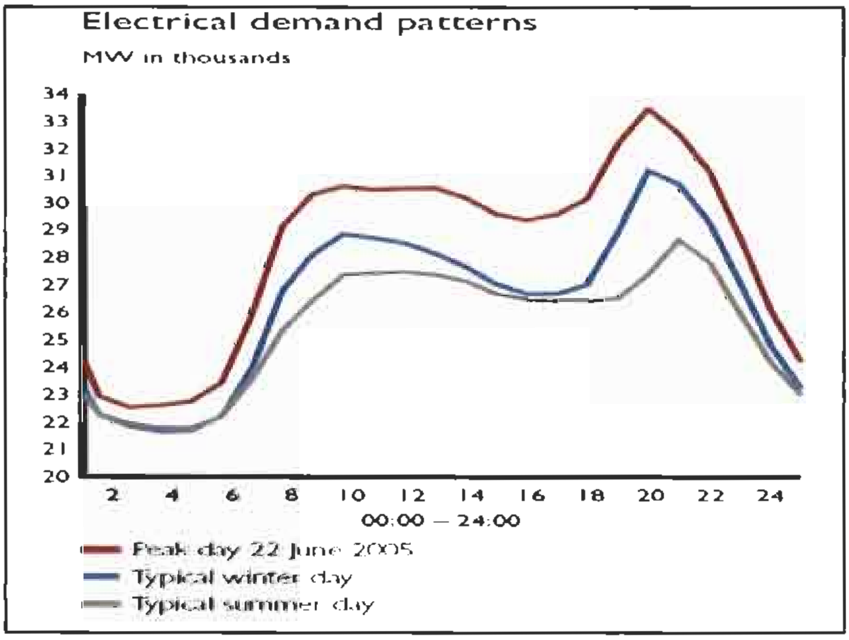


Figure 1-3: Typical winter and summer day's electrical demand.

From the above figure, it is also evident that there is a substantial difference between the low demand periods, and the high demand periods. The peak demand shows an increase of 78% and 70% over the low demand period for winter and summer days respectively [3].

It is projected that the electrical energy demand will exceed the peak generating capacity by 2007 in the winter period [11]. Figure 1-4 shows the predicted electricity consumption of two consecutive winter days [3].

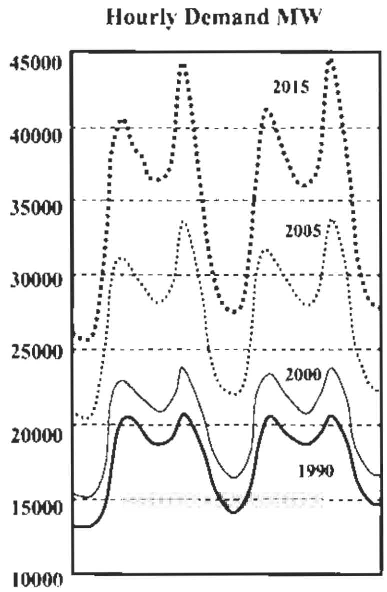


Figure 1-4: Typical average winter load profile forecast until 2015 for a period of two days

It is evident, in the above figure that not only the peak demand is increasing, but it also illustrates a steady increase in the base load. These predictions show that there will be an imminent electricity supply problem in SA. If steps are not taken to rectify this problem, Eskom will not be able to meet the demand for electricity in SA after 2007. Initially this will only appear during the peak periods and as time progresses it will emerge during base load periods as well.

1.2. SOLUTION TO ENERGY DEMAND GROWTH

1.2.1. Demand Side Management (DSM)

To postpone the predicted date where the electricity demand will reach the generated electrical capacity, Eskom has launched a Demand Side Management (DSM) program. The first DSM program was developed in the USA in 1980 and was later adopted in the United Kingdom, Europe and Australia [12]. It is fortunate for SA that research had been done in this area for over thirty years, but a scheme for the South African environment had to be established differently [13]. This DSM scheme for SA must be tailor made for the economical, environmental, social and technical factors that differ from other countries like the USA. Eskom officially recognised the DSM scheme in 1992, and the first DSM program was produced in 1994 [14].

Although the main objective of SA's DSM program is to delay the imminent shortage of generation capacity to as far as 2025, there are other benefits as well [11]. These are [12]:

- Reduction of fuel consumption at power stations
- Reduction in distribution losses
- Reduction in transmission loss
- Reduction in the emissions of CO_2, SO_2 and NO_2 from power stations.

In laymen's terms the purpose of DSM is to create more efficient systems that will consequently build a "virtual power station" [15].

Eskom used the methodology of an independent company to execute a DSM program at feasible sections on the sites of their consumers. This type of company is named an ESCO (Energy Service Company). 106 ESCOs have been registered since the initiation of DSM in SA [13].

An important representative of the ESCO industry in USA – NAESCO – defines an ESCO as "...a business that develops, installs and finances projects designed to improve the energy efficiency and maintenance costs for facilities over a 7 to 10 year time period..." [16]. The technical and performance risks of running these types of projects are the responsibility of the ESCO [17].

An ESCO offers services that play a big role in costs of the projects and are then repaid through the resulted savings introduced. The following services are included during the implementation of a typical project:

- Development, designing and financing the project,
- Installation of infrastructure for project,
- Monitoring the performance of the project,
- Take the responsibility to generate the proposed savings.

The ESCOs in SA are not only supporting Eskom in solving the energy problem, but also creating additional jobs in the ESCO industry. Contractors and facilities are also involved in their projects. One third of the capital invested in the existing ESCO implementations has been awarded to labour [17].

An ESCO investigates and executes the DSM program at a section on one of Eskom consumers' sites if the DSM potential is practicable. This is done with consideration to their tariff structure. The tariff structure is initially designed to encourage the consumers to use less electricity during the peak periods and more in the off-peak period. The five Eskom tariffs available to large electricity consumers are: NightSave, MegaFlex, MiniFlex, RuraFlex and Wholesale Electricity Pricing (WEP) [18].

MegaFlex is more suitable for large consumers that need a supply of 1MVA and higher [19]. This is ideal for large consumers capable of shifting load for long periods (4 to 5 hours per day). The only negative aspect is that this tariff is very rigid with little room for innovative scheduling.

The MegaFlex price profile is characterized by the following time of use structure:

Defined Time Periods	Weekdays	Saturdays	Sundays
Peak	07:00 – 10:00 18:00 – 20:00	N/A	N/A
Standard	06:00 – 07:00 10:00 – 18:00 20:00 – 22:00	07:00 – 12:00 18:00 – 20:00	N/A
Off-Peak	22:00 – 06:00	12:00 – 18:00 20:00 – 07:00	Whole day

Table 1-1: Time of use structure for MegaFlex tariff

The following table gives the active energy charge for the MegaFlex tariff:

High-Demand Season (June – August)		Low-Demand Season (September – May)
49.69 c/kWh	Peak	14.10 c/kWh
13.14 c/kWh	Standard	8.75 c/kWh
7.15 c/kWh	Off-Peak	6.20 c/kWh

Table 1-2: Active energy charge for MegaFlex tariff

Table 1-3 summarises the network charge for MegaFlex tariff:

Network Charge	Period	Cost	Notes
Network Access Charge	All Periods	R 5.62 / kVA	Payable each month and is based on the annual utilised capacity
Network Demand Charge	Peak and Standard times	R 6.36 / kVA	Payable for each kVA of the chargeable demand supplied during peak and standard periods per month

Table 1-3: Network charge for MegaFlex tariff

To understand the DSM structure, the responsibilities and location of all parties in the development of a DSM project must be known (see Figure 1-5). It consists of ESKOM, NERSA (National Energy Regulator of South Africa), ESCO's, M&V (Measurement and

Verification) and the client or end-user. Each participant's role is depicted in Table 1-4 and in Figure 1-5, [13]:

Nr.	Partaker	Responsibility
1	NERSA	Provide funding mechanisms, to oversee the expenditure of funds and guidance for DSM implementation to ensure monitoring and verification
2	ESKOM	Ensures meeting NERSA targets, administrate project funding and facilitating implementation of DSM projects by ESCOs. Initiate M&V.
3	ESCO	Private sector that implement DSM projects on customers facilities. Develop project proposals for ESKOM, established on a performance based contract with the customer. Ensure sustainability for the life of the projects.
4	M&V	Independent body to the NERSA and ESCO. Confirm impact on EEDSM projects implemented and report to the NERSA
5	Client	Ensure the sustainability of the programme. This is agreed through a Eskom DSM contract between ESKOM and the end user

Table 1-4: DSM structure and responsibilities

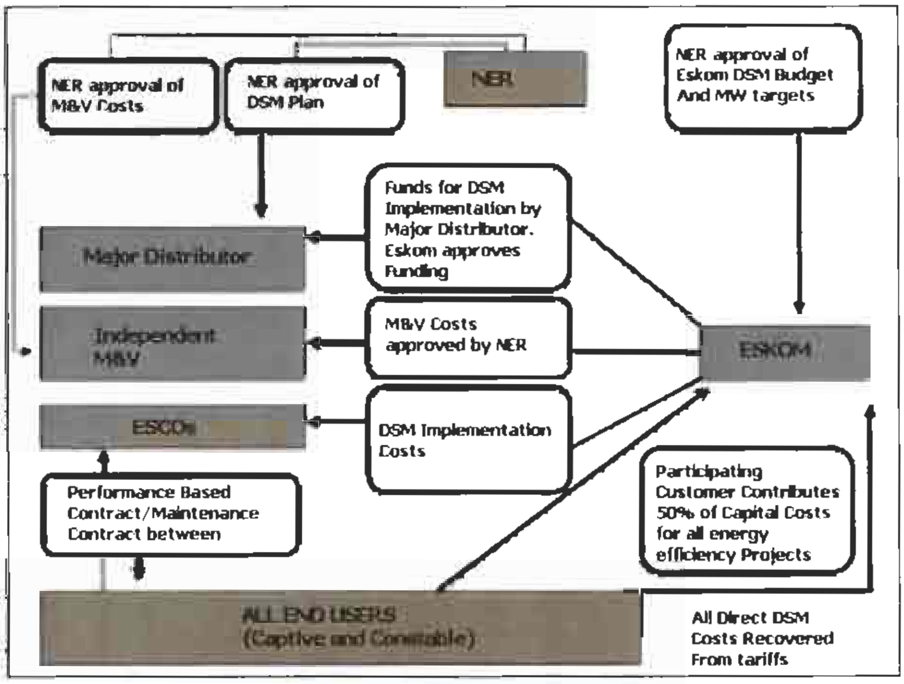


Figure 1-5: DSM implementation model and process

1.2.2. Load management

The aim of the DSM program is to restructure the load profile of its customers through load management (LM). LM is done mainly through two methods, namely the load shift (LS) and the energy efficiency (EE) method. The load shifting only focuses on the peak electricity demand problem, where EE focuses on the total 24-hour energy demand crisis.

In the USA, LM projects have been completed with great results. These projects breakdown structure per area is shown below, for the year of 2002 [20]:

- 39% of lighting installations.
- 15% from fuel switching electric hot water and electric space heating systems.
- 10% from air conditioning efficiency project.
- 36% from motors, ventilation and refrigeration.

At the moment, Eskom is more concerned about LM through load shifting during peak periods, than they are about more energy efficient implementations [11]. LS involves the shifting of load from peak to off-peak periods, as seen Figure 1-6.

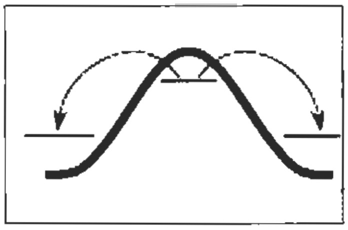


Figure 1-6: Illustration of load shifting

It is graphically illustrated in Figure 1-6 that there is a decrease in load during peak periods and an increase during off-peak periods. The application of LS on a 24-hour profile can be seen in Figure 1-7. This illustrates a result of an ideal load management (or LS) profile.

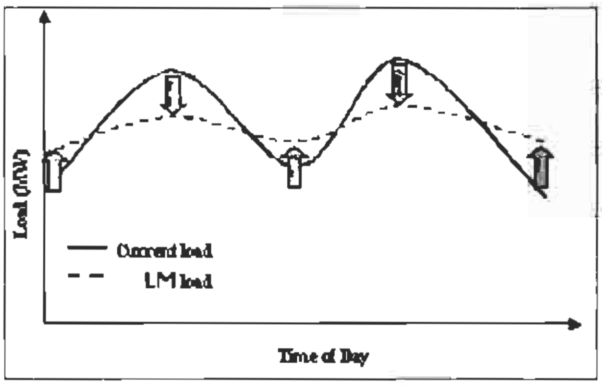


Figure 1-7: Load Shifting through LM program

An example of LS is the optimisation and utilisation of thermal storage capacity. Thermal storage appliances can be modified to replace unnecessary electrical conservation devices [21].

However, in a load reduction operation, less electricity is used in a system during a given period compared with what was previously used. Consequently, no load is shifted in this method but it is only reduced. In the case of EE this load reduction is applied for an entire 24-hour period, or merely during certain times of the day. This EE effect is illustrated in the following two figures:

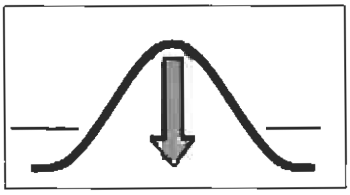


Figure 1-8: Illustration of load reduction

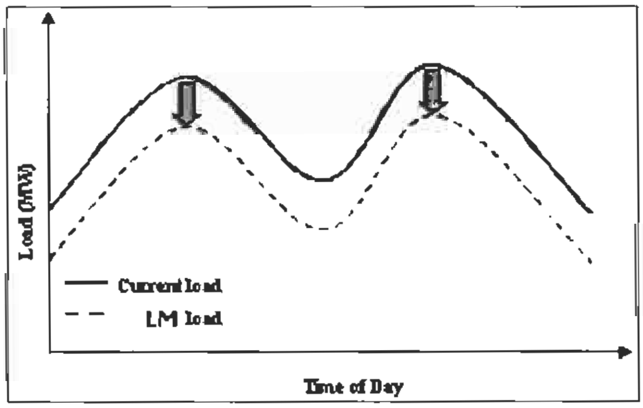


Figure 1-9: EE through LM program

EE is one of the best ways to limit the greenhouse gas releases, thus reducing the environmental impact and endorsing a sustainable use of the resources' energy. The aim of EE programs is therefore to reduce the energy used by specific end-use devices and systems. Typically, without affecting the services provided. EE savings are generally achieved by substituting technically more advanced equipment to produce the same level of end-use services (e.g. lighting, heating, motor drive) with less electricity.

To make LM possible at large electricity consumers (for example the mining industry) the commodity must be identified. The most common and easiest commodity used at a mine, is water. The water can be used in the thermal storage appliances, as previously mentioned. Water is not just a working fluid at the mine but can also serve as thermal storage for underground pumping as well as the Ventilation and Cooling (VC) systems [22].

Many VC systems make use of thermal storage (either hot or cold water) to provide a buffer in capacity. The purpose of this buffer is primarily created to ensure that all the safety regulations are achieved and that there will be continuation of the production process [23].

Figure 1-10 shows the results of a typical LS project by optimising the commodity. The previous system operation energy consumption (baseline) is shown against the consumption trend of the new system. It should be noted that the total daily energy consumption remains the same pre- and post implementation of the optimisation procedures.

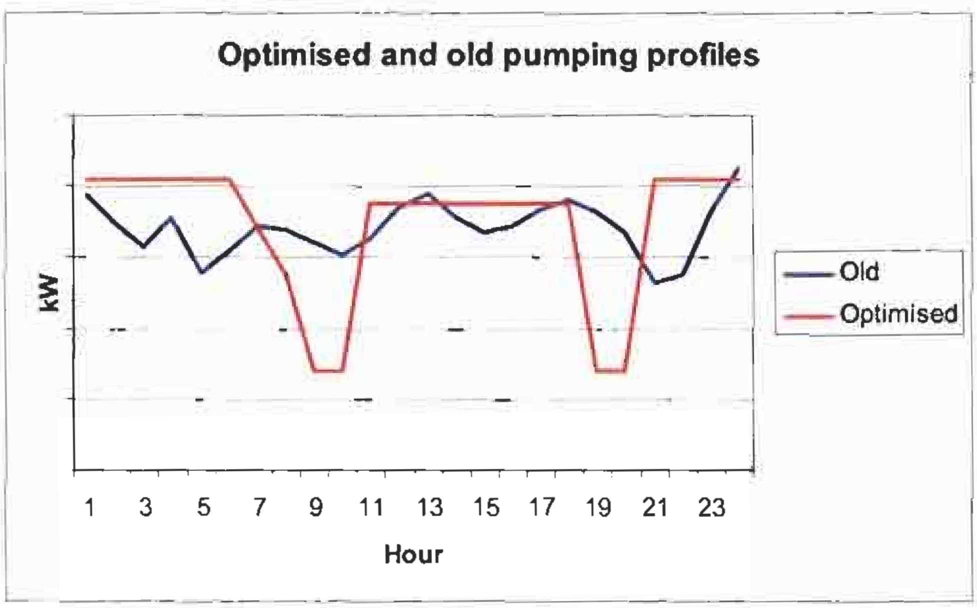


Figure 1-10: Illustration of an ideal load shifting profile

This optimised load shift profile cannot be achieved by only rescheduling the necessary equipment of the current system at the mine by using the commodity. The safety regulations and all the other mine constraints must be taken into account as well. An experienced energy specialist for that specific system must therefore do the investigation and installation of a LM system.

1.2.3. Effect of LM and DSM on energy demand

The completion of as many LM projects through the DSM program as possible, is a high priority for Eskom. For these projects to be successful, some modification to the consumer's system and preparations during off-peak periods must take place.

The application of a LM project on site will change the electricity demand profile. This load profile must be maintained within the customer's satisfaction levels [24]. This load change may also have a positive effect on the electricity cost of the client.

These projects can result in a cost saving of up to 20% on a system. Almost 70% of big energy consumer companies can benefit from a LM program/implementation [25]. As mentioned earlier, by running all the feasible DSM projects in time, reducing the total energy usage of the consumers will create a virtual power station. This effect will lower the projected energy usage up to 15% in 2014 [5], as shown in Figure 1-11.

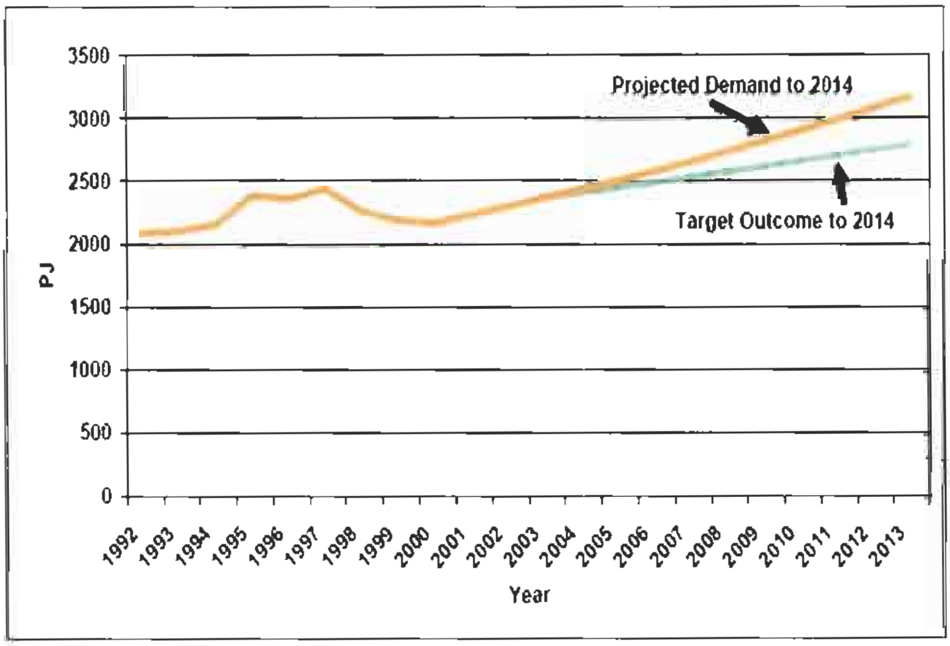


Figure 1-11: Illustration on DSM effect on projected energy

Research has shown that a cost saving is also possible of at least 11% already achieved by only using low-cost to medium-cost technical interventions [5]. This can all be a result of DSM implementation and can therefore be seen as a good temporary solution for South Africa's energy demand problem.

1.3. ELECTRICAL ENERGY IN THE MINING INDUSTRY

The gold mining industry is one of the largest mining industries in SA. In 1995, the gold resource of SA contributed 23% of the world's total gold production. Since then SA's contribution to gold production has declined over the past decade. Despite of this large declination, SA remains the world's largest gold producer and accounted for 14% of global new mine supply in 2004 [26]. The percentage of SA's gold production in the world over the past decade can be seen in Figure 1-12.

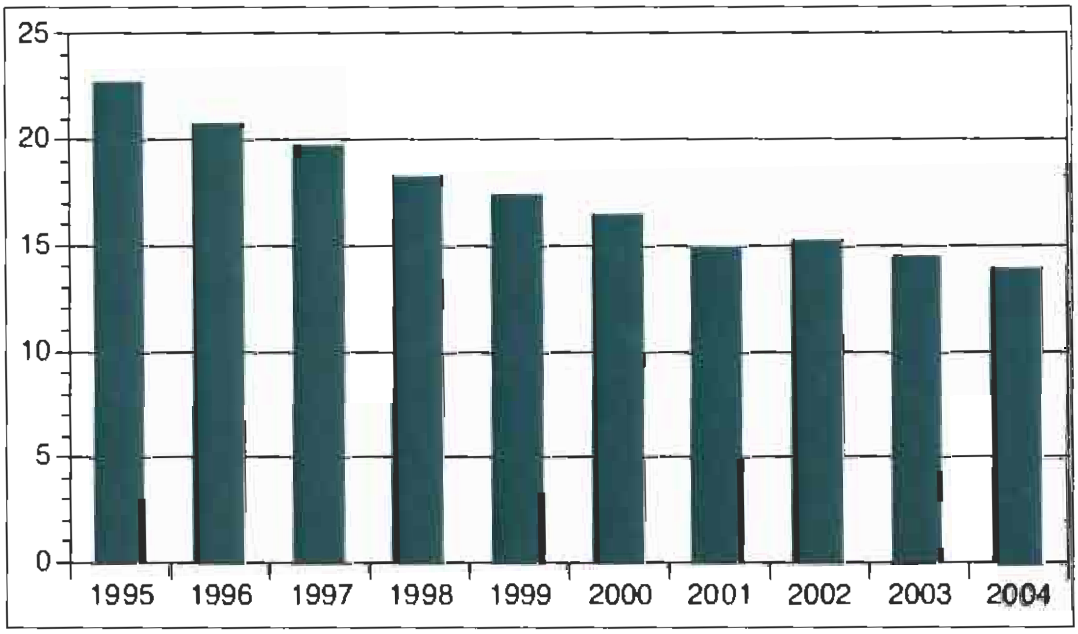


Figure 1-12: South African gold production as a percentage of total world production

Almost 10% of the gold production in South Africa came from the mining depths of 2500 m in 1995. For a gold mine with depths deeper than 2000 m, the predicted production is around 60% of the total gold production in 2010 [28]. The estimated production percentage will be 50% in 2015 [27].

The safety regulations have become the most vital part of the productivity with all mining industries. This means that production will be stopped if there were any danger for the mineworkers, underground or on the surface.

One of the most important safety factors underground is the environmental conditions. Acceptable underground conditions become more difficult to maintain as the depth increases [29]. This will also result in higher energy costs for the mine. This part of the safety conditions also has a direct impact on the production. The impact of better environmental conditions could therefore improve the productivity and production.

The foremost variables that change the underground conditions of a mine are the temperatures of the underground air and water, which are used to provide a cooler environment. An adequate surface cooling system ensures colder air and water are sent underground to maintain the underground air and water temperatures at an acceptable level.

It is also essential to consider that most of the gold mines in South Africa are operating at a depth deeper than 2000 m. It is concluded that the ventilation and cooling (VC) system of mines play an important role in the SA gold mining industry's energy costs.

The total energy usage of the mining industry constitutes an annual average of 23.4 % of Eskom's total electricity supply of 34.831 GW. This is used to preserve a constant and profitable production [30]. In Figure 1-13 the electrical energy consumption in 2003 for each sector can be seen [13].

