Investigating the effects of different DSM strategies on a compressed air ring

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Abstract

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A large growth in the South African electrical power demand has created a situation where the primary electricity supplier, Eskom, is in dire need of generating additional electricity during peak demand times.

The current electricity supply shortfall could mainly be due to a lack of planning from the suppliers' side, as well as an increase in residential and industrial development. Projections show that from as early as 2007, Eskom's current power generating ability would be insufficient for the country's peak electricity demand.

Eskom launched a programme called Demand Side Management (DSM). This programme endorses a more electrical efficient society and also focuses on lowering South Africa's peak electricity demand.

This programme has opened up many opportunities for companies, called Energy Service Companies or ESCOs, and individuals to help in this regard and also join in on a rewarding business opportunity.

To be able to reduce electricity demand, these companies, ESCOs, have different strategies. Some focus on buildings, usually heating, ventilation and air-conditioning, and other on heavy industries. By shifting or reducing electricity loads out of the peak electricity use period of a day, the peak load can be lowered. This reduces the risk of Eskom applying load-shedding as a last resort.

Although many opportunities arise, the main focus in this thesis will be on the possible electrical load reduction on gold mines through implementing Demand Side Management (DSM) on their compressed air rings.

Most gold mines are making use of compressed air for various applications. These include drilling, agitation, loading boxes, loading and many more. By studying the behaviour of a compressed air system on a gold mine, in particular a compressed air ring, large power saving opportunities occurs.

Compressors are large electricity consumers and operate throughout the day. Because of the critical role that compressors play in a mine's production, correct management of these systems are of utmost importance. One must make sure that any proposed optimisation will not contribute to any loss of production at the mine.

Samevatting

Titel: Investigating the effects of different DSM strategies on a compressed air ring
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Graad: Magister Engineriae (Meganies)

Suid-Afrika se primêre elektrisiteitsverskaffer, Eskom, sukkel tans om voldoende elektrisiteit te voorsien aan gebruikers veral gedurende aandpiektye (18:00 – 20:00). Die huidige tekort aan elektrisiteit kan moontlik toegeskryf word aan onvoldoende beplanning deur die land se elektrisiteits verskaffers, sowel as die moontlike toename in ontwikkeling in die residensiële en industriële sektore. Navorsing dui aan dat Eskom se elektriese voorsieningsvermoë gedurende 2007 oorskry sal word deur die elektriese aanvraag gedurende die Eskom aandpiektye.

Eskom het daarom 'n veldtog geloots genaamd “Demand Side Management” (DSM). Hierdie program moedig die verbruikers aan om meer energie konserwatief te wees, asook om Suid-Afrika se energieverbruik te verminder gedurende piektye. Eskom-DSM skep geleenthede deur projekte te finansier vir maatskappye (bekend as Energy Service Companies of ESCO's) wat elektrisiteitsverbruik aan die verbuiker se kant verminder of manipuleer.

Hierdie besighede (ESCO's) maak gebruik van verskillende tegnieke om elektriese energie te bespaar. Sommiges plaas hul fokus op geboue (meestal verhitting, ventilasie en lugverkoeling) en ander op groot industrieë. Deur elektrisiteitsverbruik te verlaag, of te verskuif uit die Eskom aandpiektye, word die totale kragverbruik gedurende die aandpiektyd verlaag. Dit verlaag die risiko vir toepassing van beurtkrag (load shedding) deur Eskom.

Alhoewel daar baie geleenthede ontstaan vir elektriese kragbesparings, sal die hoof fokus in hierdie skripsie handel oor die moontike elektriese las vermindering op goud- en platinummyne deur DSM op hulle saamgepersde lugkringe toe te pas.

Meeste goudmyne maak gebruik van saamgepersde lug om verskeie toerusting mee te dryf. Dit sluit in boormasjiene, laai-bakke, laaiers en vele ander. Deur die gedrag van `n saamgepersde lugkring op `n goudmyn te bestudeer, in spesifiek op `n ring, kan gemerk word dat daar baie potensiaal bestaan vir energie besparings.

Kompressors is groot kragverbruikers en is gewoonlik operasioneel oor `n volle 24 uur profiel. As gevolg van die kritieke rol wat saamgepersde lug in die myn se produksie speel, is die korrekte bestuur van die kompressors baie belangrik. Enige ge-optimiseerde model wat gebruik mag word, mag geensins die myn se produksie beïnvloed nie.