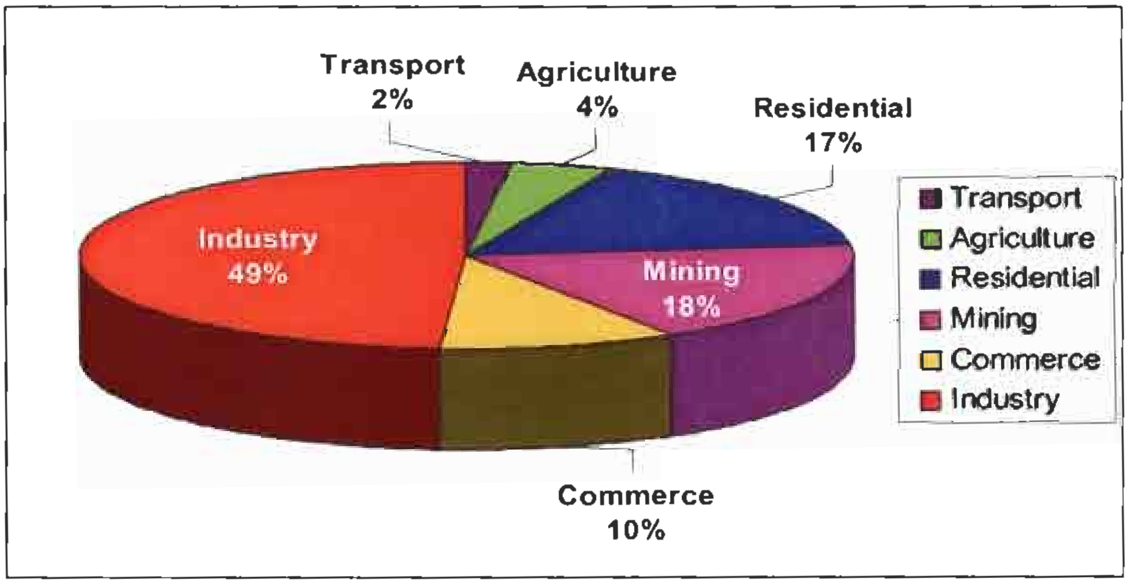


Figure 1-13: Electrical energy consumption per sector 2003 (Total 190 396 GWh)

As mentioned earlier electricity is the main energy resource used in SA. From the figure above it is therefore evident that the mining, industrial and residential sectors are the largest electrical energy consumers of SA.

Together these sectors consume an excess of 80% of the total energy consumption of SA. Each remaining sector account for less then 10% of the total energy demand [5], and therefore have a smaller potential contribution to the DSM program. It is then safe to assume that much of the electricity of SA is consumed by the mining industry, which has a direct economical influence.

Mines are the second largest consumers of electrical energy in SA, therefore a relatively high theoretical potential for energy savings is possible in these sectors. The high potential energy saving sectors, part of the 80% mentioned, consume almost 50% of the total energy consumption in SA. This high energy saving potential sectors are identified in the mining and industry sectors.

The mining industry in SA annually spends an average of R 4.2 billion on electricity [31]. An energy management program can therefore also benefit the mining industry through monetary saving. Incentive energy-efficient operations were initiated from the head offices of the various mining groups.

With consideration of all the above-mentioned facts, it is obvious that the focus of this DSM investigation directs to the mining energy consumption.

1.4. MINE REFRIGERATION SYSTEMS

The power consumption of the gold mining sector does not only consist of the production process of gold, but also of the secondary systems like pumping, necessary water flow procedures, winders, compressed air and VC systems.

Because most of the mines in SA are gold mines, as mentioned earlier, the director of BBE (Bloom Burton Engineering) Gundersen said the following [33]: "… In the mining industry, South Africa leads the way in terms of mine ventilation and refrigeration systems… ". Therefore it can be assumed that the energy consumption of the VC systems must form a large part of the total energy consumption of the mine.

The VC system of the mine is directly dependent on the underground and environmental conditions, as mentioned earlier. The main reason why the conditions change underground is due to the rise in virgin rock temperature with increased depth. At a certain depth, this temperature can become unbearable for human endurance [19].

The rise of the rock temperature can differ in mines. Generally, the ventilation system alone is adequate at the depth of 1600 m to provide suitable underground conditions. From there on the cooling system becomes a dominant operating cost factor to insure constant and acceptable underground conditions [32].

Platinum and gold mine cooling systems have a radical difference in cooling demand for the same depth. When exceeding the depth of 1400 m in platinum mines, the VC must be adjusted drastically for more cooling from the support cooling system [18]. For a gold mine, the crucial depth is around 3000 m.

Figure 1-14 and Figure 1-15 confirm that energy consumption of a mine cooling system is very high and therefore makes it feasible to investigate these systems in SA mines for cost savings.

This data is an average quantity of a typical mine divided into the following sections [15]:

- Ventilation and cooling
- Underground pumping
- Compressed air equipment
- Mineral processing and rock crushers
- Underground mining systems
- Mine winding system
- Office buildings

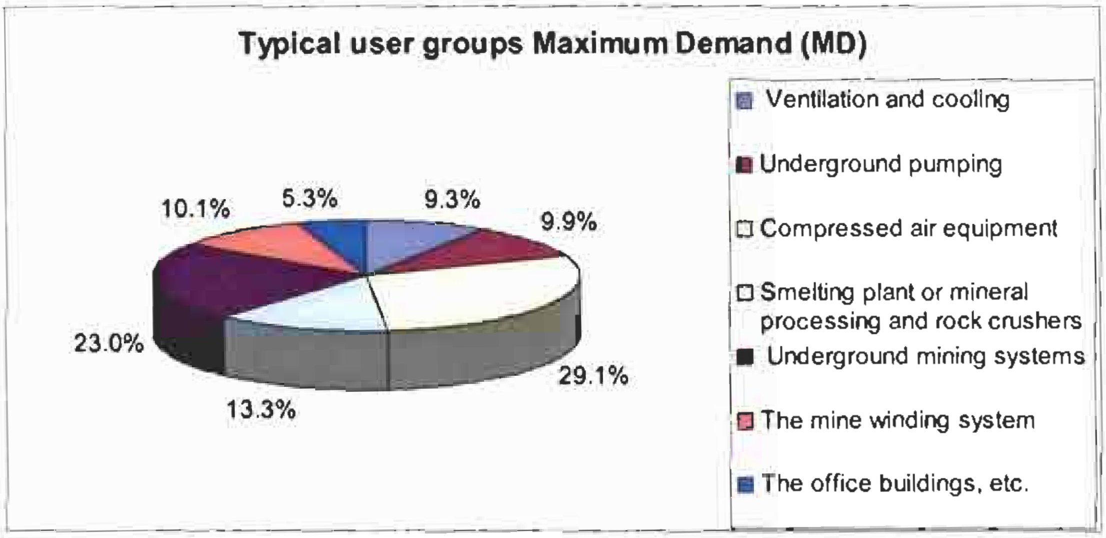


Figure 1-14: Average maximum demand (MD) of a typical mine

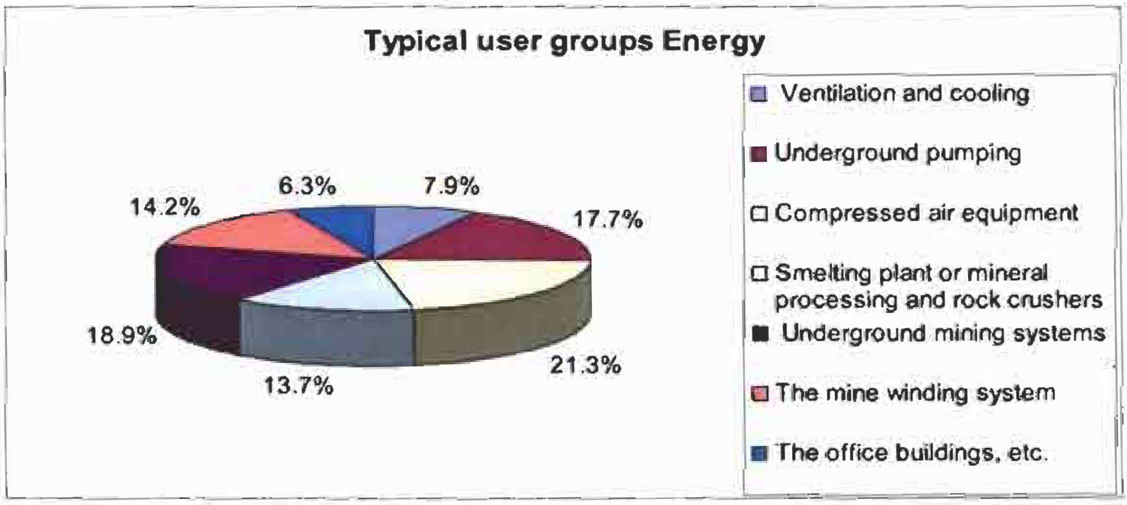


Figure 1-15: Average energy usage of a typical mine

The above figures show that for a typical mine in SA, the VC system contributes 7.9% and 9.3% to total energy consumed and the maximum demand of the mine respectively. Because it is easier for bigger load reduction in the VC system than the other sections, the figures emphasise that the reduction in power usage of the VC system can be beneficial to the mine and Eskom.

The amount of energy generated by the refrigeration plants is proportional to the work of the compressor of each plant. This work increases as the demand in cooling energy of the water rises. It can then be derived that the power consumed for this process to work, is directly dependent on the power used by the compressor.

This effect of the cooling demand (work of compressor) of the mine can then be seen immediately on the electrical bill. The VC system's combined energy constitutes 20% to 40% of the total cost of the electrical bill of the mine, especially at deep mines [34]. It must be noted that this contributes part of the electrical bill of the mine when compared to the energy consumption of 8%-9%, as mentioned earlier.

It is widely known that the fluctuating gold prices, as determined by global markets, put the gold mines under tremendous financial pressure. The alternations of gold prices and the increasing cost of gold production are causing financial instability within the mines [35]. This financial need encourages energy cost savings. The simplest way of saving on energy is by rescheduling the equipment of the system to consume more energy in off-peak periods than in peak periods.

To consider the correct change in the cooling, ventilation and pumping system scheduling, the following factors can be improved [35]:

- Healthier underground environment
- Decrease safety risks
- Release financial pressure

This rescheduling of the cooling system contributes to solving the energy crisis in South Africa. A thermal optimisation for any kind of energy system is globally acknowledged as one of the most effective and powerful tools to boost the EE process [30].

The rescheduling procedure is very innovative, because in the past the refrigeration was only improved in the rural areas (especially mines) by more efficient refrigeration systems. In the residential areas a higher standard refrigerator was purchased. In the commercial areas however, the compressors and motors were replaced with higher efficiency models [21].

It can then be concluded that by the implementation of a LM program (EE or LS) in the VC sector of the mine, the effect on finances as well as the energy demand may be immense.

1.5. PURPOSE OF THIS STUDY

The purpose of this dissertation was to contribute to the development of a DSM control system and infrastructure for a refrigeration system of a mine. Necessary and thorough research procedures must be followed to make the new control system a successful LM implementation.

The main idea was to use all the information found on DSM systems through thorough investigations, and use this to create an enhanced EEDSM (Energy Efficiency Demand Side Management) program.

The above literature survey, based on the research done in DSM systems, showed that the refrigeration system was a feasible section at a mine to install this program. Therefore the dissertation consisted of enough research in the specific field (refrigeration system) to install a new designed control system on the mine for that field, with all the constraints and safety regulations of the mine taken into consideration.

Research showed that more energy efficient control and management in refrigeration systems will save companies money and will optimise the use of the energy resources.

1.6. OVERVIEW OF THIS DISSERTATION

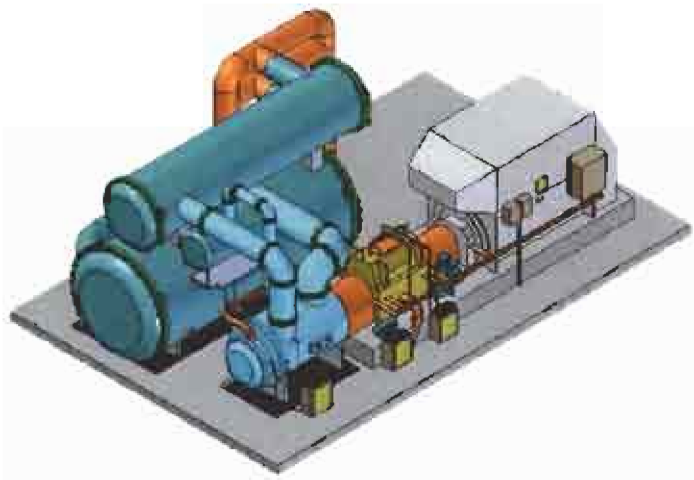
The overview of the dissertation consists of researching and identifying a problem, obtaining a solution, finding a feasible case study to install the solution, creating a modified system to ensure successful results, comparing the results and recommending any improvement if necessary. The following is a short description of this procedure divided into their separate chapters:

- **Chapter 1** consists of the background on the energy demand problem in South Africa, and the feasibility of solving the problem by starting the research in practicable areas.
- **Chapter 2** will discuss the background research on one of these areas – refrigeration plants at a mine. The procedure to implement load shifting in the cooling

refrigeration system is examined and the method to develop enough potential to make it a practical project.

- **Chapter 3** will discuss simulation and optimisation procedures to create or design a new control system for the above method in Chapter 2.
- **Chapter 4** consists of the control philosophy at a feasible mine refrigeration layout – Kopanang. This chapter explains the philosophy needed to ensure a successful DSM interaction with the other existing systems on the mine and the new control system.
- **Chapter 5** will discuss the implementation procedure before and after the new control system and philosophy were installed. It emphasises a few problems that were encountered through the implementation procedures in a case study. A verification procedure to compare the predicted results with the actual results is also discussed.
- **Chapter 6** briefly summarises the whole study and recommendation are given where needed.

2. RESEARCHING AN EFFECTIVE METHODOLOGY FOR LOAD SHIFT ON FRIDGE PLANTS



This chapter describes the methodology of load shifting in the refrigeration plants itself and the refrigeration system of a mine.

2.1. INTRODUCTION

Refrigeration systems can be modified to store thermal energy. By using the stored energy and fewer loads in the peak period, the system will result in energy cost savings. The energy savings form part of the load management DSM program in SA, which can also result in more efficient energy patterns.

In this chapter, a background study is done concerning the refrigeration plants or cooling systems, to understand the running and control process of the refrigeration plants. This will help to create a control program and a control philosophy that will generate a DSM refrigeration project.

Firstly a typical refrigeration plant is discussed where a load shift strategy is emphasised. After the load shift strategy is confirmed, the steps to redevelop an adequate control system are created which will result in a successful LM project.

2.2. REFRIGERATION SYSTEM ON A TYPICAL MINE

2.2.1. Background on refrigeration plants

To create a controller or control philosophy to generate a feasible DSM program with a refrigeration system, the breakdown structure of the system must be thoroughly understood. This chapter is therefore a short description of the structure of the fridge plant (refrigeration plants) and the internal programmed control philosophy.

The refrigeration system of the mine can be compared with the chiller of a building, based on the same fundamental and functional procedures. The main purpose of the refrigeration system on the mine is to cool down the water, sent underground, to a desired temperature.

To deliver the desired outlet water temperature at the fridge plants, heat exchange (Q_L) occurs at the evaporation side. This causes a heat intake to the refrigerant (inside the fridge plant) and must then be extracted at the condenser side (Q_H), see Figure 2-1 [37].

The refrigerant cycle is illustrated in Figure 2-1. This significant cycle must be understood because the heat transferred at the evaporator is directly dependent on the amount of heat transferred at the condenser.

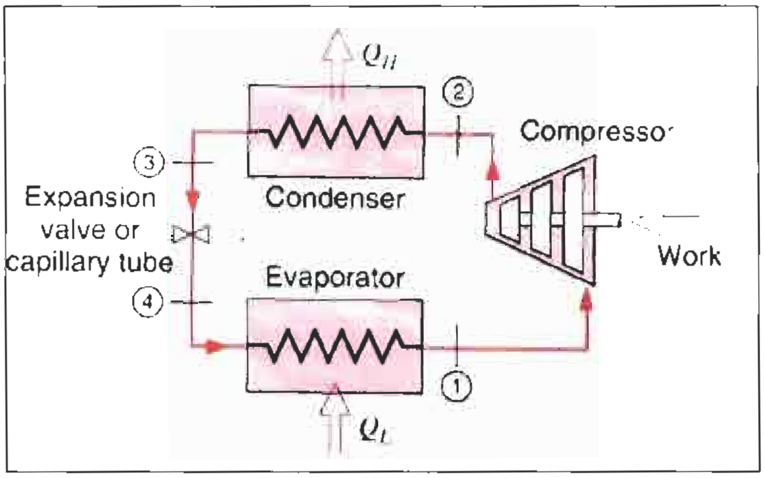


Figure 2-1: The ideal compression refrigeration cycle

The refrigerant cycle, depicted in the figure above, is as follows: the refrigerant enters the evaporator at a temperature T_4, where the evaporator heat transfer takes place. A temperature of T_1 exits the evaporator and T_2 enters the condenser. Condenser towers (water coolers) are installed here to ensure that the required heat transfer from the refrigerant takes place at the condenser. This heat transfer guarantees the outlet temperature (T_3) at the condenser, which will influence the evaporator heat transfer delivered [36].

The aperture of the valve and compressor in the chiller, controls the pressure and phase state of the refrigerant. This change in the equipment of the fridge plant will result in changing the delivered outlet water temperature. This equipment is also illustrated in the above figure.

An assumption is therefore made to calculate the refrigeration cycle processes by only considering the main equipment of the fridge plant, which has the biggest influence on the refrigerant.

With consideration of the required heat transfer at the evaporator and condenser, the quantity of heat exchanging is calculated by assuming that the total heat of the refrigerant transferred is adiabatic, thus:

$$\sum Q = 0$$
$$\therefore Q_L - Q_H = 0 \qquad [1]$$
$$\therefore Q_L = Q_H$$

In practice it can never be possible to assume it is adiabatic, for there will always occur heat loss throughout the refrigerant cycle, losses will even occur at the compressor. It can only be assumed that $Q_L = Q_H$ when all relevant factors are unknown, and only an estimated value is needed.

By considering the heat transfer section at the evaporator and condenser, the following equation is generated to calculate the heat transfer of the water used [38]:

$$Q = \dot{m}_w c_{p.w} \left(T_{w,i} - T_{w,o}\right) \qquad [2]$$

Where m_w are the mass flow of the water, the C_p value is the specific heat value [kJ/kg.K] of water. The T_i and T_o are the in and outlet temperatures respectively at the heat exchange section.

Although the process is assumed adiabatic, as mentioned earlier for estimated values, losses in the heat transferring process will occur. The inefficiency of the process is usually caused through the resistance of heat transfer in material. The heat transfer that is taking place with the atmosphere or other heat sources nearby, however, causes the losses.

A loss factor is calculated by taking the type of material, geometric parameters and the convection coefficient (if necessary) into account [38]. The total loss in heat transfer is known as a fouling factor. The effectiveness of the refrigeration plant is therefore the ratio of the heat transferred and the maximum heat that could have been transferred in ideal circumstances [39].

It is concluded by all the above calculations and procedures that the main purpose of the refrigeration system is to maintain a small variance of temperature change of the outlet water temperature, at a low temperature T_1 (temperature in state 1, shown in Figure 2-1) relative to the temperature T_3 (at state 3) of the refrigerant cycle. Therefore, the system must be build for a certain quantity of heat transfer Q_L [kW]. The measure of the performance of the system is then given in terms of the Coefficient of Performance (COP), calculated through the following [37]:

$$COP = \frac{Q_L}{W_C} \qquad [3]$$

Where W_C [kW] is the work done by the compressor (see Figure 2-1).

The COP determines the efficiency of the whole refrigeration system. If the COP value increases, the system will run more efficient and the other way around. The biggest factor that can influence the COP or heat transfer is the type of refrigerant used and the quality of the equipment of the fridge plant.

2.2.2. Layout of a typical refrigeration system on a mine

The refrigeration system on a mine is utilised to cool the underground water to a desired temperature. This temperature depends on the depth of the mine. As mentioned in chapter 1, the cooling system has a major influence on the production of the mine. A typical cooling layout at a mine can be seen in the following figure.

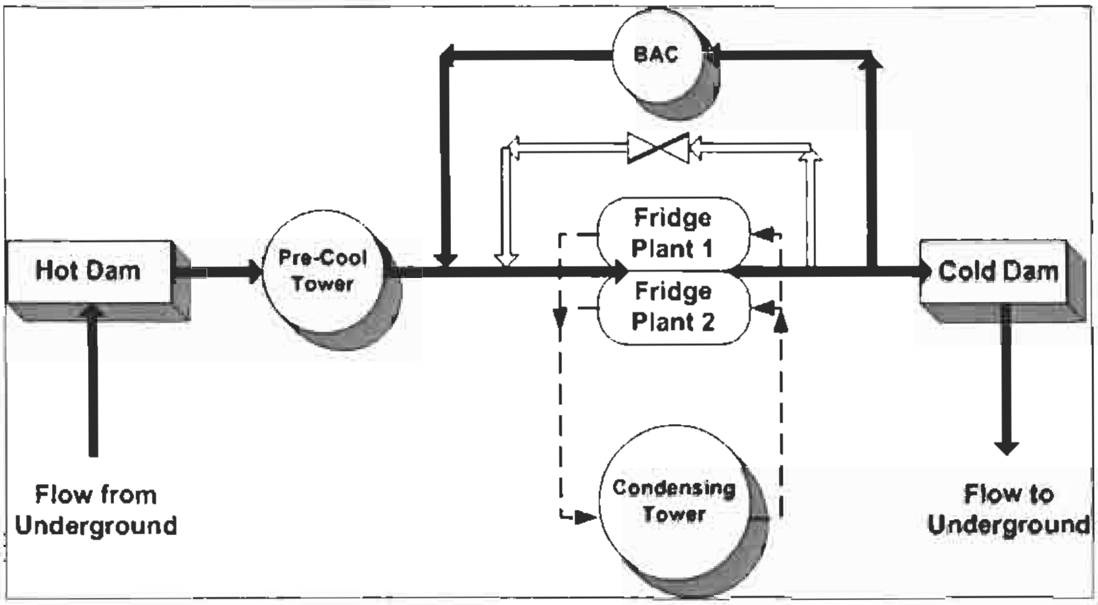


Figure 2-2: Typical cooling layout at a mine

In Figure 2-2 the components of the refrigeration system are illustrated. It shows that the refrigeration system consists of a hot dam, a cold dam, bulk air coolers (BAC), pre-cool towers and the fridge plants or chillers in between. It is also evident that condenser towers are linked with each fridge plant to provide the needed heat extraction from the refrigerant.

The water cycle, also illustrated in the above Figure 2-2, begins where the warm water is pumped from underground to the hot dam on the surface, at a temperature of ± 25-30°C. The water is then pre-cooled through the pre-cooling towers at an outlet temperature of ± 15-20°C that is then supplied to the fridge plants. From the refrigeration plants, the water is further cooled to the desired outlet temperature of around 3°C. The purpose and control of the flow and aperture of the by-pass valve will briefly be discussed in the next section 2.3.

The pre-cooling towers use the atmospheric air to cool down the warm underground water if it exceeds the temperature range of 20-25°C [40]. This heat exchange is done through an evaporation process of the water through airflow.

The cold water supplied by the fridge plants is then partly extracted by the bulk air coolers (BAC). The remaining cold water flows to the cold dam supplying water to underground areas of the mine. The main purpose of the BACs is to use the cold water to cool the air for the ventilation of the shaft. The water exiting from the BAC is wanner than the inlet temperature of the fridge plants but still colder than the outlet temperature of the pre-cool towers. The colder water, supplied from the BAC, will decrease the temperature of the warn water coming from the pre-cool tower.

The warmer the inlet temperature the more energy is consumed by the fridge plant to achieve the required outlet temperature. The internal control adjusts the compressor vanes according to changes in the inlet temperature to deliver the constant outlet temperature. When the compressor's aperture is fully open, the maximum cooling capacity of the fridge plant is reached. The cooling capacity of the fridge plants is not often reached in cooling systems of mines [40].

However, if the inlet temperature of the fridge plants becomes too low, it may surge, causing damage to the machine. It is therefore very important to consider the effect on the inlet temperature when any modifications are done to the cooling system. It is regarded as a high priority not to cause any disturbance in the SHE (Safety Health Environment) department when modifying the cooling system of the mine.

2.3. LOAD REDUCTION IN FRIDGE PLANTS

Fridge plants of a mine are normally used in Eskom's peak periods of the day, as shown in Figure 2-3. This figure shows a typical daily profile of the refrigeration system power consumption of Kopanang mines (situated in North-West province).

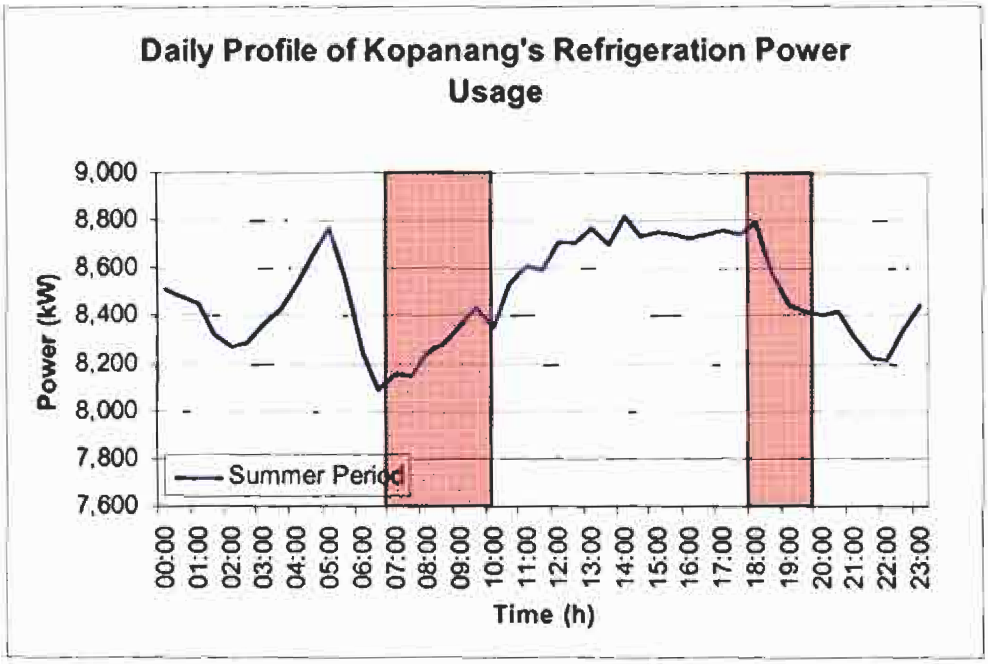


Figure 2-3: Daily summer power consumption of the refrigeration system of Kopanang

The figure shows that the power usage may vary throughout the day because the vane opening of the fridge plants compressors are adjusting to cool the water that is sent underground. Layout and working depths of the mine determine this cooling quantity.

If there is sufficient cold storage capacity to provide enough cold water underground during the peak periods, the fridge plants can be shut down or cut back during that period. The cooling process is theoretically not needed if enough cold water is stored.

It can be assumed that cold dams can react the same way as an electrical capacitor [41]. It can be filled up to store enough cooling energy before the peak period to supply the cold water demand during the peak period. This is usually done by putting extra load on the fridge plants during off-peak periods to fill up the cold dam capacity. The stored cold water can also be utilised through extra modifications and controllers, such as to control the inlet temperatures for optimum power consumption in the fridge plants [42].

The peak and off-peak periods are determined by Eskom's tariff structure for the specific mine, in most cases Megaflex. By controlling the commodity within consideration of the tariff structures, the mine and Eskom will benefit by this modification for LM.

The success of load management dependants on the tariff rates, operation strategy, thermal storage capacity and the climatic conditions [43]. Load management adjustments must take the safety of the mine personnel and continuation of production into account before the implementation can start [23].

With consideration to the above, load can be shifted in fridge plants by preparing the cooling system during off-peak periods for the peak periods. After the preparation is completed in off-peak periods, the load of the fridge plant can then be cut back by using a by-pass valve in peak periods. This valve extracts the cold water from the outlet of the fridge plants and mixes it with the inlet water flow (as seen in Figure 2-4), consequently decreasing the inlet temperature that decreases the power consumption.

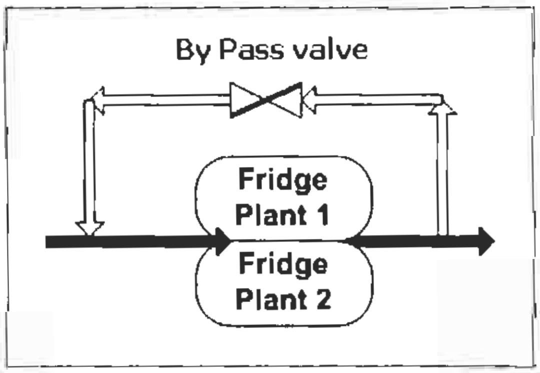


Figure 2-4: Illustration of a by-pass location in the refrigeration system.

Load shifting on fridge plants can also be done by shutting down the plants in the peak period, once again after all calculated preparations. With this procedure all constrains are monitored. It is essential to consider the mechanical strain on the fridge plant by such a shut down and start up method.

These load shift methods – by-pass valve and by shutting down the fridge plants – can operate separately but also parallel with one another. It can only operate parallel if each method runs in consideration of the philosophy of the other procedure/method.

Less load shifting is possible in the winter and more in the summer period on the cooling system of a mine, because the climatic conditions are much different during the winter period than in the summer. These conditions cause the cooling system to run with less power usage in the winter. Therefore, more load will be shifted in the summer than in the winter. As a result, less daily power consumption will occur in the summer, especially during peak time, that will give Eskom more gaps to do their daily maintenance in summer in preparation for the high winter demand period.

To summarise: the whole control philosophy on the commodity – water – is to create enough thermal capacities by using cold or hot dams. These capacities are then used to control the outlet temperature (result in controlling the power consumption) of the fridge plants. This LM control is done by loading the fridge plants more in off-peak periods and unloading the refrigeration system, within the constraints of the mine, during peak time. The unloading procedure can only be done by cutting back the fridge plant compressor vanes and/or by shutting down the fridge plants during the peak periods.

2.4. OBSTACLES FOR IMPLEMENTING A LOAD SHIFT SYSTEM ON A MINE

In SA 95% of the mines are underground operations [44]. The underground conditions at the depth of 3000 m, as mentioned earlier, especially in gold mines, become unbearable for the human body [19]. Therefore, it is imperative that a sustainable cooling system is installed at these mines.

The great impact of the underground and environmental conditions on the safety of the mine has resulted in becoming one of the biggest concerns for the mining industry. Therefore, most of the mines see their cooling systems as inflexible. The mines have a higher preference to implement EE projects on their cooling system than load shifting projects. Many successful EE projects have already resulted in big energy cost savings for the mines [11].

Research has shown that not many of the mines want to install a load shifting system or any of the DSM programs because of the following points [11]:

- Their mindset is that they know how to run their business best.
- Resistance to change – everything is going on very well; there can be no improvement.
- Energy is seen as a minor input cost relative to other inputs.

- Lack of capital to install more efficient equipment, lack of trust in the salesmen's promises.
- Uncertainty regarding the future – reluctance to commit recourses for long term projects, investors want payback periods in months rather than years.

To convince the mines in SA to install a LM project will require hard work and thorough research and investigation into their current systems. The simulations and changes in the structures of the system must ensure safety for the mine personnel and the production must not be influenced at all. This can only be done by creating an adequate control system.

2.5. REQUIREMENTS FOR AN ADEQUATE CONTROL SYSTEM

The solution to develop an adequate control system and a reliable control philosophy is to consider all the constraints as well as create a sustainable and unique LM system. Many variables must be taken into account within the control system philosophy. The control system must be reliable and simple, for lives can be in danger if a malfunction occurs. As a result of these specifications, a backup system must be in place to ensure everything will still run within the safety regulations if a system failure occurs.

The requirements and specification limits, to design a feasible control system, are listed through the following variables and constraints:

- The underground inlet temperature must remain constant and between limits to prevent any endangerment.
- There must be no influence on the production of the mine.
- Get the approval from the SHE department of the mine for implementing a new control system.
- The process must not damage the fridge plant in any way.
- The cold and hot dams must remain within the dam level limits of the mine.
- Refrigeration plant cannot be pushed to a surge state.
- The vane opening and compressor must be controlled within the constraints of the mine.

To set up a control system to present to a mine, all the above variables must be included. This will convince them that their system will run more efficient during Eskom's peak period, but will only be controlled with a new control strategy that results in bigger cost savings.

2.6. RESEARCHING AND ENGINEERING A NEW CONTROL SYSTEM

The control system is programmed by a specification document written in full detail based on all the above research. This document contains the necessary algorithm to ensure all the above variables are taken into account in both LS procedures (cut back and shut down) for the fridge plants.

Most of the document contains mathematical models. The control system based on these models will send signals to the PLC (Programmable Logic Controller) of the relevant equipment of the cooling system at a specific time. A backup system must also be in place and will be controlled by a PID (Proportional Integral Derivative) controller programmed in the PLCs of the equipment.

The control system must first be tested and modified before the implementation starts. The program will work according to a specific control philosophy; this is determined by using the information researched in this chapter and chapter 1. The algorithm and program philosophy can be seen in chapter 3, where the control philosophy of the entire cooling setup at the mine is discussed in chapter 4.

2.7. CONCLUSION

With the research done in this chapter, the information gained can be used to develop the blue prints to create a feasible DSM controller. With this research, it can be concluded that load management can be done on fridge plants by two strategies: cutting back on the compressor output and by shutting off the chiller's machines in peak period. These control strategies will be tested, modified and then implemented in the mine identified in the case study. The whole process must be done by taking into account all the constraints mentioned throughout the research.

3. DEVELOPING A NEW FRIDGE PLANT SIMULATION TO QUANTIFY DSM POTENTIAL

In this chapter, the simulation and optimisation procedures to create or design a new control system for the above method in Chapter 2 will be discussed.

3.1. INTRODUCTION

To create an adequate control system for the VC section of a mine, the main conditions to develop this system, are to be accurate and sustainable. As said in the previous chapter, the control system must consist of two main load shift control philosophies: the cut back control philosophy and shut down control philosophy for the fridge plants. A newly designed simulation model that can simulate the reality accurately will be utilised for testing these philosophies in the control system.

These tests include verifying the simulation model, to determine the accuracy in which it represents the real system. This model can then be used to test and optimise the control strategies.

Once the simulation model passes all the tests, an optimised model is built. This optimised model takes all the constraints for a specific mine into account and is interfaced with a software package. This software package is component based, which will monitor and control all the equipment of the VC system on the mine according to the optimisation, after implementation. When the above alterations and optimisations for a specific mine are finished, the new control system can be installed.

The main controller, as customised for the specific mine, is incorporated into the software package. The main controller is then optimised to monitor two sub-controllers. These two sub-controllers are designed to shut down the fridge plants or decrease/cut back the load of the fridge plants (utilisation of a by-pass valve) during peak time. The schematic layout for the control system can be seen in Figure 3-1.

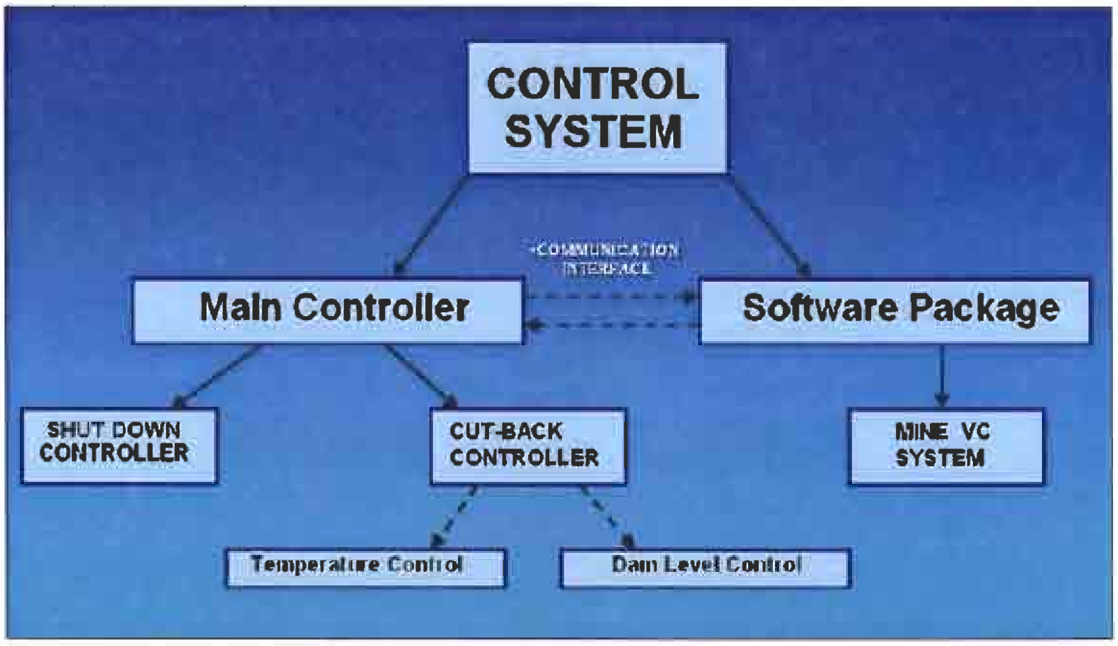


Figure 3-1: Schematic layout of DSM main load shift controller for fridge plants

As seen in the figure above, the controllers (shut down or cut back) can run in parallel taking into consideration the philosophies of the other controller through the main controller. The cut-back controller also consists of two controls (temperature and dam level) that are managed according to the constraints of the mines.

The software package, interfaced with the main controller, will communicate with the SCADA (Supervisory Control and Data Acquisition) of the mine. The SCADA controls the equipment through the instrumentation infrastructure of the mine.

3.2. SHUT DOWN CONTROLLER FOR A FRIDGE PLANT SYSTEM

3.2.1. Preamble

The fridge plant shut down controller is used to calculate the feasibility of shutting down a fridge plant during the peak period and controls the status of the chiller machines in the refrigeration system. The shut down sequence of the individual machines will be done randomly or as a fixed sequence, changeable by the user. It will consist of an input and output for the controller, compatible with any refrigeration system at a mine. There will also be an optional modification utility available for the user, in case of any special constraint requirements.

This controller can automatically control how many of the refrigeration machines can be shut down during the peak period. After the calculation is done to determine the feasibility and quantity of fridge plants to be shut down, a calculation to determine the shut down sequence can continue in two directions namely a fixed or random shut down sequence see Figure 3-2.

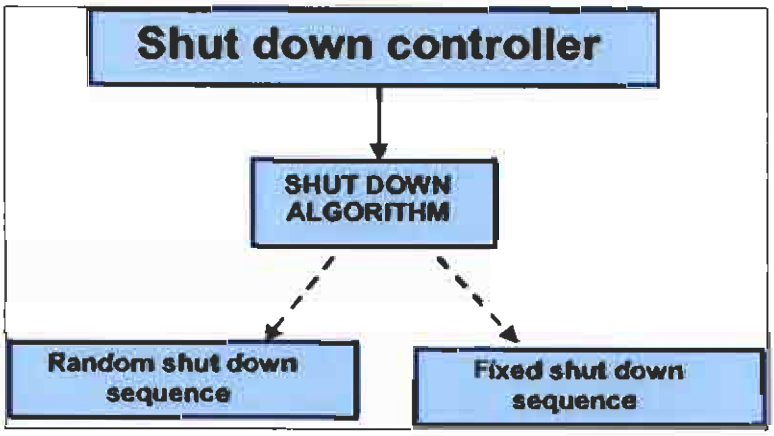


Figure 3-2: Schematic layout of shut down controller for a VC system.

3.2.2. Input

The input of the shut down controller must consist of enough information to allow the controller to control the cooling system safely and efficiently.

The following input variables/specifications are needed for the calculations of the controller:

- For which of the peak periods (morning or evening) must the controllers be activated.
- If a peak period is activated the shut down period must be specified (example 7:00 to 10:00).
- The constraints (see below) must be specified by considering the cooling layout character of the mine.
  1. Inlet fridge plant temperature monitoring.
  2. The minimum number of plants operating during peak period.

3. Minimum cold dam level (%).

- The user must enable the preferred shut down sequence.
- The required water flow supplied to the underground areas must also be specified.

The above inputs are then added as variables in the mathematical algorithm of the controller to do the necessary calculations, resulting in a successful shut down controller.

Each fridge plant has its own characteristics. Some of these are important and must be considered as inputs for the shut down controller:

- Shut down rating (preference in shut down sequence – if needed by user)
- Start up rating (preference in shut down sequence – if needed by user)
- Minimum stop period per plant (if limited by the mine)
- Delay time between start and stop of machines
- Maximum start(s)/stop(s) per day per plant

3.2.3. Shut down algorithm – Random sequence

The shut down controller decides if one or more fridge plants should be stopped. If the shut down of any fridge plants are possible, then the shut down sequence will be utilised.

The purpose of this algorithm is to determine how many of the fridge plants can be shut down during peak period. This is calculated by considering the shut down of a fridge plant(s) within all the given constraints.

i.) Before peak and in peak period:

There are three constraints that can limit the amount of fridge plants to be shut down:

- No extra plant can be shut down if the T_{in} (inlet temperature of the plants) is above the given limited temperature.
- No plant can be shut down if the cold dam level is below the minimum dam level specified.
- No extra fridge plants can be shut down if less than the minimum allowed plants will run in peak time.

The calculation to determine the amount of fridge plants to be shut down is firstly done by calculating the remaining amount of peak seconds (ps). This result is then used in the next algorithm (shut down time per fridge plant) to determine if a fridge plant can be shut down, by considering all the above.

Algorithm calculation for the remaining amount of peak seconds (ps):

If before peak period:

ps = 10:00 (end of morning peak) – 07:00 (morning peak start time)

Or

ps = 20:00 (end of evening peak) – 18:00 (evening peak start time)

If during peak period:

ps = 10:00 (end of morning peak) – ct (current time)

Or

ps = 20:00 (end of evening peak) – ct (current time)

Algorithm calculation for the shut down time per fridge plant:

$$C = \frac{\left(C_{C\%} - C_{\min\%}\right) \times C_{\max}}{100} \qquad [4]$$

Where C - current available cold water dam capacity (l), $C_{c\%}$ - current cold-water dam level (%) and $C_{min\%}$ - minimum cold water dam level (%) specified at the input.

$$M_{SUPPLY} = \left(N \times M_{CH}\right) - \left(\left(N - i\right) \times M_{CH}\right) \qquad [5]$$

With i = 0,1,2,3....N; [i = number of fridge plants active during peak period; N = total number of fridge plants]. Where M_{SUPPLY} - total supply flow through fridge plant (l/s) and M_{CH} - flow per plant (l/s).

$$St_i = \frac{C + ps \times M_{SUPPLY}}{M_{\min c}} \qquad [6]$$

Where St_i - shut down time for the specific plant and M_{mine} - water flow to the mine (l/s).

If all constraints are satisfied, the above algorithm and equations are combined in the following algorithm to determine if the fridge plants can be shut down, see below.

```
If      ( St_i ≥ ps )
Then
        Shut down N-i plants
But
Before shut down:
If (MSt of 1st plant to stop > ps left)
Then
        Do not stop that specific machine and try next one
```

Where MSt - minimum stop period for a specific machine, as prescribed at the input of each fridge plant's characteristics. This algorithm is essential when running in peak time, for its main purpose is to determine the feasibility of shutting down a quantity of fridge plants during peak time. This shutting down order is random, but within the constraints.

ii.) After peak – start up sequence:

Start up procedure will follow the ratings, as mentioned in section 3.2.2, specified by user/mine at the input, or by utilisation of the random start up.

The first fridge plant must start directly after peak time or the time delay specified at the input. The next fridge plant must then start after the delay time has passed since the start of the previously started machine.

This procedure continues until the number of fridge plants operating, equals the number before peak period. As previously mentioned in Chapter 2, the fridge plants do not operate at full cooling capacity. The cooling demand after peak time is usually a bit higher than before peak, because of the loading and unloading phases. It is therefore essential that the same amount of fridge plants must be operating after peak time to satisfy the after peak cooling demand.

Maximum starts or stops allowed per day for each fridge plant, entered at the input of the shut down controller, will influence the shut down or start up sequence. For example when the mine has stopped and started a machine for maintenance earlier in the day, the controller must shift that machine to the last start rating *or* control permission to make that machine unavailable for that day.

3.2.4. Shut down algorithm – Fixed sequence

The shut down and start up sequence can be determined randomly, as mentioned in the previous section. The shut down and start up procedures can also be done on a fixed sequence that can change daily. The shut down algorithm for the fixed sequence in peak periods is based on the same fundamental equations as in the previous section with the random shut down algorithm. It varies *only* when the controller decides the sequence in the shutting down or starting of the fridge plants.

When using the *fixed* shut down procedure, the controller must be within the given constraints to determine if a plant *can* be shut down. If this is true, this procedure will then shut down a different fridge plant(s) every day in the given peak time. The procedure must take into account whether a fridge plant has been shut down earlier the day. If it has, the controller will then change the shut down order to compensate for the extra shut down of that fridge plant. This is also relevant for the random shut down sequence.

The next example illustrates the following cooling system status:
Plants available: 6
Days of the week to shut down: 5
Minimum number of plants allowed to run in peak period: 5

The shut down procedure will then be determined for every day as follows: machine number 1,2,3,4,5 in the first week and the next week 6,1,2,3,4 etc. where the numbers represent each specific fridge plant.

In the case where fridge plant *one* was shut down the first day of the first week, the procedure for the next week will change automatically to 2,3,4,5,6 etc. This calculation must be done daily before the beginning of each peak period.

If the constraint that limits the allowed maximum number of plants to shut down at peak time is changed to two (or more), the controller must select the next plant in the sequence to be shut down as well.

The following example illustrates the above case:
Plants available: 7
Minimum number plants that are allowed to run in peak period: 5

If the minimum plants allowed to run is one under the available plants, the shutdown sequence is 1,2,3,4,5 ... 6,7,1,2,3 ...4,5,6,7,1...etc. This will then change for the above constraint to: 1+2, 3+4, 5+6, 7+1, 2+3 ... 4+5, 6+7, 1+2, 3+4, 5+6... etc.

It is essential to consider that no fridge plant can be shut down if the constraints, specified in the previous section, are not satisfied.

3.2.5. Output

The user will be notified of the results of the calculations done by the shut down controller. It will also show all the satisfaction levels of the constraints during these calculations.

The information that is given to the operator is determined by the following calculations:

- Number of peak seconds left (ps): As calculated in section 3.2.3
- Calculated shut down time (St): As calculated in section 3.2.3
- Nr of plants to shut down (N – i): As calculated in the above algorithm
- Predicted cold water dam level at the end of the peak period, calculated through equation 7:

$$Dam\ level\% = \frac{\left[\left(\frac{C_{C\%}}{100} \times C_{max}\right) - \left(M_{mine} \times ps\right) + \left(M_{SUPPLY} \times ps\right)\right] \times 100}{C_{max}} \qquad [7]$$

- Total fridge plant water supplied: The sum of the water flow through each plant.
- Mine water flow: The sum of all the water used by the mine.
- Predicted load shift calculated through equation [8].

$$Q = \frac{\left(M_{mine} - FridgePlant\ water\ supply_{live\ tag}\right) \times C_p \times Typical\ \Delta T}{COP} \qquad [8]$$

Where the C_p is the specific heat of water (4.2 [kJ/kg-C]) and the typical ΔT are also inserted in the input interface.

3.3. CUT BACK CONTROLLER FOR A FRIDGE PLANT SYSTEM

3.3.1. Preamble

The function of the fridge plant cut back controller is to control the available by-pass valve at the mine to load or unload the fridge plants. This control output is calculated by considering the minimum inlet temperature constraint, dam level limits and the monitoring of the water flow through the system. Therefore, the controller is divided into the following head sections:

- Temperature controller (controlling the inlet temperature)
- Dam level controller (monitoring the dam levels)

The cut back controller can operate the two controls (temperature and dam level) simultaneously. This is done by monitoring/controlling each controller according to its privileges specified.

The main purpose of this controller is to control the load on the refrigeration plants by preparing for load shifting during the off-peak periods and by unloading the fridge plants during peak periods. The first priority is therefore to decrease the inlet temperature of the plants during the peak period, but not causing any danger in the VC or underground systems of the mine.

3.3.2. Input

The input for the cut back controller consists of choosing and specifying the needed constraints. The input is based on the same principle as the shut down controller – no cut back on the fridge plants are allowed outside the limits of the constraints.

It is important that these constraints are monitored at every hour of the day while the LM procedure modifies the refrigeration system and control output to the by-pass valve changes. The enabling of each constraint is done according to the cooling system of the specific mine.

The following constraints must be entered or activated in the cut back controller:

- The temperature and/or dam control can be enabled.
- An hourly privilege for each controller can be specified.
- The minimum and maximum level limits of the dam specified.
- A set point outlet temperature of the fridge plants.
- Control range for the temperatures and dam level must be specified to prevent oscillation or cycling of the valve output.
- The underground water temperature must be included.

All the above inputs are used to optimise the control algorithms below.