Deur `n oppervlak saamgepersde lug simulasie-model te skryf en dit te gebruik in die voorspelling en analisering van verskeie beheerstrategieë, kan `n ge-optimiseerde beheerstrategie vasgestel en ontwikkel word. In hierdie verhandeling is so `n proses gevolg en ook bevestig deur toetse wat gedoen is.

Die lang- en korttermyn effekte op Eskom en die lugkring gebruiker, van die ge-optimiseerde beheerfilosofie word ook uitgelig in die verhandeling. Groot elektriese en finansiële besparings kan verkry word, deur die voorgestelde beheerfilosofie te implementeer. Deur van die voorgestelde stelsel op verskeie myne gebruik te maak, kan Suid-Afrikaners as `n geheel daarby baat, omdat elektriese kragonderbrekings en ander soortgelyke probleme verminder sal word.

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- Thank you to all whom have given their advice and knowledge, God bless you.

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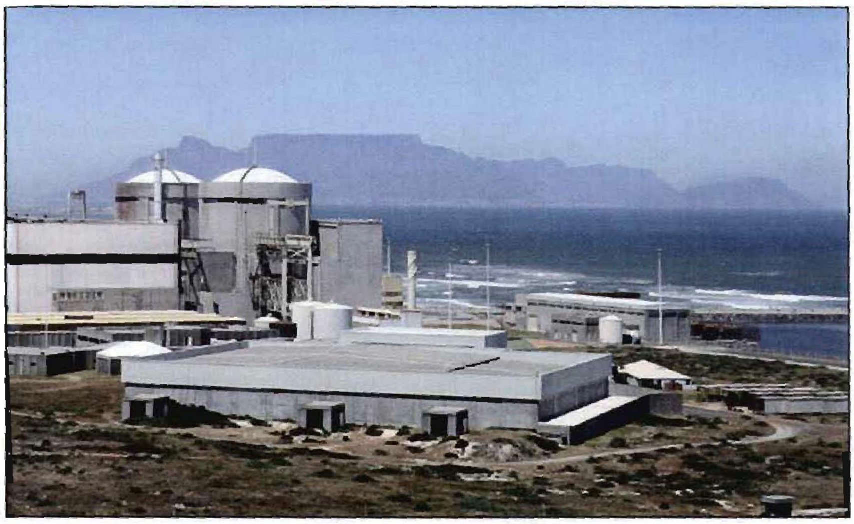
List of Abbreviations

Btu	:	British thermal units
bkWh	:	Billion kilowatt-hours
CDM	:	Clean Development Mechanism
CM	:	Compressor Manager
DSM	:	Demand Side Management
ESCO	:	Energy Service Company
EIA	:	Energy Information Administration
EC	:	Eastern Cape Province
FS	:	Free State Province
GJ	:	Gigajoule
GP	:	Gauteng Province
kPa	:	KiloPascal
KZN	:	Kwazulu-Natal Province
LP	:	Limpopo Province
MP	:	Mpumalanga Province
MW	:	Megawatt
NB	:	Nominal Bore
NC	:	Northern Cape Province
NW	:	North West Province
Pa	:	Pascal
REMS	:	Real-time Energy Management System
SA	:	South Africa
WC	:	Western Cape Province

CHAPTER 1: Introduction



A brief introduction to the electricity shortage in South Africa, as well as countermeasures taken by South Africa's primary electricty provider, Eskom, to provide enough electricity to South Africa.

1. Chapter 1: Introduction

1.1. Background on Electricity Demand in South Africa

World-wide Electricity Demand and South Africa

The energy field is a growing one mainly because of the world's rapidly growing electricity needs. Many countries are developing faster than originally anticipated by their governments and power suppliers. Economies are expanding, populations are growing and more households are receiving electricity [1]. In addition everyday new inventions see the light to simplify the human's daily lifestyle. These new discoveries also end up using more electricity [2]. Large growth in the industrial and private sectors leads to increasing electricity demands.

Studies show that more efficient use of traditional energy resources is vital as the worldwide energy demand is increasing [3]. The total worldwide energy demand has increased from 207 quadrillion British thermal units (Btu) to 412 quadrillion Btu between 1970 and 2002 [4]. This realises an increase of 50% in energy demand in just 32 years. It is projected that it will only take 20 years for the world energy consumption to increase by a further 50% [4].