3.3.3. Temperature controller

The following abbreviations will be needed for the calculations procedure for the temperature controller:

T_{open}	= Temperature where the valve must be fully open
T_{closed}	= Temperature where the valve must be totally closed
$T_{current}$	= Current temperature of the specific water in the system

$V_{opening}$	= Proportional opening of the valve
T_{wanted}	= Set point inlet temperature

As the by-pass valve opens, the inlet temperature of the fridge plant will decrease. The aperture of the valve is based on Figure 3-3 and the calculations that follow:

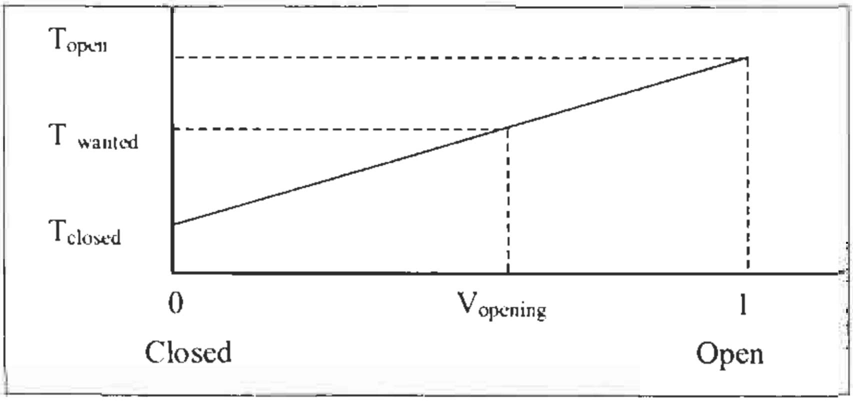


Figure 3-3: FP inlet temperature relation with the by-pass vane opening

The required valve opening that controls the inlet temperature of the FP is calculated through the following equations ([9], [10]):

For the initial value:

$$V_{opening\ i} = \frac{T_{wanted} - T_{closed}}{T_{open} - T_{closed}} \qquad [9]$$

Then for the next interval value:

$$V_{opening\ i+1} = V_{opening\ i} + \frac{T_{current} - T_{wanted}}{T_{open} - T_{closed}} \qquad [10]$$

If $V_{opening} > 1$ then $V_{opening} = 1$

If $V_{opening} < 0$ then $V_{opening} = 0$

Where *i* represents a time interval of control monitoring during the day.

A control range and T_{closed} are specified at the input of the cut back controller and are used as a safety restriction on the valve opening status, see Figure 3-4. It can be seen that the by-pass valve will close as soon as the inlet temperature reaches the T_{closed} temperature constraint. It will open again at the calculated quantity (see equation [9] and [10]) as soon as the inlet temperature reaches the T_{closed} temperature plus the control range temperature {thus when $T_{current} < (T_{closed} + \text{control range})$}.

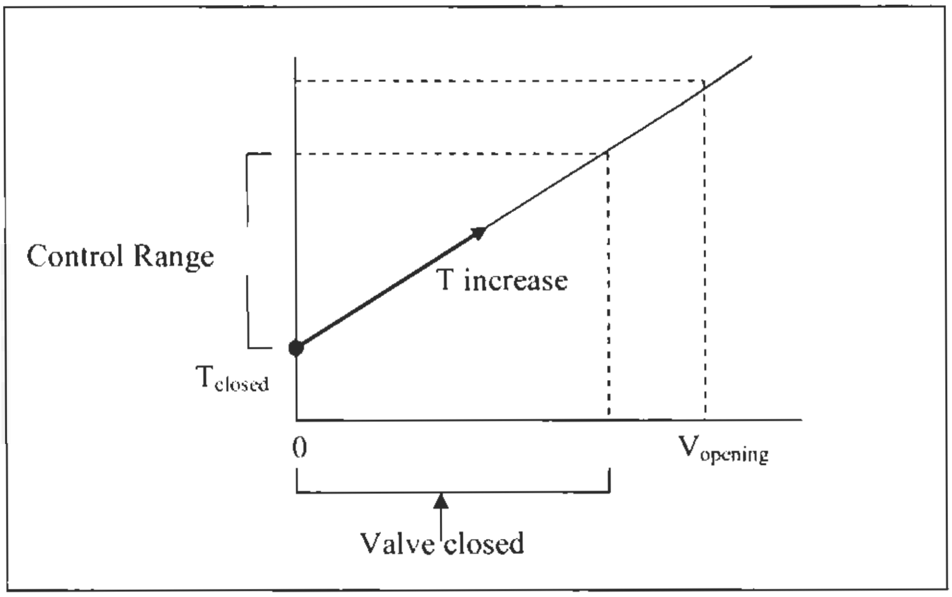


Figure 3-4: Illustration of control range on the valve controller philosophy

3.3.4. Dam level controller

The dam level controller will change the valve opening as the level of the dam varies. It is based on the same principle as the temperature controller, but only dependent on the level of the dam and not the inlet temperature, see Figure 3-5 and the following calculations.

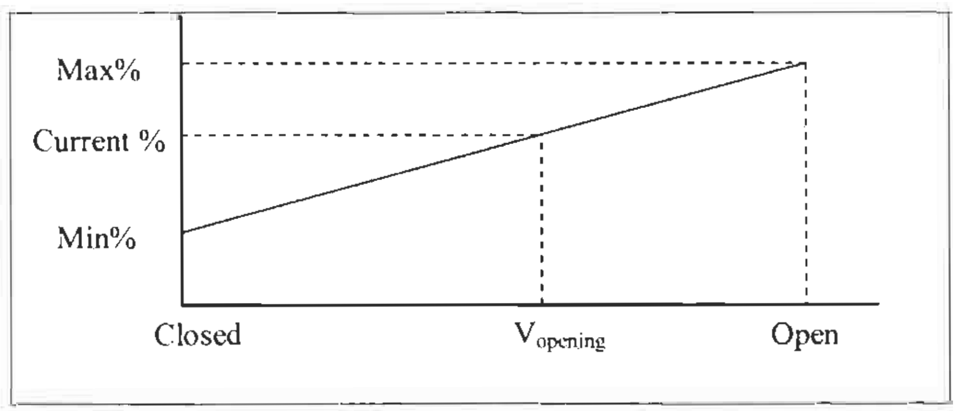


Figure 3-5: Dam level relation with the by-pass vane opening

The dam level can be controlled by controlling the amount of water that flows into the dam and through the valve. First it can be controlled by maintaining the dam level at a specific quantity from Max% (maximum dam level percentage) to Min% (minimum dam level percentage) and in between as illustrated in Figure 3-5, and by changing the valve aperture.

To maintain the dam level at a specific level, the following equations are used to calculate the valve opening percentage:

For the initial value:

$$V_{opening\ i} = \frac{Wanted\ \% - Min\ \%}{Max\ \% - Min\ \%} \qquad [11]$$

Then for the next interval value:

$$V_{opening\ i+1} = V_{opening\ i} + \frac{Current\ \% - Wanted\ \%}{Max\ \% - Min\ \%} \qquad [12]$$

This valve opening must be controlled within the opening and closing entity, therefore:

If $V_{opening} > 1$ then $V_{opening} = 1$

If $V_{opening} < 0$ then $V_{opening} = 0$

3.3.5. Combining the two control philosophies in the cut back controller

The cut back controller consists of operating the temperature and dam level controllers according to their ranked privileges, specified in the input. This cut back controller also considers the underground water demand temperature. The following paragraphs will show how these controllers interact with each other according to the prior constraints and privileges.

The variables, which must be considered in the control of the cut back controller, are located in the typical overview of the cooling system of a mine, see Figure 3-6. The following paragraphs analyse the possible situations that may occur and develop the algorithm for the cut back controller in solving those situations.

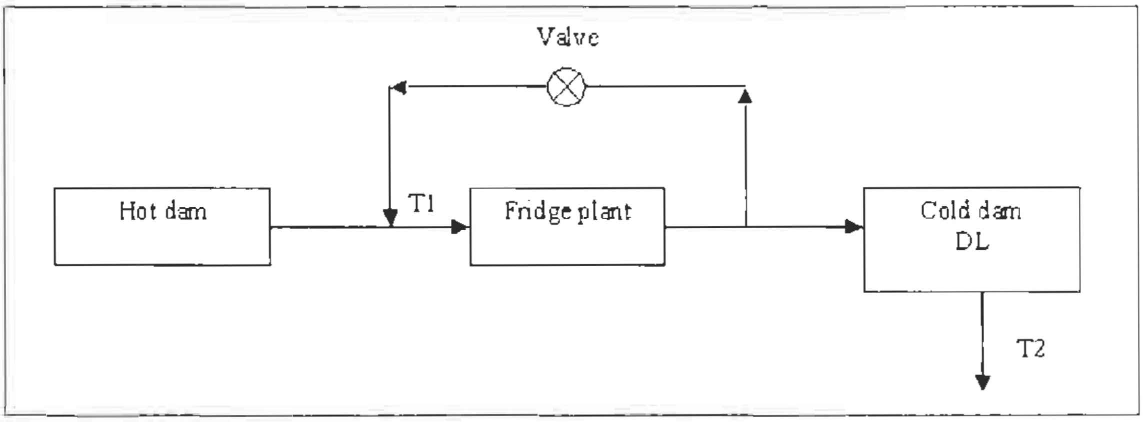


Figure 3-6: Overview illustration of constraints on the cut back controller

It can happen that the valve controller must control either: a.) two different temperatures, b.) a temperature and a dam level or c.) two temperatures and a dam level. The temperatures and dam level are shown through T1 (inlet fridge plant temperature), T2 (underground temperature) and DL (dam level) respectively, as seen in Figure 3-6.

Each control privilege of the above cases can be specified at an exact hour during the day. This is done at the input of the controller. As each case is initiated, the control privilege must be specified, rank from 1 to 2 if two constraints are enabled and 1 to 3 if all three constraints are activated. The controls of these cases, as a multi task cut back controller are depicted below.

Control philosophy of the multi-task cut back controller:

In the case where the valve must control two temperatures and one dam level; the boundaries for these variables are set:

- Temperature 1 (T1) calculation: X {maximum (X_{max}) and minimum (X_{min})}
- Temperature 2 (T2) calculation: Y {maximum (Y_{max}) and minimum (Y_{min})}
- Dam level (DL) calculation: Z {minimum (Z_{min}) and maximum (Z_{max})}

First case is when the control privilege (CP) ranking: 1 = DL, 2 = T1, 3 = T2. (This means that T2 must be controlled except when DL or T1 overshoots its limits/boundaries). The algorithm for this case is then as follows:

```
Test if DL is between limits:
    If DL not between dam limits
        send V_opening of DL controller to PLC
    Else
        Test if T1 is between limits
        If T1 not between limit
            send V_opening of T1 controller to PLC
        Else
            if (T2>Y_max) or (T2<Y_min)
                Send V_opening = closed to PLC
```

The *second case* is where the DL controller has the first privilege: The valve must be controlled until the dam level changed from (Z_{min} + control range or Z_{max} – control range), then let T1 (temperature control) take over. To ensure that the supply dam never runs empty a minimum level (Min%) for the supply dam must be monitored. If the DL reaches this value, the valve must close totally. The valve can then reopen at the value (Min% + control range).

The *final case* is where temperature T1 control has the first privilege: The temperature controller will control the valve until temperature decreased from X_{min} to (X_{max} – control range) before T2's limit monitoring takes over, as seen in the above algorithm.

When only two or less constraints must be monitored (see **a.**) and **b.**) above as example for two constraints), the privileges will be shifted to compensate for the change. For example if you look at the *first case*, where only the two temperatures must be monitored and not the dam level, the privileges will shift as follows: T1 control as first privilege, T2 monitoring as second privilege. The algorithm will then continue without considering the other constraint (DL), if it is not specified. This is relevant for each case.

3.4. SIMULATION MODEL

To verify the validity of the controllers it must be tested with a simulation model. The simulation model must simulate the actual conditions of the system on the mine. The easiest way to simulate the control philosophy is by using a spreadsheet solver such as Microsoft Excel.

Through the utilisation of the simulation model it can be determined if all the constraints are satisfied in the final and optimised model. The simulation is based on mathematical formulae to imitate the reality system cycle and reactions.

The water flow is simulated from the hot dam, through the refrigeration plants to the cold dams. From the cold dams, the water flows underground and pumps back to the hot dam on the surface again, where the cycle starts all over. The simulation is also component based, for every component identified in the previous chapter, it is simulated according to their characteristics (example: the water flow of the BACs and pre-cool tower as well as the water inlet to outlet temperature will drop). At every stage of the refrigeration system, the water temperature is calculated, including the temperature drop caused by the fridge plants.

The controller and simulation is limited and optimised according to the constraints (given by the mine) of the temperatures, dam level limits, etc. The power consumptions of the fridge plants calculated in the simulation are also based on the investigation done in Chapter 2.

The following figures resulted from the excel simulation.

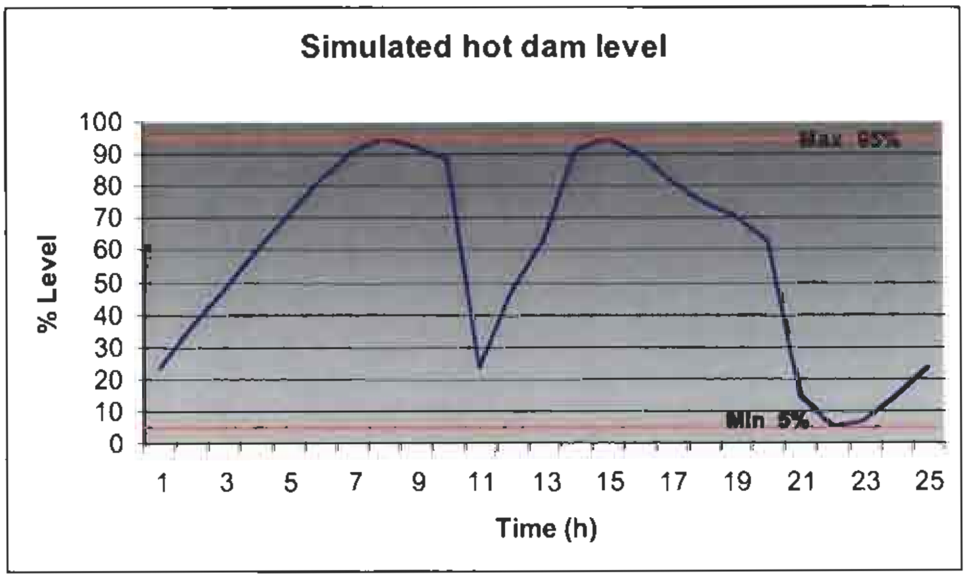


Figure 3-7: A 24-hour profile of the resulted simulated hot dam level

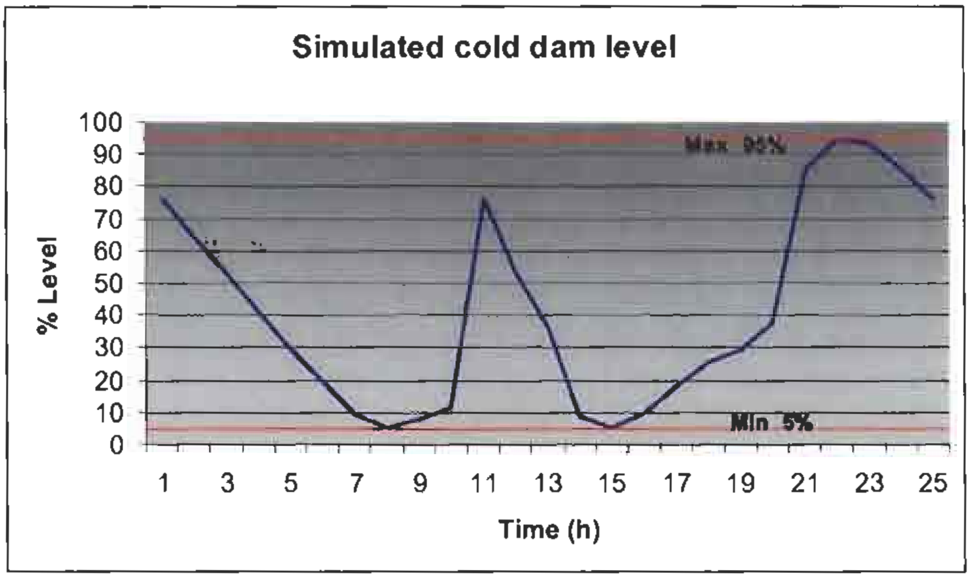


Figure 3-8: A 24-hour profile of the resulted simulated cold dam level

It is evident in the above two figures that dam level limits are not exceeded. The results of this figure show that LM can be done by using the water capacities of the refrigeration system within the minimum and maximum limits of each dam. The minimum and maximum dam limit is set to be 5% and 95% respectively.

The following figure illustrates a 24-hour profile of the water outlet fridge plant temperature and the minimum and maximum temperature limits.

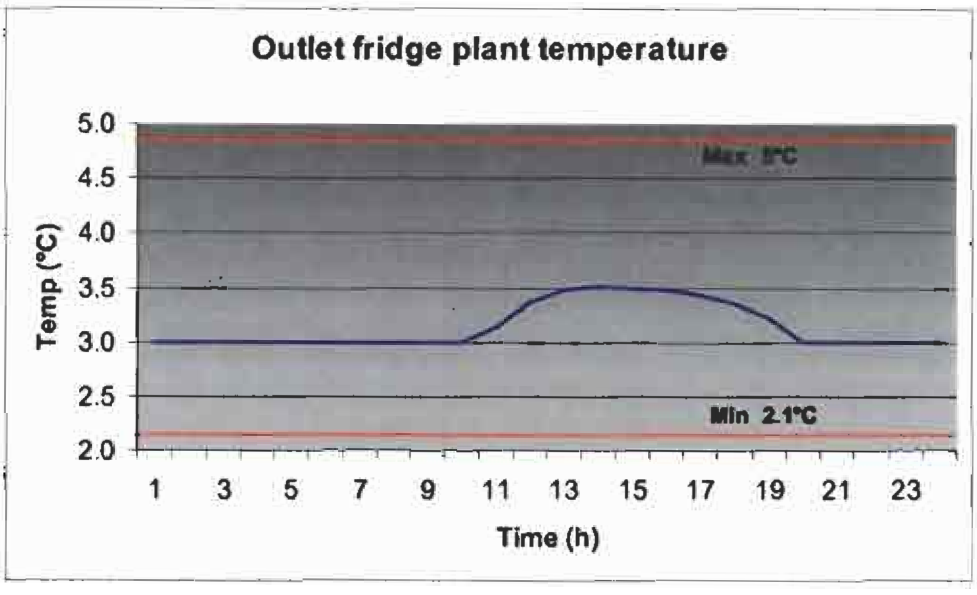


Figure 3-9: A 24-hour profile of the water outlet temperature of the simulated fridge plants

The above figure shows a small increase in temperature for a few hours of the day. It is also evident that the outlet temperature is within the minimum and maximum limits of 2.1°C and 5°C respectively.

With consideration to the simulation results, the procedures of the controllers can be seen as successful and accurate. It can also be noted that all the constraints of the refrigeration system components in the simulation model are within their limits.

3.5. INSTALLING THE CONTROLLERS IN A SOFTWARE PACKAGE

After the simulation and testing of the control philosophies have been done to ensure such load shifting in a VC system of a mine, it can be incorporated in a software package. This software package can then be implemented at a mine.

The equipment of this cooling system will be manipulated by the constraints and the schedules given by the controllers. A typical cooling system installed in the software package can be seen in Figure 3-10, where the shut down and cut back controllers are functional.

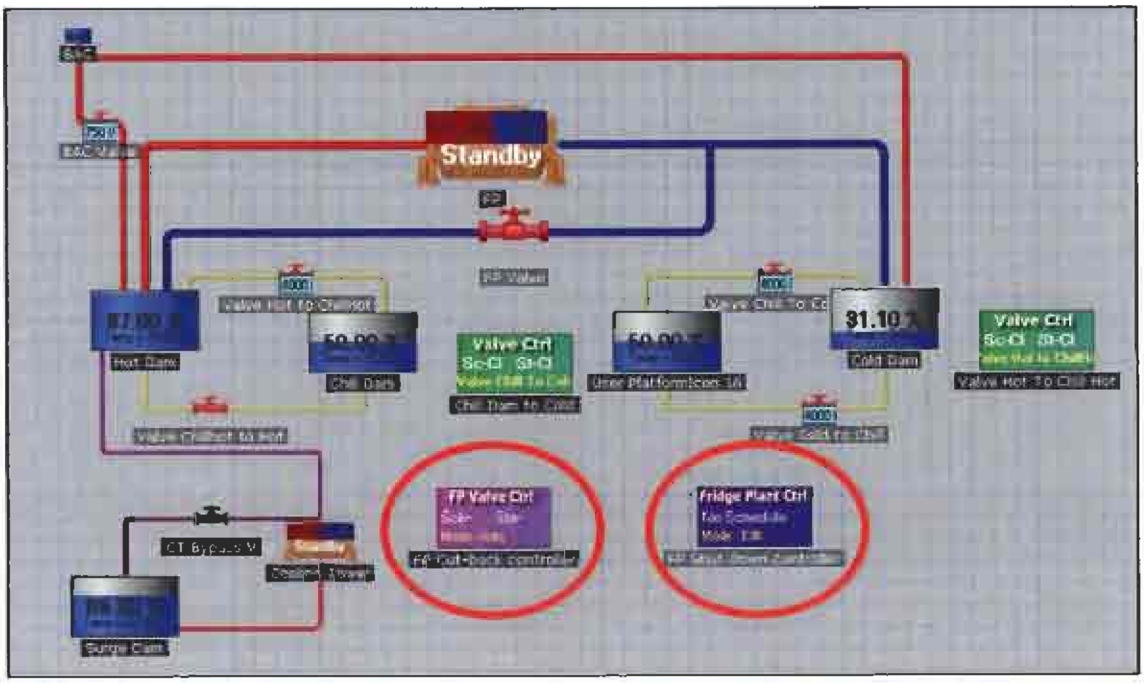


Figure 3-10: A typical cooling system in a software package consisting of the two control philosophies

To install this software package the utility of the SCADA system at the mine must be understood. A SCADA system can be defined as an intermediate communication structure between the PLC of the equipment and the software package system.

The SCADA receives information through electronic pulses, from the PLC of the equipment (example the status, in and output signals, etc.) and sends it through to the software package system. The controllers in this software package calculate the scheduling of the different equipment in the cooling system according to the received data. This rescheduling signal is then sent back to the SCADA to communicate with the significant PLC to change their status according to the information sent via the electronic pulses.

'Tags' is the term used for a medium in which data is sent between the PLC and the SCADA. It is also known as the electronic pulses mentioned above. The input of the shut down and cut back controller use these tags if data needs to be read or written. A typical input interface of a shut down controller can be seen in Figure 3-11, which illustrates an example where the tags are used in the software package.

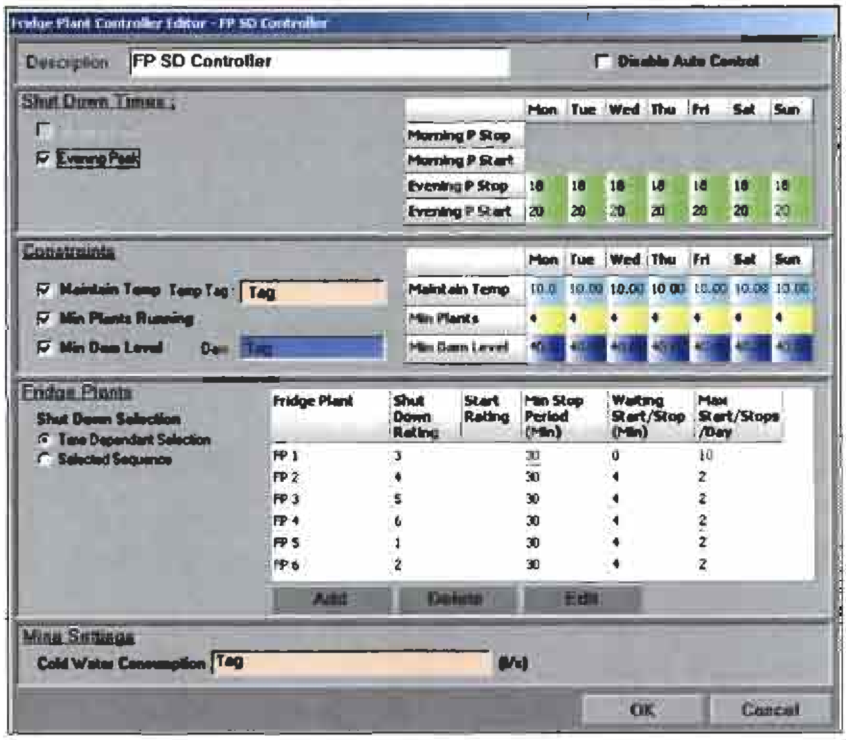


Figure 3-11: Input interface of the shut down controller

The shut down controller needs information from the mine to operate. This information is then used by the controller to do calculations. These calculations result in rescheduling of equipment in the cooling system. It is also evident, in the above figure, that the constraints are also specified in this input interface. The input for the cut back controller is based on almost the same information (constraints, relevant tags, etc.) as that of the shut down controller.

The layout of the software package system with all the components that form part of the information network, in order to remotely control the actions of the refrigeration system in the mine, is shown in Figure 3-12. The software package system with all its components will be located on-site, while the actual performance and reports of the system are monitored and analysed off-site.