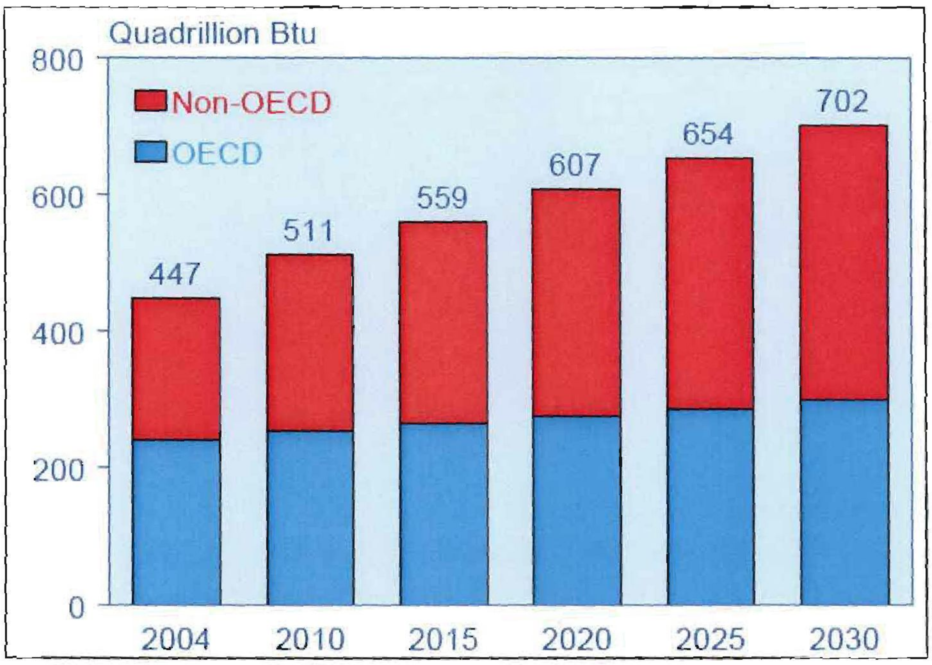
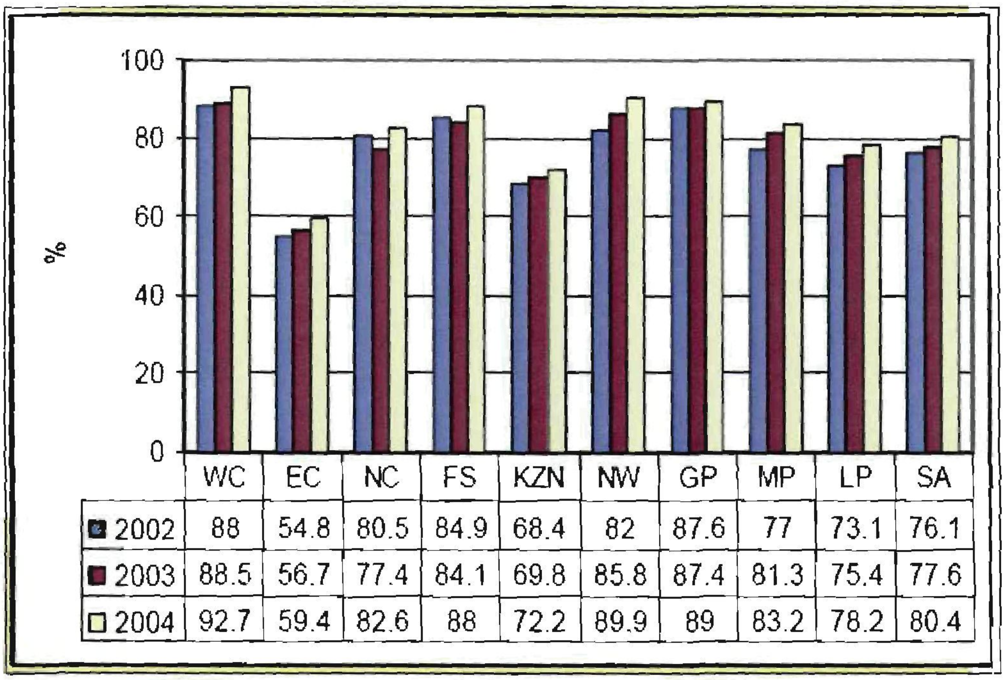


Figure 1-1 EIA's (Energy Information Administration) world markets' historical and projected energy consumption [4]

Currently the South African electricity consumer demand is nearly equivalent to the maximum available electricity supply. It is important to maintain a proper reserve margin to ensure the stability of a national electricity grid. New power plants are currently being built and new technologies being developed to increase electricity supply. This increased electricity supply might not be operational in time or generating enough additional electricity to prevent the consumer demand from exceeding the available electricity supply [5]. A further problem might be that additional electrical supply is likely to stimulate further growth in the demand.

In order to prevent South Africa and its neighbouring countries from having an electricity supply shortfall, strategies to reduce the current consumer demand, reducing the growth in further electricity demand and manipulation of the daily electricity demand profile should be considered [2]. This study will focus more on the manipulation of the electricity demand profile of compressed air systems in the mining industry. Although the impact of DSM studies such as this study is small, it does help to alleviate the current electricity supply challenge.



	WC	EC	NC	FS	KZN	NW	GP	MP	LP	SA
■ 2002	88	54.8	80.5	84.9	68.4	82	87.6	77	73.1	76.1
■ 2003	88.5	56.7	77.4	84.1	69.8	85.8	87.4	81.3	75.4	77.6
□ 2004	92.7	59.4	82.6	88	72.2	89.9	89	83.2	78.2	80.4

Figure 1-2 Percentage of households connected to the main electric supply in South Africa [1]

Figure 1-2 shows that:

- Nationally there has been an increase in households connected to the main electricity supply, with about 76.1% of households connected in 2002, 77.6% in 2003 and 80.4% in 2004.
- Western Cape Province had the highest percentage of households connected to the main electricity supply in all three years, with 88% connected in 2002, 88.5% connected in 2003 and 92.7% connected in 2004.
- Eastern Cape Province was the province least connected to electricity supply in all three years, with 54.8% connected in 2002, 56.7% connected in 2003 and 59.4% connected in 2004.
- Limpopo Province had 73.1% of households connected to the main electricity supply in 2002, with 75.4% connected in 2003 and 78.2% connected in 2004.

Electrical energy is important to the economic and social development of a country [6]. South Africa has always also been seen as a developing nation throughout the world and the South African electricity sector has always been at the centre of the country's development [7]. South Africa's economy is very electricity intensive [8]. New mining and housing developments, increases in mining production, as well as the upgrade of existing mines and houses can all contribute to a possible electricity shortage in South Africa.

As of January 1, 2003, Southern Africa's total installed electric generating capacity was 52,272 MW. The largest electricity generator by far was South Africa, with 215.9 GWh, followed by Mozambique with 15.1 GWh, Zimbabwe with 8.9 GWh, and Zambia with 8.4 GWh. In 2003, total regional electricity consumption was 244.4 GWh, led by South Africa (197.4 GWh), Zimbabwe (11.6 GWh), Mozambique (10.5 GWh) and Zambia (5.8 GWh) [9]. South Africa is also an exporter of electricity to its neighbouring countries.

According to Eskom's Annual report – for the year April 2006 to March 2007 – the total electricity sold by Eskom was 218 120 GWh (Gigawatt hour). The sale of electricity to other countries, which include Botswana, Mozambique, Namibia, Zimbabwe, Lesotho, Swaziland and Zambia, amounted to 13 589 GWh. This means that around 6% of Eskom's total electricity sales were to other countries in Southern Africa. [10]