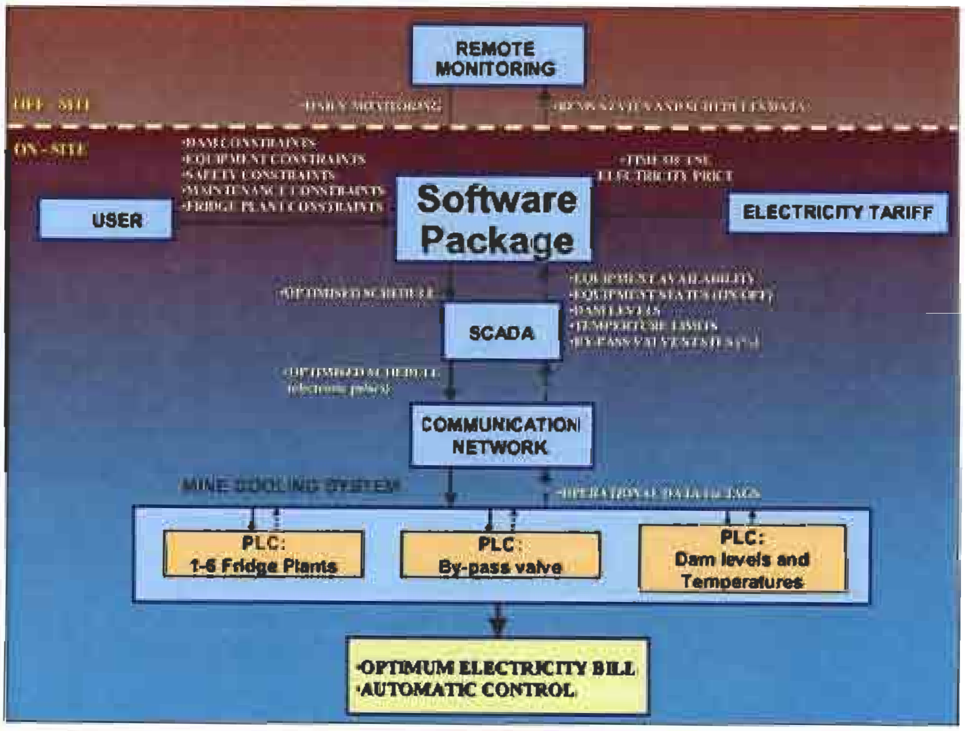


Figure 3-12: Schematic diagram of the software package system for a cooling system at a mine

The above figure is a graphical illustration of the communication network system between the software package and the mine cooling system. The software package system is dependent on three sets of inputs.

The first input is the specifications and constraints given by the user when the software package is setup on-site. The operating schedules are determined in order to manage the fridge plants according to the limitations of the dam levels and other constraints specified.

The second input to the software package system is the price of electricity for different times of the day that influences the control. The third input to the software package is the real-time operational data obtained from the SCADA system. The operating status of the cooling system is communicated back to the software package and is continuously taken into consideration for the optimised scheduling of the fridge plants and other equipment that result in a better load shift profile.

4. ESTABLISHING A PRACTICAL CONTROL PHILOSOPHY TO IMPLEMENT THE CONTROL SYSTEM ON A MINE

This chapter consists of the control philosophy of the mine layout of Kopanang. It explains the philosophy needed to ensure a successful LM interaction with the other existing systems on the mine and the new control system.

4.1. INTRODUCTION

In the preceding chapters, the research showed that there exists potential for load management on the surface refrigeration plants of a mine. In view of that, a general control philosophy was established. However, the refrigeration systems of the various mines differ in terms of layout and the way that it is operated. Because of this difference in operational parameters between mining sites, the control philosophy must be customised for each specific refrigeration system.

The site to be identified to implement this new control system and philosophy, must have a feasible load management potential. When this control philosophy for a refrigeration system is formed, the sections that have an influence on the refrigeration system, like the pumping section of the mine, must be taken into consideration. The pumping system is controlling the water in and out flow of the surface dam to and from underground. These surface dams can play an immense role in the water cycle of the refrigeration system.

This applicable section (pumping system) must be interdependently monitored when the rescheduling status of refrigeration system's equipment is changing according to the output of the controllers (shut down or cut back) in the new control system. A control philosophy for the pumping system must then be recognized as well.

It is necessary for the mine to know at every hour of the day how the systems are controlled. This knowledge of the control philosophies is essential for personnel to take the required precautions and ensure their safety according to the rescheduling procedures.

For a safety precaution, the new control system will monitor constraints that might cause any danger to the system and personnel. This is done through consideration by both the control philosophy of the pumping and refrigeration section of the mine.

This type of control philosophy is set up for Kopanang mine – situated near Orkney, in the North-West province. The case study is focussing on their refrigeration system, due to the said system consuming almost a third of the total power consumption of the mine.

Although the refrigeration system of an average mine consumes approximately 8%-10% of the total power consumption on the mine, as seen in chapter1, this mine was identified as an exception with the refrigeration system consuming 22.3% of the total mine power consumption.

A probable reason for the higher energy consumption on this mine may be caused by inefficient water usage of the mine underground or inefficient ventilation system. It can also be a result of higher cooling demand because of the higher than an average mine's gold production at Kopanang mine. Whatever the cause the DSM potential was determined for the refrigeration system that resulted in a higher than average percentage of the total mine power consumption.

Through research and modified simulation models for the refrigeration system of Kopanang, the load shift potential is determined for this site. These results of the simulation are based on the utilisation of the new control system mentioned in the previous chapter. Philosophies are therefore generated for the Kopanang mine system layout. The background research is done on Kopanang mine and the predicted results, based on the research, are discussed in this chapter.

4.2. DETAILED RESEARCH OF KOPANANG COOLING SYSTEM

4.2.1. Background

The sinking of the shaft at Kopanang started in 1978 and reached a depth of 2 240m. The first gold from the shaft was produced in 1984. The shaft currently hoists 22 600 tons of material, including waste, per month. They have 6 700 employees, including contractors [46].

Their refrigeration system uses an average of 22% of the total power consumption of the mine as can be seen in Figure 4-1 [47]. This electricity usage is dependant on the total water used by the mine, environmental conditions and the efficiency of the equipment.

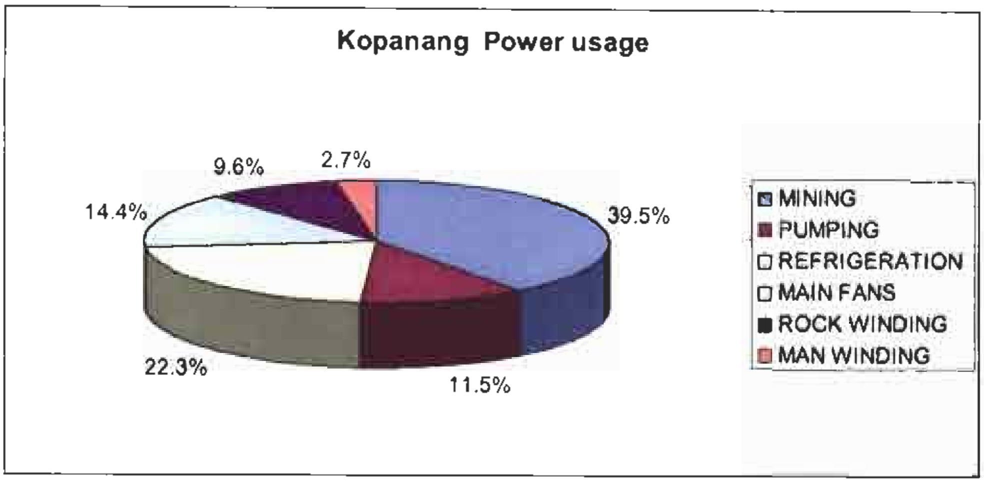


Figure 4-1: Power usage at Kopanang mine

The power consumption of the refrigeration system is more dependent on the atmospheric conditions and can therefore change in different seasons. The contribution of the refrigeration system to the total power consumption can drop from 25% to 13% when the seasons change from summer to winter [47].

4.2.2. Pumping system layout

At Kopanang, shaft water is used to cool the underground mining conditions and operations. This water is cooled via the surface fridge plants. From the fridge plants the water flows to the mining operations and then to the settlers. From the settlers the water is pumped by means of the clear water pumping system back to the surface. This water cycle continues throughout the day.

The power consumption of the refrigeration plants depends on the underground water demand. If this water demand increases, more water would be extracted from the surface cold dam, and more thermal energy is needed from the refrigeration plant to cool the water.

This extraction of cold water on the surface is done through the scheduling process done on the turbines on the 38 level pump station, according to the underground water demand. The water then fills the 38 level cold dam which capacity is used to provide water for the underground activities.

The surface hot dam is filled according to the water provided from the 38 level pump station. The scheduling of the 38 level pump station also depends on the level of the 38 level hot dam, which is controlled by the water supply of the 75 level pump station.

Because of this dependent water cycle to the refrigeration plant, it is important to understand the control philosophy and layout of the pumping system, see Figure 4-2.

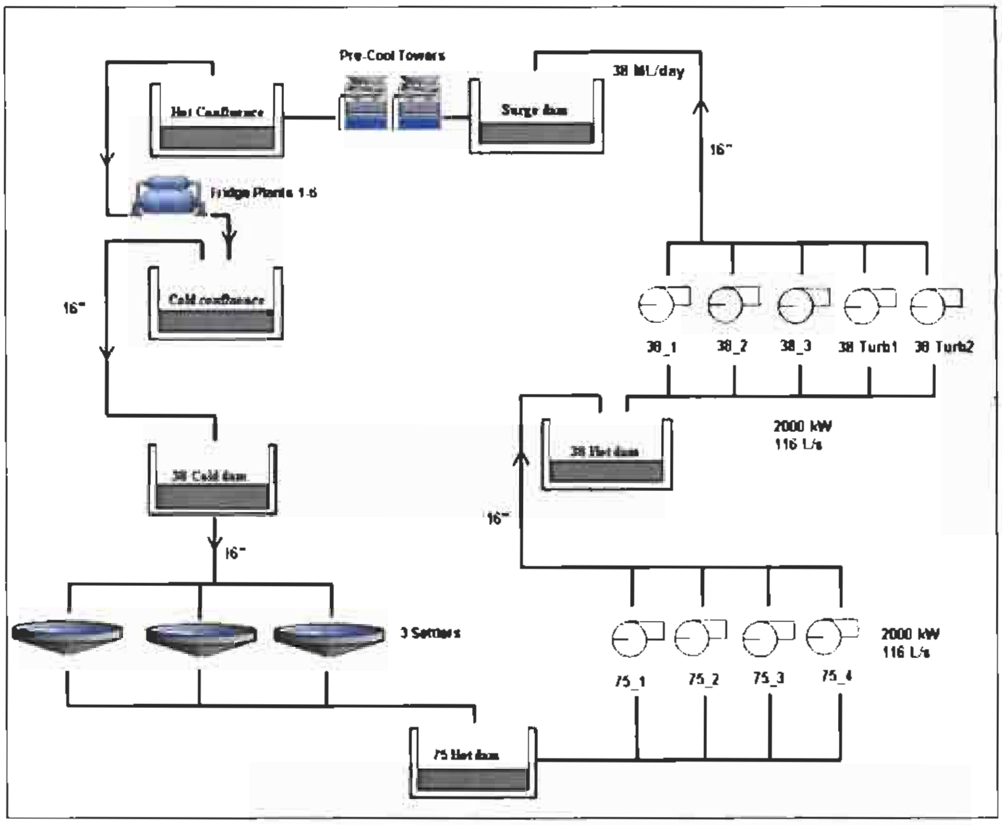


Figure 4-2: Schematic layout of pumping system at Kopanang

It is evident in the above figure that the 75 level pump station is equipped with four clear water pumps. The 38 level water is equipped with three pumps and two turbines. To describe the water cycle of Kopanang's pumping system in short: hot water is pumped from the 75 level to the hot water dams on the 38 level water throughout the day. From the 38 level, the water is pumped to the surface.

4.2.3. Refrigeration system layout

The water of the mine enters the surge dam from underground at ± 27°C. This water is pumped through the two pre-cooling towers at an exit temperature of ± 15°C. The transfer pumps pump this water to the hot confluence dam. In the hot confluence dam, this pre-cooled water mixes with the return water from the bulk air coolers to produce the inlet mixed water for the fridge plants.

This mixed water enters the fridge plant via the evaporator pumps. The refrigeration system consists of six identical chiller machines with a combined cooling capacity of 33 MW (5.5 MW cooling capacity each). The COP of the chiller machines is approximately four.

The evaporator pumps pump the hot water through the evaporator to the cold confluence dam. The water leaves the evaporator at a temperature of 3°C after the necessary heat exchange was done. Each chiller machine has its own condenser-cooling tower to provide the calculated heat transfer for the refrigerant at the condenser side of the refrigeration plants.

This water cycle of Kopanang's refrigeration layout is clearly depicted in Figure 4-3.

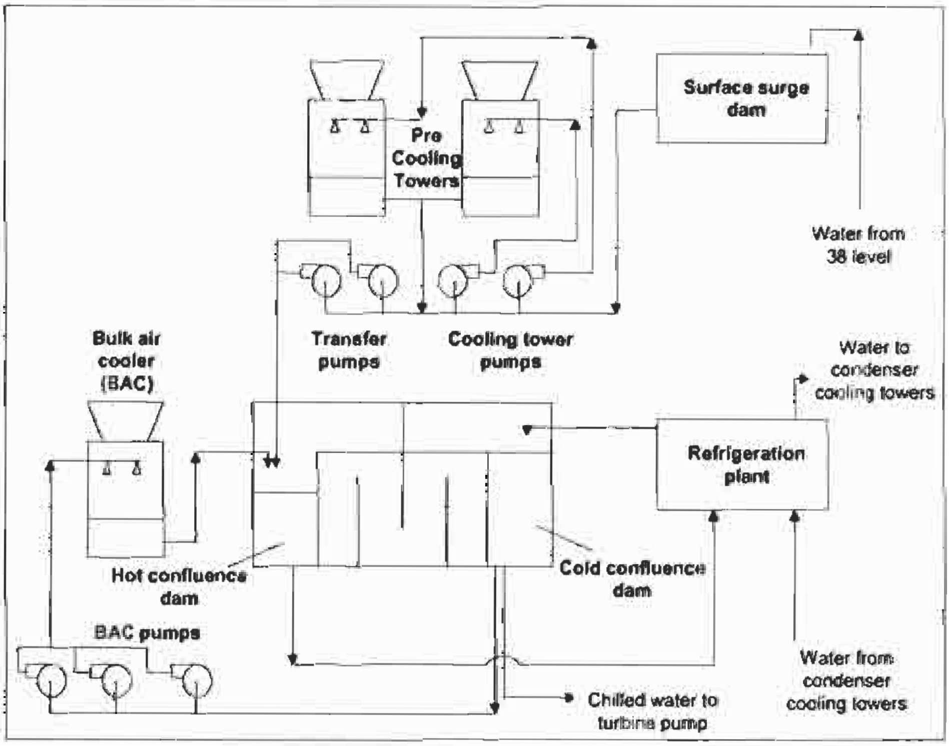


Figure 4-3 : Schematic layout of refrigeration system at Kopanang

As seen in the above figure the water from the cold confluence dam is sent to the underground turbine pump, usually set at 223 l/s, and to the BACs (250 l/s per cell). The BACs consist of three cells in parallel, each with its own water pump. The BACs are used to cool the entering ventilation air of the mine shaft by utilizing the chilled water for heat extraction. The heated water then leaves the BAC at ± 8°C. This whole cycle continues throughout the day.

4.3. PREDICTED RESULTS

Due to the high-energy consumption of the refrigeration system at Kopanang, the load shift potential must be determined. With modifications and optimisation procedures done in a simulation model, based on the above research, the following results are predicted.

For the results to be calculated it must be compared with a baseline that is determined through collecting data, from January 2004 until December 2004 at Kopanang's cooling system database. This data consists of information specifying hourly energy consumption of the refrigeration plants that result in a 24-hour energy consumption profile. This baseline is then split into a 9 summer months' and 3 winter months' profile to finalise the baseline seen in the figures below. This split is according to Eskom's high and low demand seasons, mentioned in section 1.2.1.

The summer Mega Watt (MW) predicted load shift is around 3.5 MW during the Eskom evening peak (18:00 – 20:00). See Figure 4-4 for the summer predicted load profile.

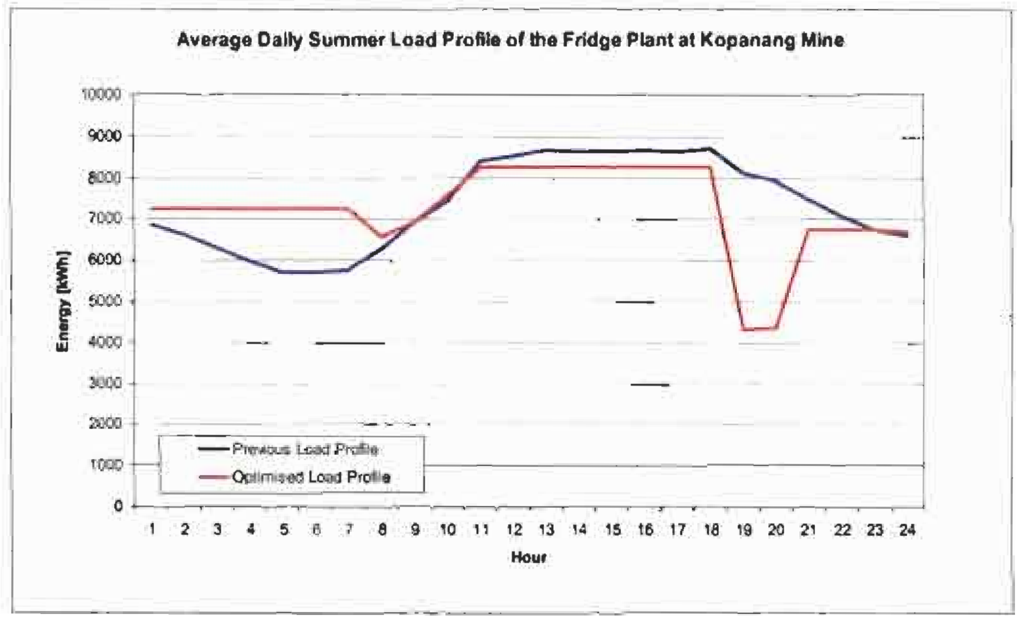


Figure 4-4: Average daily summer load profile of the fridge plants at Kopanang mine

The winter load shift saving is lower than that of the summer period, because of a lower baseline resulting from less cooling required in the colder winter conditions. The predicted load reduction for Kopanang during the winter is around 1.9 MW. See Figure 4-5 for the winter predicted load profile.

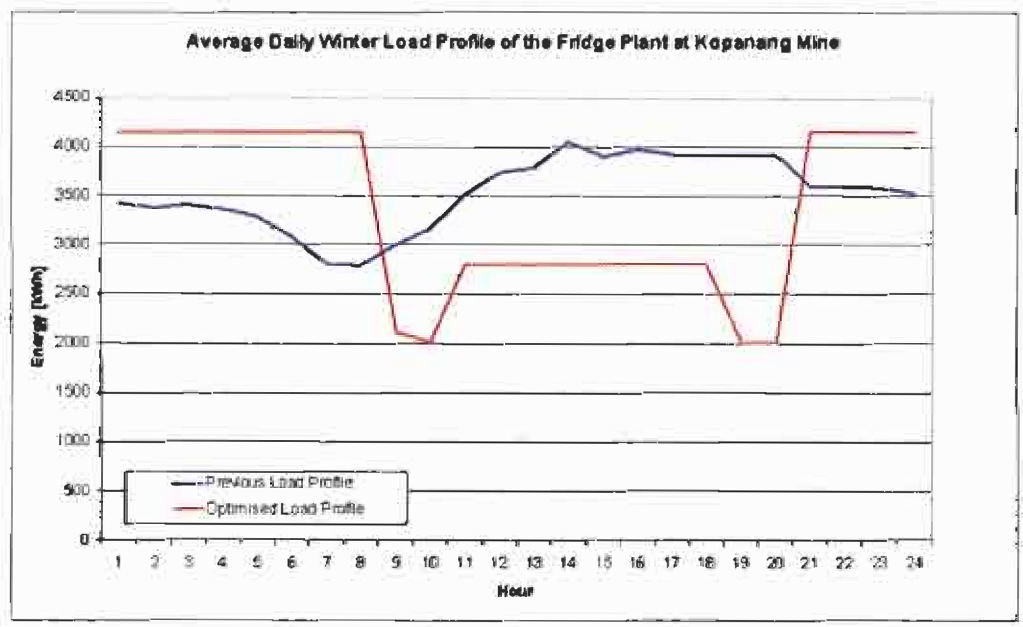


Figure 4-5: Average daily winter load profile of the fridge plants at Kopanang mine

It is evident in the above two figures, that the power consumption, in both winter and summer, is rising from 9am and stabilises at a much higher power consumption approximately around noon until 6pm where it decreases again. This 24-hour profile is caused by a warmer ambient temperature during the midday, which results in more power consumption of the refrigeration system to deliver the required cooling for the mine.

The full potential of the new control technology can be realised when the current profile is compared to the recommended optimised profile. The optimised profile is generated, according to Kopanang's layout, in the simulation model within all the constraints set by the mine, as mentioned in the previous chapter. By comparing the current load profile with our recommended optimised profile it can be seen that a weighted average exists of not more than 2.9 MW load shift potential in the evening peak (3.5MW for nine summer months and 1.9 MW for three winter months). This annual average includes a safety factor that will ensure the actual result to over deliver.

First, the calculation of the 24-hour baseline cost (R/c) is done according to the MegaFlex tariff, mentioned in chapter1, and then the optimised profile cost is calculated with the same method. These calculations are then used to generate the savings by subtracting the difference of the two costs.

Because of the 2.9 MW load shift, it means that the new installed control system and controllers will lead to an extra energy cost saving of R160 000 for the summer period, and R140 000 during the winter period. The total saving in electrical energy cost will be R300 000 per annum for Kopanang mine. These savings are not a marginal figure for gold mines but not one of the largest figures either. Nevertheless, because no additional expenses are needed from the mine to implement this control system any savings will be a virtue for the mine.

4.4. INTERACTION OF NEW FRIDGE PLANT SYSTEM WITH EXISTING PUMPING SYSTEM

4.4.1. Preamble

The research and predictions show that there exists a feasibility to implement a DSM program on the refrigeration system of Kopanang. To make this possible the control philosophies for all cases and systems must be determined or accepted.

The pumping system controls the water flow to the surface hot dams. These hot dams supply the water to the refrigeration plants. Therefore, the knowledge of the operations and scheduling of the pumps can be beneficial for the control philosophy of the refrigeration system.

Another effect of these dam levels is on the operational strategy of the turbines. When the surface chill dams are too low, the turbines on the pumping stations cannot operate to deliver the underground chill water demand, thus limiting production efficiency. Based on the above facts, it is therefore essential to understand and know the pump control philosophy. This control strategy can then be used to develop an optimum refrigeration system control philosophy.

The following control philosophy is researched for the pumping system, by mainly concentrating on the 38 level pump and turbine control. The 75 level pump control is also briefly discussed.

4.4.2. Summery of the pumping philosophy

The pumping system will try to fill the surface surge dam with as much water as allowed before the Eskom's peak period. The water of the 75 level dam will also be pumped out as much as possible in this period.

Once the dam level preparation on these critical dam levels (38 hot and cold dam, surge dam, etc) are completed, it will cause the 75 level dam to be filled up with water without the need to pump more water, during the peak time. The surface dam will be able to provide enough water needed for the refrigeration plants, without using any other water resources.

Kopanang mine limited the minimum amount of operating refrigeration plants during the peak periods. This limit resulted in developing an additional method to cut back the energy consumption of the plants. Therefore the surface dam must supply enough warm water for the refrigeration plants to prevent any surging of the machines.

The turbine and pumping control philosophy ensure that the electrical pumps and turbines of both the 75 level and the 38 level will not start unnecessarily during the evening peak. As a result, no extra water will be supplied to the hot and cold dam on the surface and cause an unstable water balance. With this as a result of the pump philosophy, it can be seen as a successful strategy for the load management process of the refrigeration system. This will consequently effect the refrigeration system to be more than half way prepared for the load shift period.

The following peak and off-peak control philosophy is initialised on the pumping stations:

i.) Off- peak period:

During off-peak periods the 75 level pump station pumps as much water as possible to the 38 level dam in preparation for the peak period. The limits (maximum and minimum) of the dam levels are always taken into account.

The 38 level pump station works the same as the philosophy of the 75 level pump station, but with only the 38 level dam level and the Surge dam (on surface) level being monitored. The 38 level pump philosophy also takes the limits (maximum and minimum) of the dam levels into account.

ii.) Peak Period:

The pump control philosophy during the peak period is opposite to that of the off-peak philosophy, seeing that as few pumps as possible are running. This must also be done within the constraints of the dam levels and mine regulations. The limits of the dam level will be changed for peak hours to ensure the optimum LS in the pumping system, as illustrated in Figure 4-6.

Figure 4-6 is a graphical illustration of the pumping control philosophy during peak and off-peak periods.

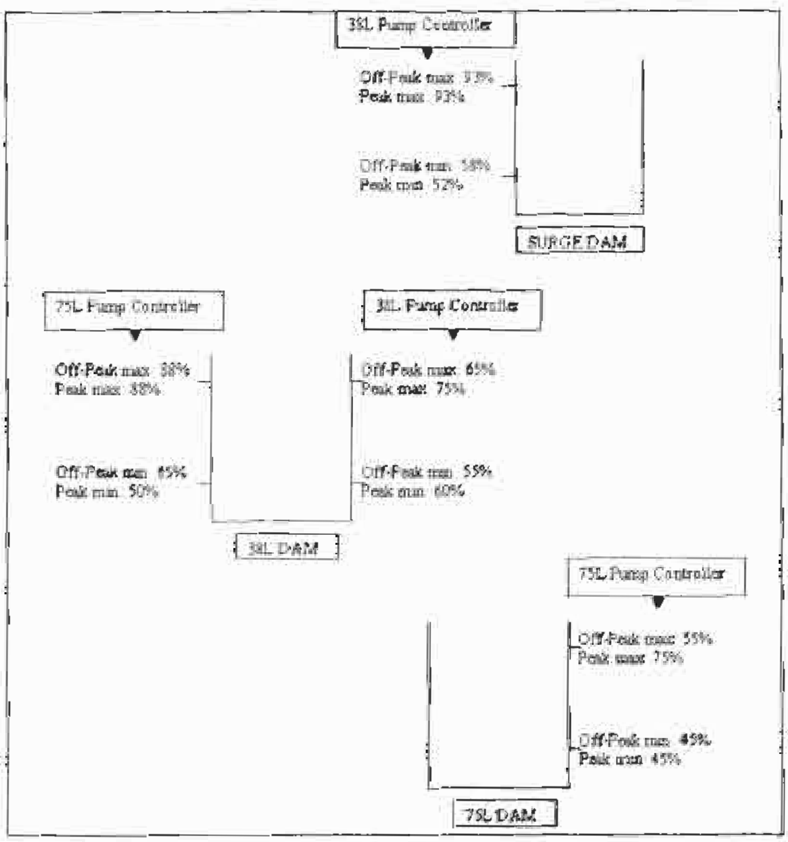


Figure 4-6: Graphical illustration of the control philosophy of each pump station

4.4.3. Control of turbines on 38 level pump station

The two turbines on the 38 level have a more direct influence on the surface refrigeration system. It controls the water outtake from the cold confluence dam on surface and the inlet of the surface surge dam. If the cold-water consumption is too high, the fridge plant will be unable to shut down.

The 38 level pump control setup must strive to keep one turbine running during the peak period. The second turbine is only allowed to run when the 38 cold dam level is too low, or when the level must be filled for preparation of the working shifts.

When two turbines are running, a minimum of one electrical pump must run on the 38 level in peak period. This will ensure water balance on surface dams. Two turbines must not be started unless all the needed refrigeration machines are running (6 in summer, 2 or 3 in winter).

The quantity of refrigeration machines needed, two or three during the winter and six during the summer is set because of the cooling demand that differs in season, also to ensure the water balance in the confluence dam which can ensure a more stable outlet temperature.

For example : the confluence dam supply enough water for the underground demand in the winter with two or three machines in operation, because the cold confluence dam will still stabilise at the required outlet temperature with this amount of plants running, see next section. However, if more water is extracted from the confluence dam with fewer plants required to be in operation, there will not be a water balance in the confluence and this will cause higher or unstable outlet temperatures.

4.5. FUTURE CONTROL OF THE FRIDGE PLANT SYSTEM AT KOPANANG

4.5.1. Preamble

The method of creating load reduction/shifting at the refrigeration system is to use the new control system consisting of the shut down or cut back controllers. The controllers' intended purpose is to shut down the fridge plants during the given time and to control the vane opening of the by-pass valve in pre-, post- and during peak time.

The fridge plants will be shut down or cut back according to the specified time and/or be shut down by a calculated or exacting sequence. These procedures will consider all the dependent constraints.

To create a control philosophy to compensate with the new designed control system, the old philosophy must first be researched and then optimised. This optimisation procedure in the new control philosophy, for the refrigeration system, will ensure optimum load management. All parameters and constraints, as mentioned above, will be monitored together with considering the new control philosophy in the designed control system (shut down and cut back controllers).

4.5.2. Constraints and parameters

The main constraint on the refrigeration system is not to exceed an underground inlet temperature of 4 °C. The limits on the dam levels must not be exceeded. Everything must run as smooth as before the implementation of the new control system. In consideration of the above, the following parameters are formulated:

- Do not shut machines down during weekends. For Eskom's energy demand isn't that critical over the weekends, as seen in the MegaFlex tariff specifications. This constraint will therefore result in less mechanical strain on the fridge plants during the week.
- Do not shut machines down when the evaporator inlet temperature is higher than 10°C. For the designed inlet temperature is an average of 8.5°C. This limit is specified for when the inlet temperature exceeds 10°C, the thermal energy demand for Kopanang is higher than normal and all the available thermal energy is needed.
- Do not shut down the machine when two turbines on 38L pump station are running, for the cold confluence dam level will decrease too quickly and the BACs might trip if it is not supplied with enough cold water.
- Do not shut down a machine when one is already out of order, thus control the quantity of plants running according to the specification of the mine, and the minimum plants running in peak time constraints (mentioned in chapter 3).
- The new control must not cause any variation in control of the equipment (example: valves vane aperture, compressors vane opening etc.), for instability may cause more maintenance in the long term.

4.5.3. Old philosophy

The parameters that need to be considered in the new refrigeration philosophy are described below. These parameters are identified through research and monitoring of the refrigeration system.

The first restraint identified is the pre-cool by-pass philosophy. The surge dam supplies water to the pre-cooling towers, where the pre-cool by-pass valve controls the hot confluence dam level. This valve is installed to control the water flow to the hot confluence dam, by passing the outlet water from the pre-cool towers back to the surge dam. The pre-cool by-pass valve will close when the hot confluence dam level is too high. An internal PLC program controls this valve.

This valve is set at a point of 73% to control the hot confluence dam at a constant level. It is also programmed to monitor the cold confluence dam level in extreme cases, for example when the cold dam level decreases to 60%, the valve will close and be reset by the internal PLC program when the level stabilises again at 70%.

A constant underground water temperature of 3°C, with a 1°C variance (2°C -4°C), is essential to be maintained at all times during the day. Through out the day, the outlet water of the fridge plants flows directly to the cold confluence dam that supplies water to the underground areas and the BACs. The excessive cold water flows from the cold confluence dam through to the hot confluence dam where the inlet fridge plant temperature stabilises at 8-9 °C.

4.5.4. New philosophy

When installing the new control system (including the cut back and shut down controllers) the system might become unstable and the following precautions and redesign must be done on the refrigeration system. This must be done especially for the cut back controller, due to its big influence on the water balance in the confluence dam.

The internal PLC program for the pre-cooling by-pass valve, mentioned earlier, was changed slightly for better flow control throughout the whole system and the confluence dam. Previously the program only monitored the level of the hot confluence dam at 73%. The new philosophy controls the average dam level of the cold and hot confluence dam at a set point of 80%.

This set point is inserted as a variable and can be changed for fine-tuning. It is changeable and adjustable because by implementing the new control system for the refrigeration system, the cold confluence dam level varies more than before implementation. Because of this variation, the pre-cool valve must monitor the average dam level of the cold and hot dam at the higher set point. This change will also prevent the cold confluence dam level to drop below 55%, which will consequently avoid the level to reach 50%, in which case the BACs will trip.

An extreme case control for the low cold confluence dam level, as done in the old philosophy, is changed from 60% to 55% (within the limits). The cut back controller will also command the new installed by-pass valve to close (if open) until the level rises back to 65%. This will ensure better, sustainable and safer LM results.

At evening peak, the pre-cool tower by-pass valve stabilises at a 74% opening, for this setting allows a flow to the hot confluence dam of approximately 223 l/s. The exiting flow will also be around 223 l/s, which is caused by one turbine on the 38 level pump station. This ensures that the water inflow is equal to the water outflow in the confluence dam – water balance.

The outlet temperature of the fridge plant is still controlled at a set point of 3°C. During the off-peak time, the excess cold water flows from the cold confluence dam through to the hot confluence dam via the centre confluence dam and not through the by-pass valve, as it was done in the old control philosophy. Then during the peak period, the flow switches, as seen in Figure 4-7. This flow switch is caused by the output of the cut back controller to command the installed by-pass valve for the new control system.

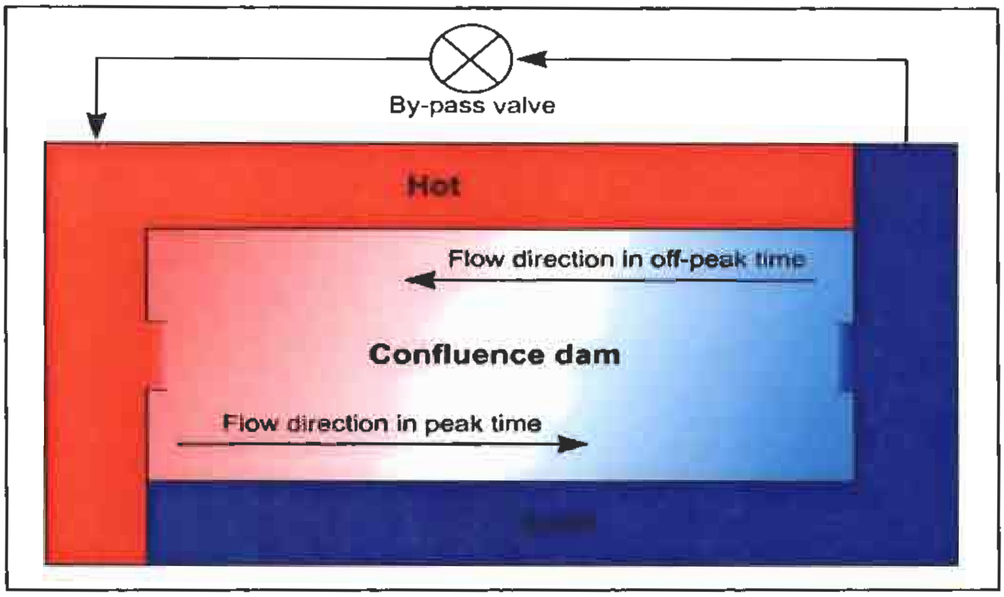


Figure 4-7: Flow direction during peak and off-peak periods in confluence dam

When the by-pass valve, see above figure, opens during the peak period, the chilled water will flow directly into the hot confluence dam. This causes the temperature of the hot confluence dam to decrease, thus decreasing the inlet temperature of the fridge plants.

The by-pass valve stabilises at an opening (normally from 90% - 95%) where a steady low inlet temperature is achieved. The minimum inlet temperature of the refrigeration plants is determined through inspection and testing. If the inlet temperature is lower than the minimum temperature determined, the fridge plants will surge. This temperature limit is mounted into the extra modifications input of the cut back controller as well as the input specification of the constraints.

This by-pass valve will also close partially, or fully if necessary, to prevent a surge occurrence with the running fridge plants. Surging in fridge plants is usually caused when the outlet temperature is not monitored correctly for the fridge plants, and becomes too low because of the cold inlet temperature. To prevent the BACs to trip, caused by the lack of cold water supply, the cut back controller will monitor the cold confluence dam level twenty four hours a day, seven days a week.

In order for the fridge plant to have a constant outlet temperature, because of the change in inlet temperature, the vanes of the compressor will automatically adjust and reduce the electricity usage according to the inlet temperature drop.

There is a preparation period (starting 17:40) for the evening peak, where the by-pass valve partially opens to cool the inlet water to the fridge plants. This is done to lower the evaporator inlet temperature, gradually.

After peak period (approximately one hour), the valve will close slowly to prevent the inlet temperature to increase dramatically after peak time. The valve also monitors the dam levels (hot and cold confluence) to prevent too low or too high dam levels.

The cut back controller will monitor the temperature of the water at all times. If the outlet water temperature is too high, the valve will close, and the cold water from the fridge plant will flow directly to the cold confluence dam again, restabilising the cooling system.

4.6. CONCLUSION

A control philosophy must be tailor made for the refrigeration system, consider the pumping philosophy, and optimise each philosophy where necessary. This is done by taking their various constraints and system cycles into account. The mine identified to determine this control philosophy must have enough LM potential to make the redesign feasible. A control philosophy is therefore determined for the refrigeration system of Kopanang mine, by considering the interrelated systems' control procedures.

This control strategy must then be implemented at Kopanang to compare the deviances of the theoretical control with the practical control philosophy via the new control system. The control system will then be monitored and changed, according to the practical philosophy which is based on the theoretical control philosophy.

5. PRACTICAL IMPLEMENTATION OF THE NEW CONTROL SYSTEM AND CONTROL PHILOSOPHIES FOR A FRIDGE PLANT DSM SYSTEM

This chapter explains the implementation procedure before and after the new control system and philosophy are installed. It emphasises a few problems that are encountered through the implementation procedures in a case study. A verification procedure to compare the predicted results with the actual results is also discussed.

5.1. INTRODUCTION

In the preceding chapter, a load management potential was determined, at a site identified in Chapter 3, to implement the new designed control system mentioned. A control philosophy was then tailor made for the specific site to compensate with the new control system, which will result in a load management system.

To test and verify the validity of this load management control system, it was implemented at a mine. By doing this, the discrepancy between the theoretical and practical system could be established.

This chapter therefore illustrates the implementation of the fridge plant load shifting system at Kopanang mine. It describes the implementation procedure of the load management system, the problems that occurred, how these problems were solved and what the performance is after the final stages of the implementation.

5.2. DESIGNING THE NEW SYSTEM FOR KOPANANG

5.2.1. Procedure

The first step before implementing a new DSM program is to evaluate the DSM potential at the identified site. In this case the feasibility for implementing a successful DSM program at Kopanang mine's refrigeration plant, is quite high as seen in Chapter 4. All the possible cases must be considered in the evaluation process, to ensure a sustainable result.

Data is collected to assess the characteristics of the refrigeration plant of the mine. The data is also used to determine the baseline for the power consumption during the winter and summer months, from which the potential can be evaluated, as seen in the previous section.

These logged features are then used as a reference in a simulation program. The simulation program is set up to simulate the typical response of the refrigeration plant to the variety of input variables.

The simulation is then optimised and modified to simulate an accurate refrigeration system cycle at a mine. After succeeding in this, more adjustments are made to terminate all the possibilities in failing to achieve an optimum DSM or load shift profile.

A thorough examination must be done in the refrigeration hardware system to list all the hardware needed for full automation (see section 5.2.2). The mine, the ESCO and a hired sub-contractor mainly do this investigation. When the implementation starts, the listed hardware must be installed according to the specifications set up by the mine and sub-contractor. The sub-contractor is employed to commission the refrigeration system and guarantee that the automation process runs as smooth as possible from the SCADA system of the mine.

The time schedule for the implementation process of all the hardware and software for the automation depends on the season of the year. Unlike the pumping systems, the refrigeration plants can only be shut down for annual maintenance during the winter period.

The cold atmospheric air in winter can provide enough cooling to the ventilation system underground as well as an allowable underground water temperature. Even in this case it is very dangerous if no fridge plants are running.

An automation installation schedule for each fridge plant must therefore be set up to ensure that the shut down, for the hardware installation, is only done during the winter period and must be finished within that season. Therefore, it is essential not to let the implementation process fall behind schedule. If this occurs, the safety of the mining personnel can be in danger. One of the worst consequences that may occur when the underground temperature rises above human resistance is loss of life.

The shaft engineer of the mine must therefore first approve the automation schedule or project plan. The shaft engineer must be present at every weekly project meeting to ensure that everything within their reach is done to be on schedule.

The commissioning of each refrigeration plant can be signed off if the hardware and software are up and running without errors for that specific plant. The software installation and programming is done in the PLC memory of the equipment. This program can then be used to manipulate the equipment or override the system if any danger occurs. The control system, including the software package, is then installed as a new system to result in a successful DSM project.

5.2.2. Hardware specifications

As mentioned in the preceding paragraphs, there must be extra hardware specified to automate most of the refrigeration plants in gold mines, depending on the technology already installed at the mine. The hardware for Kopanang mine is specified in Appendix A, where all types of hardware are listed to ensure the automation of the refrigeration plants at Kopanang mine.

Here is a short list of all the hardware necessary for the automation process:

- PLC connections and fibre cables
- PLC programming
- Necessary IO (Input Output) – digital/analogue
- HMI (Human Machine Interface) programming
- PLC panels
- Field instruments and cable
- SCADA engineering

An overview of the new modified hardware and communication network is illustrated in the figure below. The new installed by-pass valve for the cut back controller is also depicted in Figure 5-1.

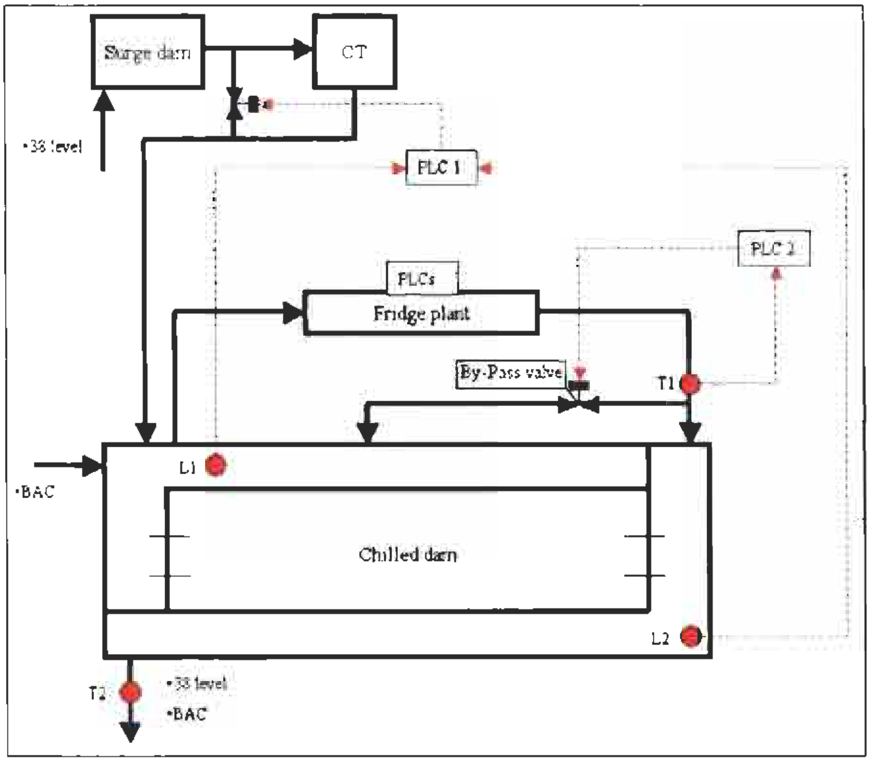


Figure 5-1: New schematic control layout of the refrigeration system

This figure illustrates a simple PLC communication network of the equipment needed to be monitored in order to satisfy all the specified constraints. This schematic layout is a more simplified system layout.

A software algorithm is programmed into the memory of the fridge plant PLC that is written to ensure a fixed start up and shut down sequence for the fridge plants. This sequence starts for each fridge plant when the start or stop bottom/tag is activated. The sequence, which can be seen in Appendix B, is calculated and determined to ensure safety for all personnel that form part of the VC system of the mine.

The software and hardware must operate in such a way that the installed controllers in the control system of the refrigeration plants will ensure a feasible LM project. Nevertheless, as with any other implementation there are always problems that may occur during the installation and fine tuning of the controllers in a practical environment.

5.2.3. Fridge plant control system

After the installation of the infrastructure, as mentioned above, the new control system is installed and customized according to the control philosophy of the mine system and its conditions. This can take a few weeks, but the refrigeration plant will be operational in this period to provide enough cold water for the mine and prevent any unnecessary danger. There will be no risk in this implementation, test and optimisation process of the control system as long as the control runs within the constraints of the mine.

In the post-commissioning period (period while installing hardware for full automation), the software package of the control system is implemented and tested, where the final software package and control system set-up can be seen in Figure 5-2. This figure illustrates a few relevant components that must be monitored and changed in the refrigeration system, to create a feasible DSM project. Therefore, all the dependent components must be controlled by the software package via the installed controllers.

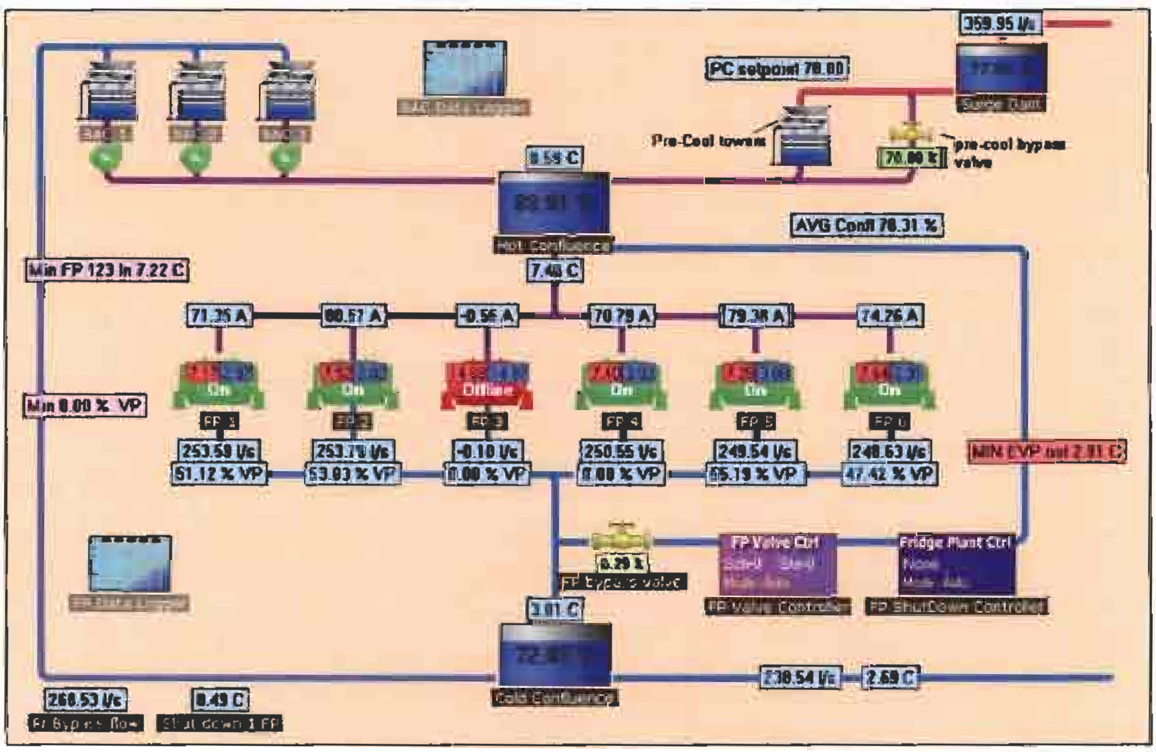


Figure 5-2: Refrigeration system layout at Kopanang mine

The above figure illustrates the pipe works, valves, BACs, pre-cool towers, fridge plant by-pass valve, pre-cool by-pass valve, fridge plants, hot and cold confluence dams and the controller's user interface. This figure also demonstrates the location of each component in the cooling system.

The automation process of the fridge plants can cause the plants to run more efficient than in the pre-automation state. The fridge plants may also become more efficient when the refrigerant is replaced by a better grade of refrigerant.

The component variables can all be monitored by the software package illustrated above. All the variables are logged to determine the efficiency of the new fridge plant control system.

5.3. ISSUES ENCOUNTERED DURING IMPLEMENTATION

5.3.1. Problems

The biggest problem that may occur during the implementation process is when an operational fault occurs in the cooling system. This can cause the constraints to exceed their designed limits. The origin of this problem is usually when a few variables have a dramatic change in the cooling system and the controllers of the new control system are not fully compatible with the phenomena.

The mine constraints must always be satisfied with the automation process; therefore the controllers must keep the following variables within their limits:

- The inlet and outlet Fridge Plant temperature.
- The limits of the dam levels.
- Climate.
- Temperature of the mine inlet water.

When each constraints limit is exceeded a new problem occurs, therefore all the above constraints are monitored on a 24-hour basis by the control system controllers.

Another problem can occur when the sections of the cooling system, which are not in the control range of the controllers, can cause instability during the rescheduling process.

One of these sections is the by-pass valve PID control program of the pre-cool tower. This PID program monitors the dam levels and the inlet temperature of the refrigeration plants. The program is written to stabilise the water flow of the cooling system under normal conditions. The problem however occurs when the cut back controller of the control system reschedules the new installed by-pass valve vane opening in the peak period, which will cause unstable water balance in the confluence dam. This consequently causes the output of the PID controllers to oscillate the vane opening of the pre-cool tower by-pass valve.

In effect, the dam levels will then aim to exceed the minimum or maximum level settings. Because of the monitoring of the dam levels by the cut back controller, the above situation will also result in a fluctuation effect in the output of this controller.

These problems may occur during the implementation process. It can therefore be concluded that for every problem a snowball effect takes place in the whole system. This can only be avoided when the philosophy of the indirect dependent controller is rewritten and modified to compensate for each new problem.

5.3.2. Solution to the problems

All of the problems that occur during the implementation process must be fixed by considering a trail and error angle for a solution. This solution is only initiated in the control system after running additional simulation models successfully. This solution approach is the only way to test the solution program accurately on a practical system. The fixed control program is still based on the same philosophy, but with extra modifications.

For example, in the case of the pre-cool tower by-pass valve PID program, an initial stable value must be found. This is determined through thorough investigation and tests. The program is then modified according to the tests and the experiments of the new philosophy. The updated program is also put through a simulation program before implementing the final product.

Not only independent control of the mine will be modified, but the controllers of the control system will also be adapted to ensure even better LM results. The result of the adjusted controllers will be a smoothly operating and stable system.

5.4. VERIFICATION AND RESULTS

5.4.1. Preamble

The verification of the results for a load shift project can be done by comparing the old load profile (baseline) with the new optimised profile. This comparison is done by normalising the baseline according to the total power usage during the day of that specific section, in this case the cooling system.

Through the implementation and automation process of the cooling system, the new DSM system can deliver energy efficiency as well as the predicted load shifting during the evening peak. A combination of energy efficiency and load shift makes the verification process even more difficult. Therefore a new procedure to confirm the actual results for load reduction in a cooling system must be developed. This verification procedure must show the results in either load shift or energy efficiency, or both.

5.4.2. Verification procedure

The baseline at the Kopanang fridge plants is determined by collecting the electrical feeder data (from January 2004 to December 2004) of the refrigeration plants that includes the BAC and extra-unspecified equipment in the cooling systems. This data contains daily-logged data of the power consumption.

The calculation for load shift DSM projects, as mentioned earlier, is done by the normalisation method, where the total kWh used per day is used to scale the baseline. Although the refrigeration system is a DSM project, it may include load reduction in addition to load shifting.

Load reduction takes the improvement of efficiency in the cooling system together with the COP of the refrigeration plants and load shifting into account. The fridge plant usually runs even more efficiently after the yearly maintenance. It also improved when the plants were automated, calibrated, and even when the R-12 refrigerant was replaced with a R134a refrigerant.

The only logical way to consider this effect and to determine the load reduction at the peak time is not just by normalising the baseline. It is done by comparing the actual kW used for the day with a scaled baseline kW reading before the automation (pre-implementation) process.

A method is researched to develop this scaled baseline, to result a feasible verification procedure that takes all the variables for load reduction into account. The method consists of an equation related to the pre-implementation conditions of the refrigeration plants, by comparing the ratio between the thermal energy and the electrical power consumption respectively; see Figure 5-3 [48]. This figure therefore represents the amount of energy used to generate the thermal energy, needed for cooling in the pre-implementation period.

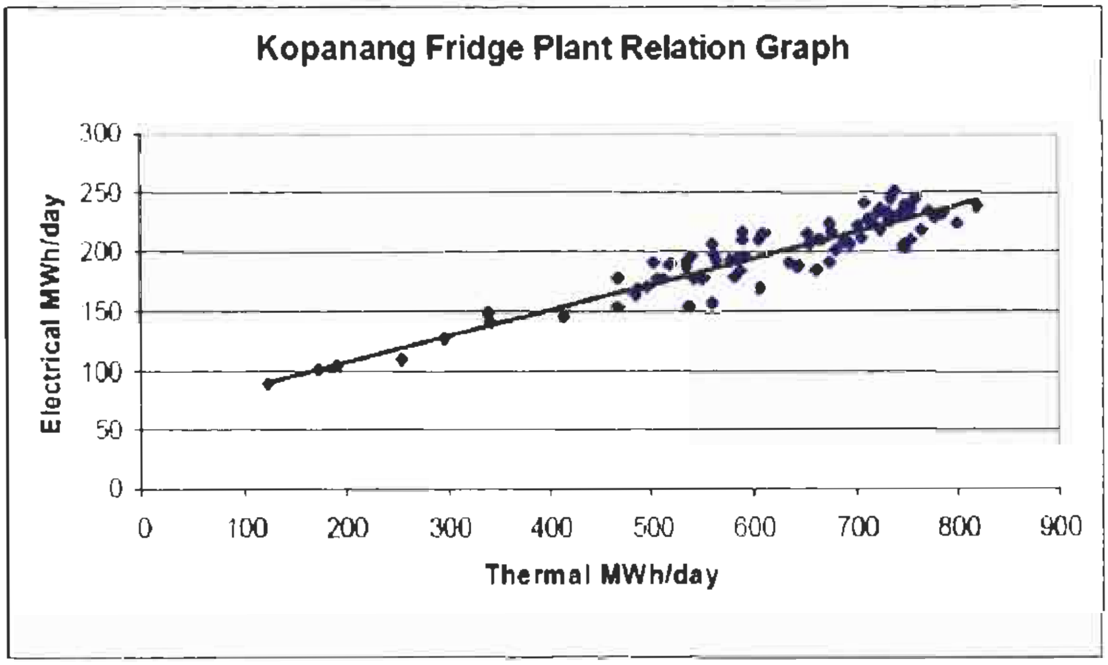


Figure 5-3: Kopanang thermal and electrical power relation graph

The baseline is then scaled by using the thermal energy, logged daily by the utilities of the control system, in the post-implementation period in the equation $y = 0.2184x + 64.657$ to determine what the electricity usage would be before the automation process. The resulting electrical energy usage (MWh/day) calculated in the equation is then used to scale the baseline and the load reduction can be determined for that specific day.

The effect of a new-scaled baseline can then be seen in Figure 5-4, where X is the result of the EE and the load shift during the peak time. The 'feeder data' in Figure 5-4, represents actual kW usage logged during the day.

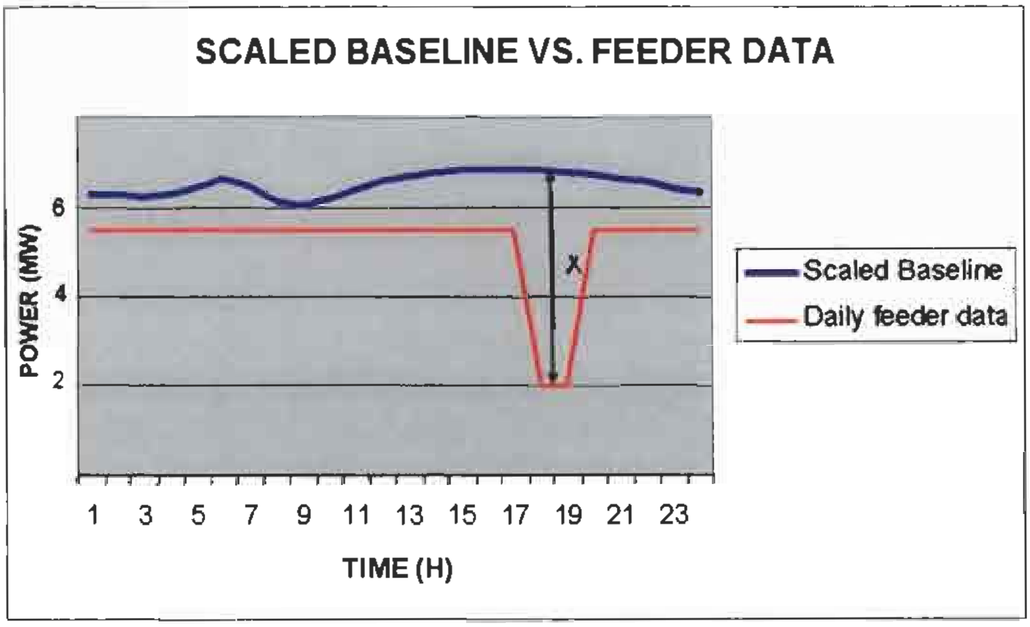


Figure 5-4: Resulting scaled baseline according to new developed equation

5.4.3. Delivered load reduction and financial benefits

After the implementation and automation period of the new control system for Kopanang's refrigeration plants, the verification procedure was determined as seen above. This procedure is initialised to determine the performance of the new control system. This procedure must therefore be used to calculate the actual load reduction results in winter and in summer, and compare it with the predicted results.

The predicted average annual load reduction for the refrigeration plants at Kopanang is 2.9 MW during the evening peak. The calculated annual savings will be R 300 000 per annum.

The verification results are based on two sections. First, the actual load shift must be determined, and secondly the actual performance of the control system must be estimated. The figures and tables depicted in the following paragraphs compare the actual performance with the predicted performance.

i.) Summer

These predicted savings (load reduction and costs) are compared with the savings of the first summer assessment months of the new implemented refrigeration DSM system. This assessment will determine if the newly installed system is sustainable and reliable according to the expected savings in the summer.

The following figures represent the optimised load profile for the cooling system of Kopanang mine during the performance assessment period. Figure 5-5 [49] illustrates the resulting load profile for the first assessment month December 2005. Figure 5-6 [50] and Figure 5-7 [51] illustrate the performance for January 2006 and February 2006 respectively. Note that in the following figures the baseline represents the scaled baseline, mentioned earlier.

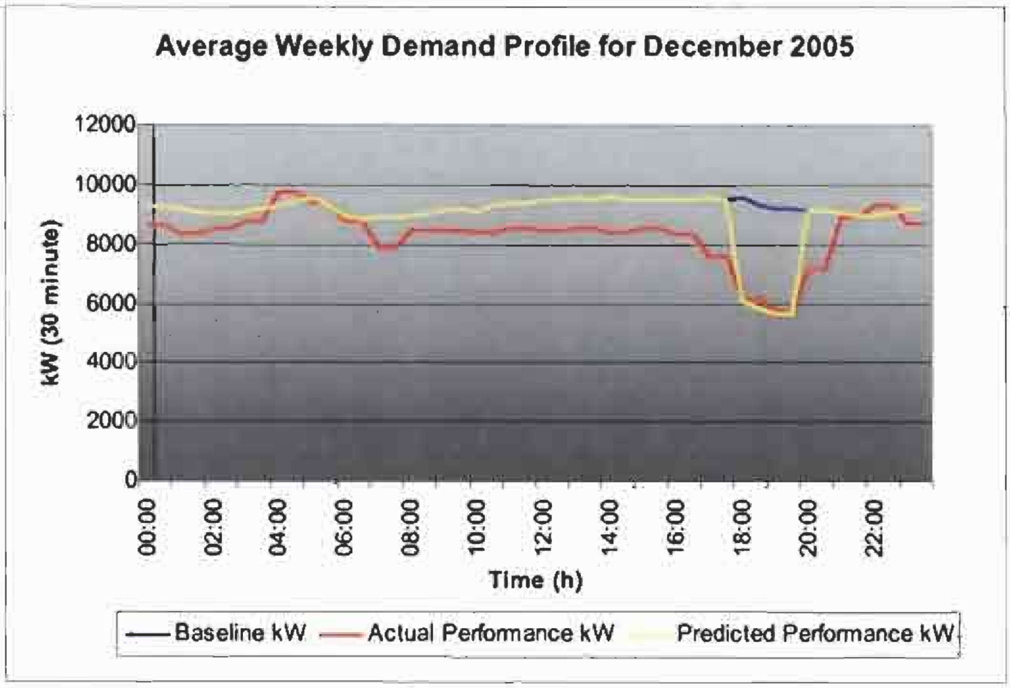


Figure 5-5: December 2005 optimised load profile vs. scaled baseline

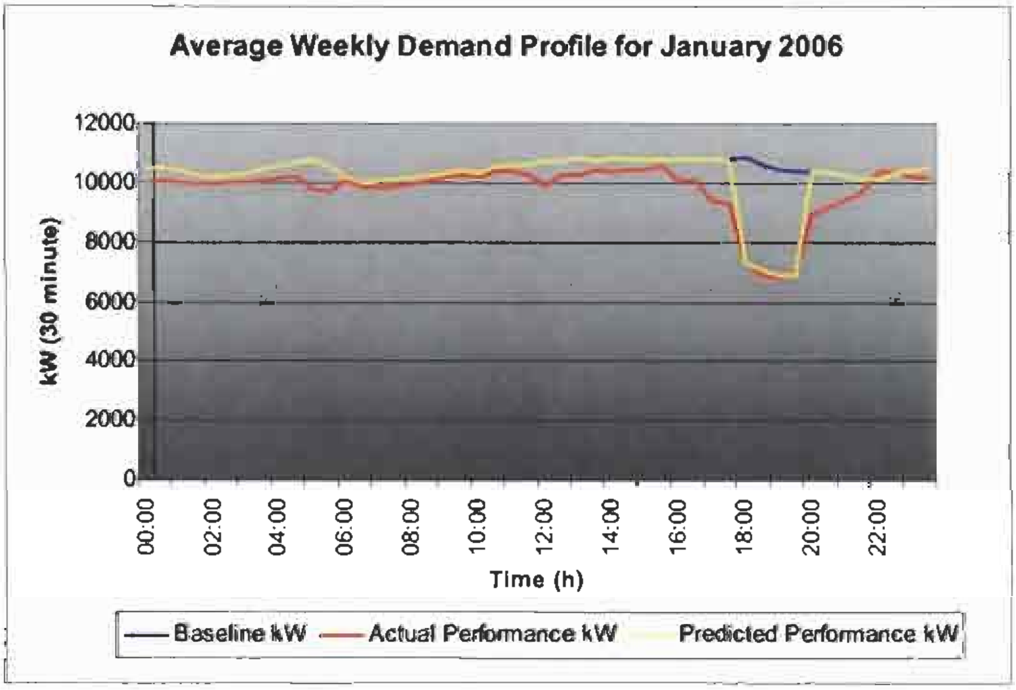


Figure 5-6: January 2006 optimised load profile vs. scaled baseline

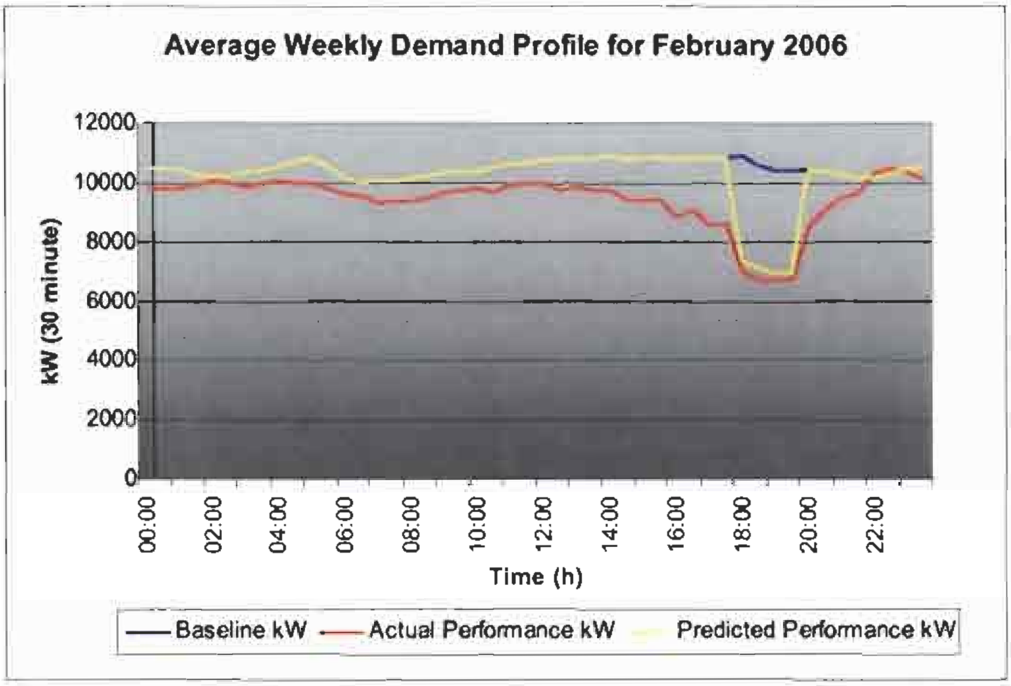


Figure 5-7: February 2006 optimised load profile vs. scaled baseline

In the above figures, the achieved load reduction profile, scaled baseline and the predicted load profile can be seen. The EE results with the new implementation are also visible. It is therefore concluded that load reduction is taken into account with the scaling procedure of the baseline, and the calculation of the savings.

The following table compares the predicted savings (load shift only during Eskom's evening peak and R/c monthly savings) and achieved savings.

	Predicted MW	Achieved MW	Predicted savings (monthly)	Achieved Savings
Dec 05	3.5	3.4	R 39,480	R 49,798
Jan 06	3.5	3.6	R 39,480	R 40,204
Feb 06	3.5	3.8	R 39,480	R 49,144
Average Savings	3.5	3.6	R 39,480	R 46,382

Table 5-1: Predicted saving vs. actual savings in the summer period

It is evident in the above figures and tables that the predicted performance of the newly installed control system in the VC section of Kopanang is achieved during the summer period.

ii.) Winter

These actual savings (load reduction and costs) resulting from the new control system is also compared for the winter period. The comparison is done with the predicted load reduction results of two winter assessment months. This assessment will determine if the recently installed system is sustainable and reliable in the winter period as well.

The following figures represent the actual performance plotted against the predicted performance for the two winter months. Figure 5-8 illustrates the resulting load profile for the first winter assessment month June 2006. Figure 5-9 illustrates the performance for July 2006. Note that the baseline also represents the scaled baseline.

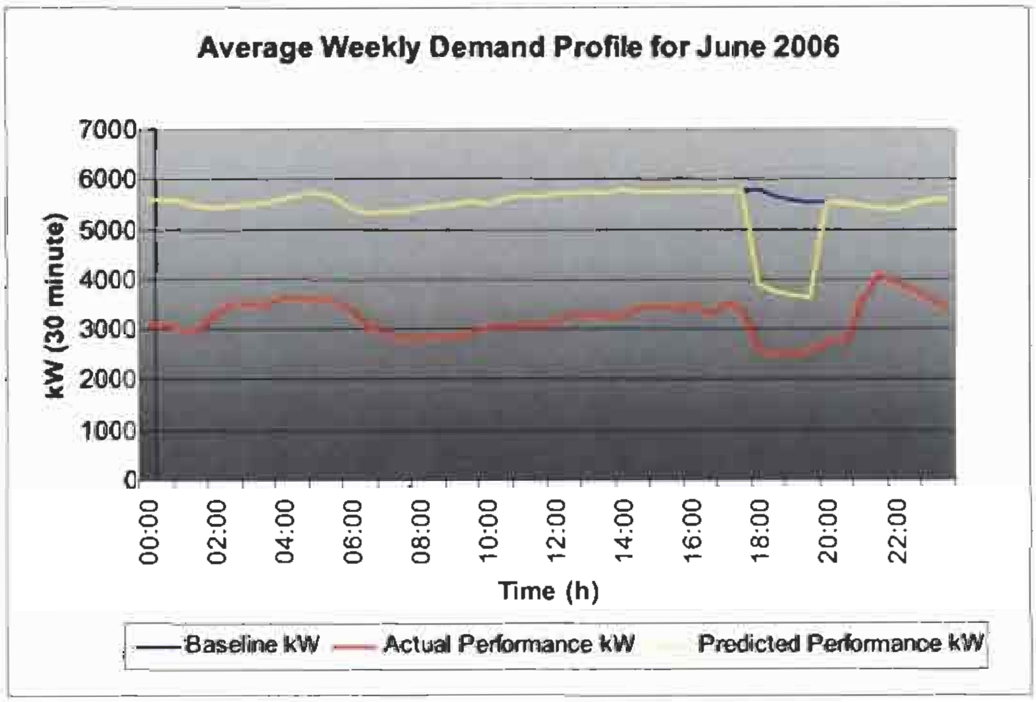


Figure 5-8: June 2006 optimised load profile vs. scaled baseline

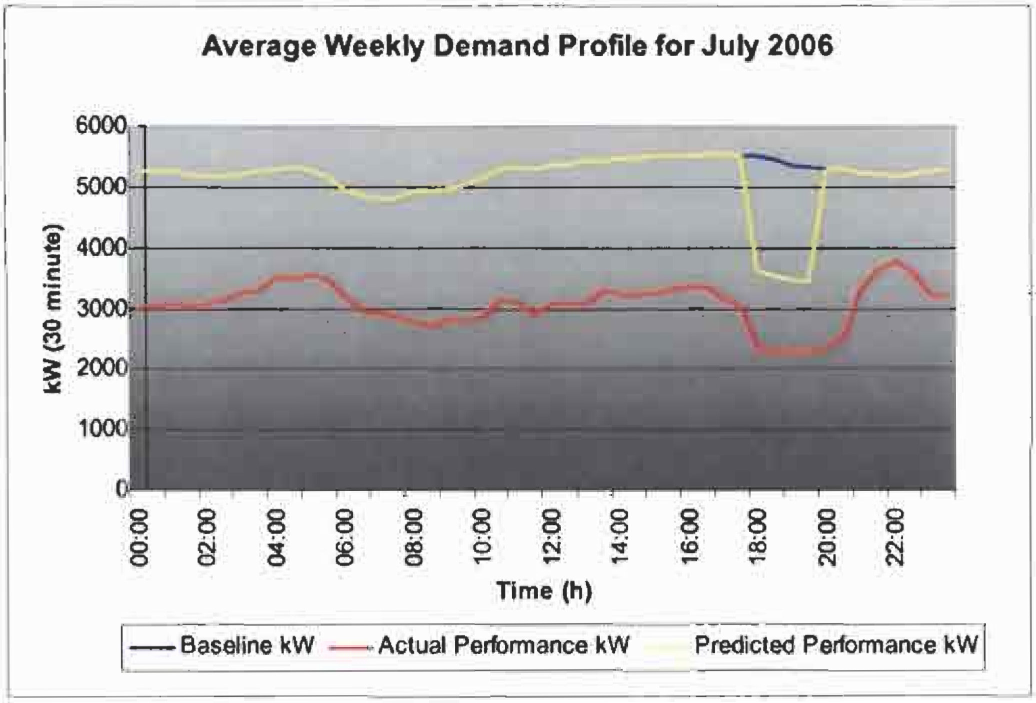


Figure 5-9: July 2006 optimised load profile vs. scaled baseline

In the above figures, it is evident that the energy efficiency is larger than it is in the summer months. Because of the more efficient power consumption of the refrigeration plant during this period, less power was consumed in the cooling system during 2006 resulting in a large energy drop.

The baseline however, was constructed for the winter of 2004 from electrical feeder data, where the total power used by Kopanang's cooling system was more than the power consumption in the winter of 2006. It was confirmed by the mine that the BACs (only the fans) were used during a large part of the winter of 2004 and not in 2006. It is calculated that the total power usage of the BACs ranges between 1.9 MW and 2.1 MW, which causes the large energy drop

It is also evident that the simulation model's predicted 24-hour power consumption profile varies with the delivered 24-hour profile. This deviation was because the simulation model calculated the predicted power consumption of the refrigeration system by assuming the same components (example: BACs) will be operating during the winter of 2006 as in 2004.

Due to the logged reading of the electrical feeder, consisting of the BACs, fridge plants and other unidentified electrical utilities' power consumption, the adjusted equation took the additional energy used in 2004 into consideration to scale the baseline. These results of the scaled baseline show that energy efficiency occurred in the winter of 2006 when compared to the power consumption in the winter of 2004, from where the baseline was formed.

The following table illustrates the predicted savings (load shift only during Eskom's evening peak and R/c monthly savings) and achieved savings for the winter period.

	Predicted MW	Achieved MW	Predicted savings (monthly)	Achieved Savings
June 06	1.9	3.1	R 43,656	R 227,773
July 06	1.9	3.1	R 41,672	R 207,612
Average Savings	1.9	3.1	R 42,664	R 217,692

Table 5-2: Predicted saving vs. actual savings in the winter period

It is also evident in the above figures and tables of the winter results that the predicted performance of the newly installed control system in the VC section of Kopanang over performed in the winter period.

The control system is seen as a successful execution in a surface refrigeration system of a mine, and compatible for the winter and summer period's cooling demands. The success of the control system is determined by delivering the promised load shift that result in generating savings through the comparison of the new 24-hour profile cost with the baseline cost.

These savings can be seen as an additional cost savings for the mine without investing any capital for the project, the only contribution needed from the mine is their co-operation during the implementation phase. These results also prove that the control system can deliver the predicted load shift within all the constraints specified in the previous chapters.

5.5. BENEFITS FOR SOUTH AFRICA

The impact of this DSM project's implementation on the cooling system on Kopanang mine, will have an enormous effect on the mine's maximum demand, yearly savings and even decrease environmental pollution (less emission impact – CO_2 generated by Eskom, etc.).

The results of the new control system in Kopanang's refrigeration system prove that there is a large load reduction potential in the refrigeration systems of South African mines via the new control system. This can therefore be seen as a breakthrough in energy savings and efficiency in the cooling systems of the mining industry.

To prove this contribution, calculations are done to determine the electrical and cost savings through implementing the new control system for other refrigeration systems. These calculations are based on additional research and simulations for the refrigeration systems in other mines in South Africa.

The same simulation model used to determine the predicted load shift (MW) and cost saving for Kopanang mine was utilised to determine the potential for the mines stated below. The following mines are identified with large LM potential in their refrigeration system(s):

- Surface and underground refrigeration system of Elandsrand Mine, situated near Carletonville in the North-West province.
- Surface refrigeration system at Tshepong Mine, situated near Welkom in the Free-State province
- Surface refrigeration system at South Deep Mine, situated in Western Areas, Gauteng province

Table 5-3 illustrates the results, generated by the simulation model, for the predicted summer, winter and annual load shift (MW) and average cost savings for these mines.

	Predicted Summer MW	Predicted Winter MW	Annual MW savings (monthly)	Annual cost savings
Elandsrand	7	7	7	R 800,000
Tshepong	3.7	1.6	3.2	R 300,000
South Deep	4.4	3.8	4.2	R 500,000

Table 5-3: Predicted savings in the refrigeration systems of South African mines through a new control system

The impact of this new field of a DSM implementation project will provide an additional solution to the energy crisis in South Africa. The implementation of this DSM project will cause enough savings for the platinum and gold mines in South Africa to invest in more energy efficient projects. These savings are only calculated in case of load shifting, but in case of load reduction, the predicted average annual savings can be much higher.

5.6. CONCLUSION

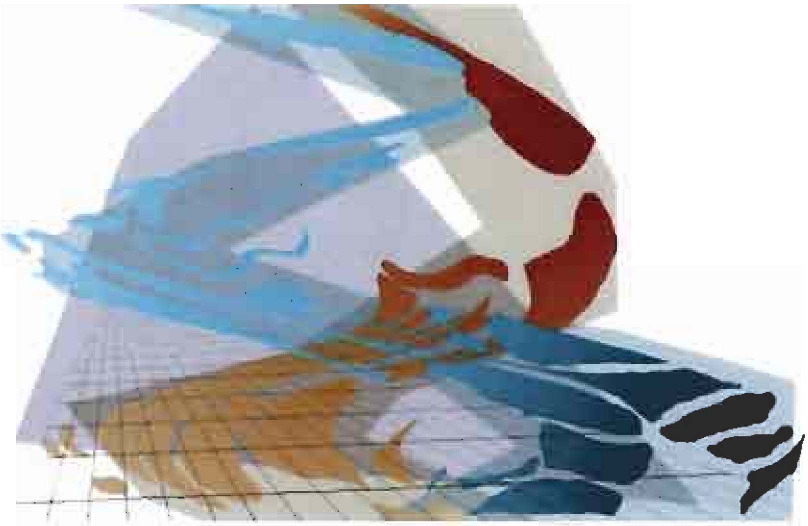
After modifications and optimisation of the refrigeration system at Kopanang and based on the performance results of the implementation, the load management model (consisting of the new control system and designed philosophy) can be seen as a success.

It can also be concluded that the new verification procedure for the load reduction project is accurate and reliable. The procedure may differ for each LM project, but can be determined through enough collaboration with all parties.

With this calculation method, the actual results were concluded to be on target, and with even better LM as predicted. The outcome of this implementation proved that the new control system is adequate to provide an improved LM of a cooling system within the given constraints.

This verification of results therefore proves that a sustainable foundation is created for the LM in cooling systems across the country. It can therefore be perceived as an asset for Eskom as well as the mining industry.

6. CLOSURE



This chapter gives an overview of the thesis, and discuss any given recommendations if needed.

6.1. CONCLUSION

Load management in different sectors of South Africa is becoming a higher priority by the day. It is important to first develop a LM simulation model and then an optimised model for specific fields. All the different sections of the main energy consumers in South Africa can then use the optimised models to contribute to the solution of the current energy demand growth problem.

In this research study, a control system was developed with additional controllers and software for a specific field that is identified in the mining industry. This field – refrigeration plants – is one of the larger energy consumers and electricity expenses of mines in South Africa. It is therefore concluded that a proposed optimised control system, containing the relevant software, will be beneficial for the mine as well as the energy provider – Eskom.

Two new area-constraint controllers, in the control system, were then developed according to the specification based on thorough investigation of the refrigeration plant procedures and mine cooling operations.

These controllers can monitor all the necessary constraints of the mine, and use the related equipment to generate an optimised load profile. Each controller is running in concurrence with one another to prevent any contradictions during the rescheduling procedures. These controllers are now known as the fridge plant "shut down" controller and the fridge plant "cut back" controller.

The second objective was to test, optimise and implement this control system on the cooling system of the mine. The whole process can only be successful after making the dependent cooling systems compatible with the new control system implemented. This can only be done by on-site testing and by developing a sufficient control philosophy.

An accurate verification procedure for a specific field is needed for the results of the new control system. This verification study was conducted to ensure that all the resulting effects of the implemented program are taken into account. The verification procedure however, determined that the predicted outcome of savings (load shift and cost savings) of the new control system over performed. Therefore, the new control system is a successful and accurate design for a refrigeration system on a mine.

6.2. CONTRIBUTION OF RESULTS

The DSM program and control system of the refrigeration system will result in promoting less greenhouse emission and environmental stress. A contribution has also been made by this project to create a more effective management of valuable energy consumption.

The specifications of the control system were written to be compatible for most surface refrigeration systems, and will only need a few modifications if required by the system setup. The worst-case scenario that can occur will be to develop an add-on if any additional monitoring of constraints is necessary. Consequently, most refrigeration plants can benefit by these developments and increase the development of LM programs.

6.3. RECOMMENDATIONS FOR FURTHER WORK

During the case study and research, it was found that a bigger DSM potential at Kopanang's surface cooling system could be achieved by utilising ice tanks for additional thermal capacity. Additional cold storage capacity will increase DSM potential by shutting down more or even all refrigeration plants during the peak periods.

The cooling systems of mines can differ by enormous factors. The newly developed controller cannot compensate for all kinds of cooling setups. The groundwork is set and can still be used in all refrigeration systems, but add-ons must then be generated for the additional modifications that must be made outside of the original specifications. Further research on developing a universal controller that will result the same LM load profile or even better, is suggested.

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8. APPENDICES

Appendix A: Hardware specifications for automation

ITEM		QTY	DESCRIPTION
			HVAC Fridge Plant (Per Plant)
A		4	PLC - Main
	A1	1	Simatic S7-300, load power supplies 307, 120/230V ac, 24V dc, 5A Part no.: 6ES73071EA000AA0
	A2	1	Simatic Net, CP 343-1 communications Processor for connection of Simatic S7-300 w.ind Ethernet using ISO, TCP/Ip and udp, S7, comm., fetch/write. Part no.: 6GK73431EX110XE0
	A3	1	Simatic S7-300, CPU 315-2DPCPU with MPI interface integrated 24V dc power Supply 128Kbyte working memory , Interface DP-master/slave Part no.: 6ES73152AG100AB0
	A4	1	Simatic S7, Micro memory card, S7-300/C7/ET 200S IM151 CPU, 3.3V Nflash, 128Kbytes Part no.: 6ES79538LG110AA0
	A5	2	Simatic S7-300 rail = 530mm Part no.: 6ES73901AF300AA0
	A6	3	Simatic S7-300, Digital input sm 321, Optically isolated 32DI, 24V dc (1 x 32DI), 40 Pin Part no.: 6ES73211BL000A00
	A7	1	Simatic S7-300, Digital output SM 322, Optically isolated, 32DO, 24V dc, 0.5A, 40 Pin, sum of output, currents 8A Part no.: 6ES73221BL000AA0

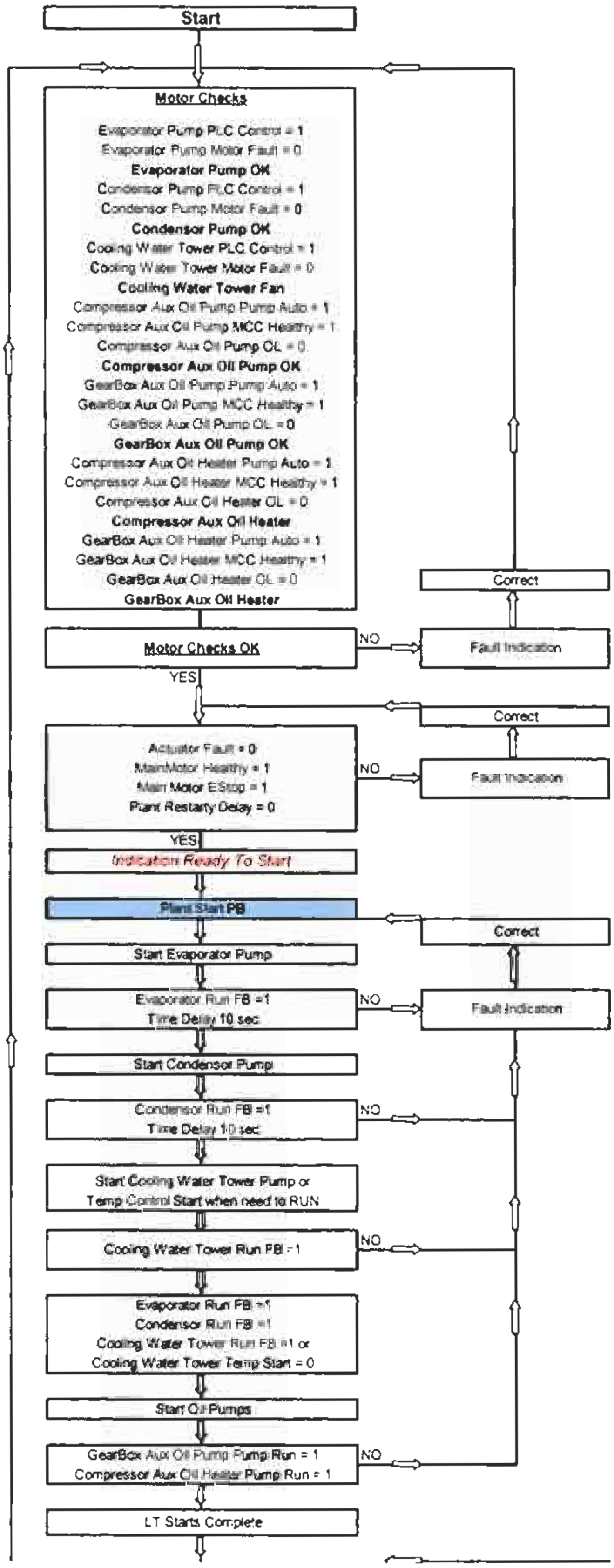
ITEM	QTY	DESCRIPTION
A8	6	Simatic S7-300, Analog input SM 331, Optically isolated, U/I/Thermocouple/ Resistance interrupt, diagnostics Resolution 9/12/14 bits, 8AI Part no.: 6ES73317KF020AB0
A9	7	Simatic S7-300, front connector for signal Module switch with screw contacts, 20 pin Part no.: 6ES73921AJ000A00
A10	4	Simatic S7-300, front connector 392 with Screw contacts, 40-pin40-polig Part no.: 6ES73921AM000AA0
A11	1	Simatic IM360 Part no.: 6ES73603AA010AA0
A12	1	Simatic IM361 Part no.: 6ES73613CA010AA0
A13	1	Simatic S7-300 Analog output 4AO 20 pin Part no.: 6ES73325HD010AB0
A14	1	Simatic 1m connecting cable Part no.: 6ES3683BB010AA0
		Total for x 4 PLC's
		HMI:
A15	1	Simatic multipanel MP37012" color TFT Display, touch/windows CE3.0 configurable With pro tool from Version V5.2+SP3 Part no.: 6AV65450DA100AXO

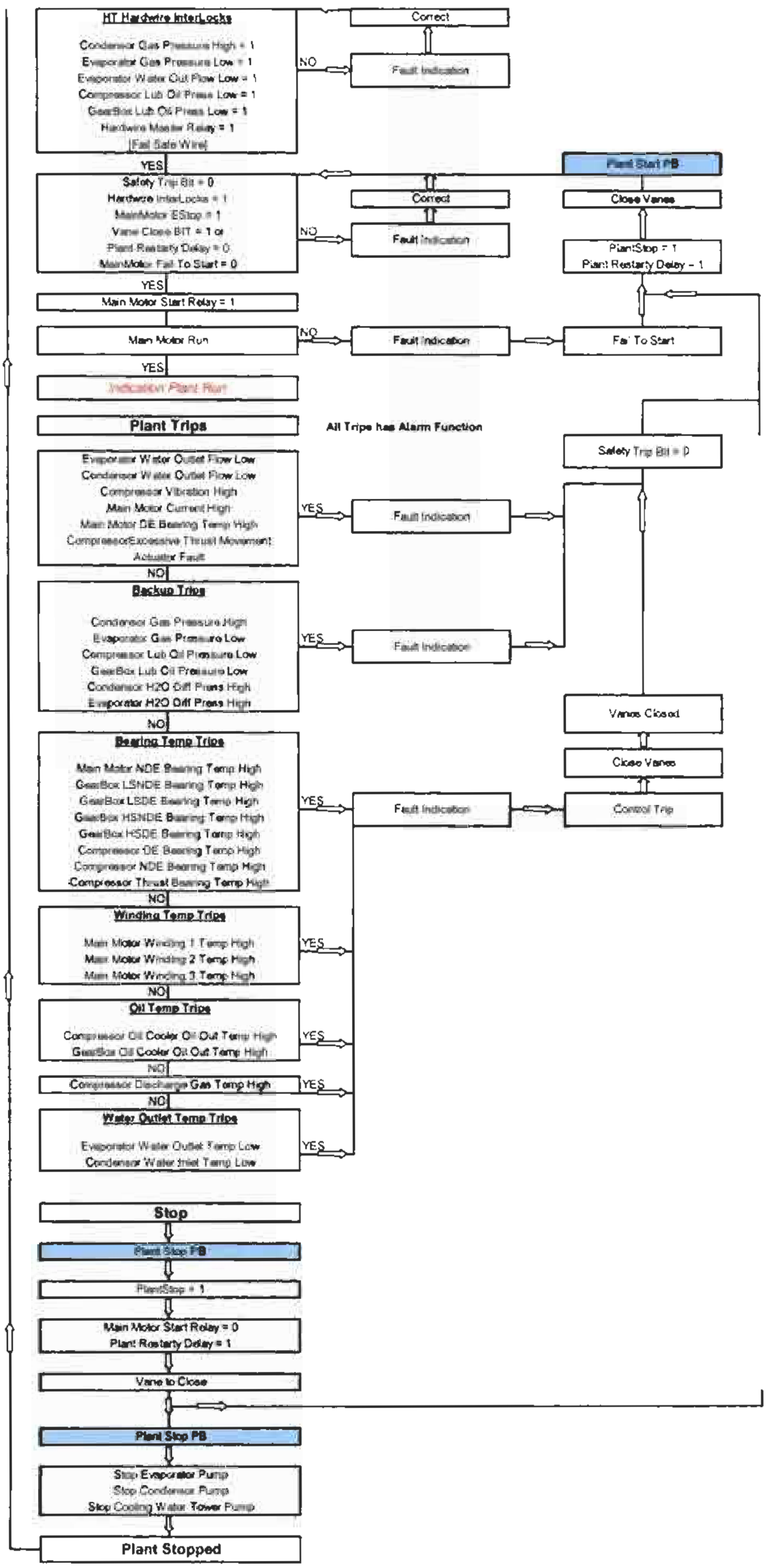
ITEM		QTY	DESCRIPTION
	A16	1	Hirschmann Industrial Line Switch 2 Port 10/100 Base-TX, RJ45 connection, 2 Port 100Base-FX Multimode 2 x 24V dc Power input. SC Connections, support hipering, RSTP,RMON, Port security, port mirroring, auto negotiation, Auto polarity, auto crossing, VLAN's prioritisation, Fault control relay Part no.: RS2-4R 2MM SC
			Total for 4:
			HVAC Fridge Plant (Per Plant)
B		**6**	**PLC - Panel**
	B1	1	Panel complete with 100mm plinth, power supply, circuit breakers, relays, Terminals, sirens, start and stop buttons, Panel lights, trunking, earth terminals, slotted DIN rail, end stops, panel drawings etc.
			Total for 6:
			HVAC Fridge Plant (Per Plant)
C		**6**	**Field Instruments and cable**
	C1	300	Metres 8 fibre 50/125 6 element 2LT (PBT) 2.20mmm GRP Gel filled aramid PE Heavy duty duct (HDD)
	C2	1	3M Splice boxes, trunking, pigtails, entry Glands, midcouplers etc
	C3	300	1 Pair 1.0mm PCW PE Instrument AL/Mylar PVC SWA LSZH cable
	C4	200	2 Pair 1.0mm PCW PE Instrument I/OA Mylar PVC SWA LSZH cable

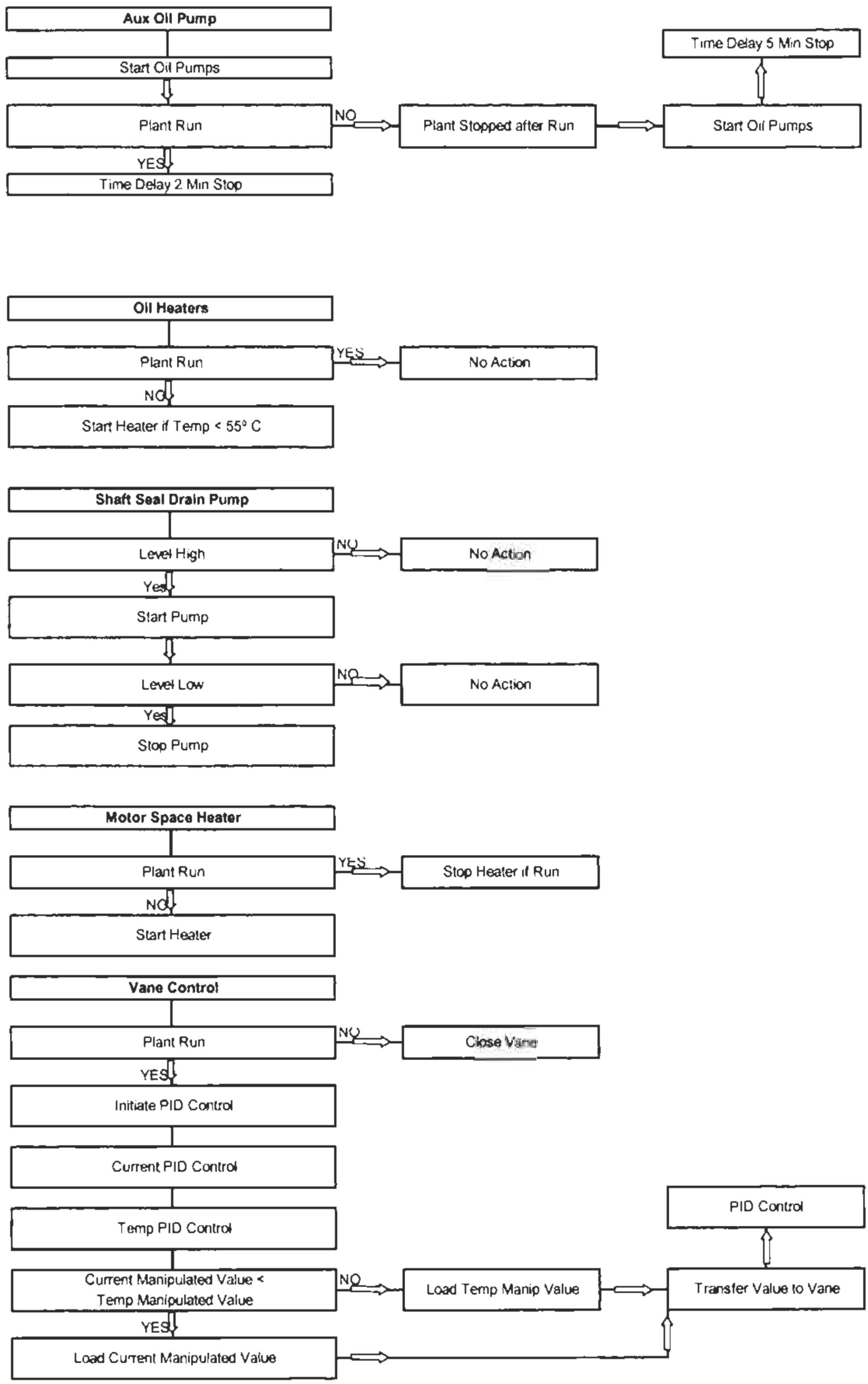
ITEM	QTY	DESCRIPTION
C5	500	8 Pair 1.5mm PCW PE Instrument I/OA /Mylar PVC SWA LSZH cable
C6	1	Flow condensor – PROMAG 10W DN 500 20" Electromagnetic flowmeter Part no.: 10W5H-UD0A1AA0A4AA
C7	1	Flow evaporator – PROMAG 10W DN 400 16" Electromagnetic flowmeter Part no.: 10W4H-UD0A1AA0A4AA
C8	2	Delta bar S PMD235 (DP) c/w Oliver 5 way Manifold Part no.: PMD235-LU4P2EH3C
C9	4	Cerabar M PMP41 Part no.: PMP41-GE13S2J11MA
C10	1	Auma Multi-turn actuator Part no.: SA07.5-B3-22RPM
		Total for 6:
D		**HVAC Fridge Plant**
		Installation and Commissioning:
D1	6	PLC Engineering
D2	6	HMI Engineering
D3	6	Scada Engineering
D4	6	Panel drawings

ITEM		QTY	DESCRIPTION
	D5	6	Field Drawings
	D6	6	PLC Panel installation
	D7	6	Installation and modification of field Instruments
	D8	6	Cabling and wiring of field instruments to Junction boxes and PLC Panel
	D9	6	Cabling and wiring of Remote I/O Base to MCC Panels
	D10	6	Commissioning of Plant
			Total for 6 Plants:
E		1	**Site establishment and de-establishment**
			Includes security screening, induction, Medical entry and exit clearance

Appendix B: Automated start-up sequence per fridge plant




HT Hardwire InterLocks
Condensor Gas Pressure High = 1
Evaporator Gas Pressure Low = 1
Evaporator Water Out Flow Low = 1
Compressor Lub Oil Press Low = 1
GearBox Lub Oil Press Low = 1
Hardwire Master Relay = 1
(Fail Safe Wire)
Correct
Fault Indication
NO
YES
Plant Start PB
Safety Trip Bit = 0
Hardware InterLocks = 1
MainMotor EStop = 1
Vane Close BIT = 1 or
Plant Restarty Delay = 0
MainMotor Fail To Start = 0
Correct
Fault Indication
Close Vanes
PlantStop = 1
Plant Restarty Delay = 1
Main Motor Start Relay = 1
Main Motor Run
Fault Indication
Fail To Start
Indication Plant Run
Plant Trips
All Trips has Alarm Function
Safety Trip Bit = 0
Evaporator Water Outlet Flow Low
Condensor Water Outlet Flow Low
Compressor Vibration High
Main Motor Current High
Main Motor DE Bearing Temp High
CompressorExcessive Thrust Movement
Actuator Fault
Fault Indication
Backup Trips
Condensor Gas Pressure High
Evaporator Gas Pressure Low
Compressor Lub Oil Pressure Low
GearBox Lub Oil Pressure Low
Condensor H2O Diff Press High
Evaporator H2O Diff Press High
Fault Indication
Vanes Closed
Close Vanes
Bearing Temp Trips
Main Motor NDE Bearing Temp High
GearBox LSNDE Bearing Temp High
GearBox LSDE Bearing Temp High
GearBox HSNDE Bearing Temp High
GearBox HSDE Bearing Temp High
Compressor DE Bearing Temp High
Compressor NDE Bearing Temp High
Compressor Thrust Bearing Temp High
Fault Indication
Control Trip
Winding Temp Trips
Main Motor Winding 1 Temp High
Main Motor Winding 2 Temp High
Main Motor Winding 3 Temp High
Oil Temp Trips
Compressor Oil Cooler Oil Out Temp High
GearBox Oil Cooler Oil Out Temp High
Compressor Discharge Gas Temp High
Water Outlet Temp Trips
Evaporator Water Outlet Temp Low
Condensor Water Inlet Temp Low
Stop
Plant Stop PB
PlantStop = 1
Main Motor Start Relay = 0
Plant Restarty Delay = 1
Vane to Close
Plant Stop PB
Stop Evaporator Pump
Stop Condensor Pump
Stop Cooling Water Tower Pump
Plant Stopped


Aux Oil Pump
Start Oil Pumps
Plant Run
NO
Plant Stopped after Run
Start Oil Pumps
Time Delay 5 Min Stop
YES
Time Delay 2 Min Stop
Oil Heaters
Plant Run
YES
No Action
NO
Start Heater if Temp < 55° C
Shaft Seal Drain Pump
Level High
NO
No Action
Yes
Start Pump
Level Low
NO
No Action
Yes
Stop Pump
Motor Space Heater
Plant Run
YES
Stop Heater if Run
NO
Start Heater
Vane Control
Plant Run
NO
Close Vane
YES
Initiate PID Control
Current PID Control
Temp PID Control
Current Manipulated Value < Temp Manipulated Value
NO
Load Temp Manip Value
Transfer Value to Vane
PID Control
YES
Load Current Manipulated Value