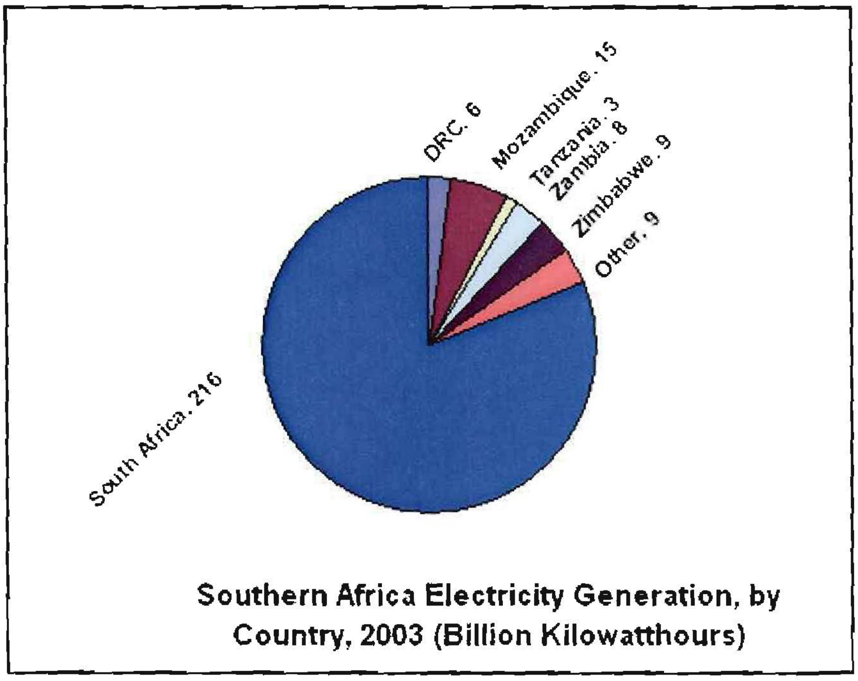


Figure 1-3 Southern Africa electricity generation, by country, 2003 [9]

The main primary energy used in the generation of electricity in South Africa is coal [11] Illustrated as a percentage in Figure 1-4 [12], in 2000 coal contributed 79% of the total energy used. Based on this fact, the assumption can be made that electricity and the generation thereof contribute more than half of the total energy consumed in South Africa [12].

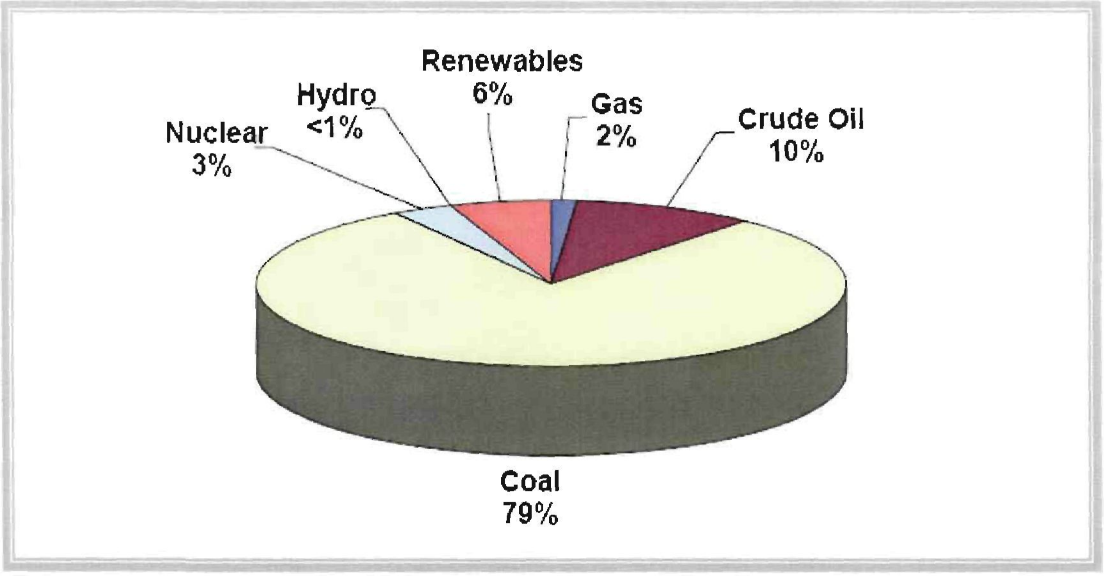


Figure 1-4 Energy sources used in electricity generation [11]

South Africa is a developing nation with significant heavy industry, which by nature is energy intensive. This energy intensive economy largely relies on indigenous coal reserves for its driving force. At first sight there would appear to be an apparent paradox between using less energy and developing a healthy and prosperous nation based on energy intensive activities. This is not the case. In recent years energy efficiency has significantly gained in stature and has become recognised as one of the most cost-effective ways of meeting the demands of sustainable development [12]. Every rand of value added to the economy by development, consuming larger amounts of energy [13].

In 2005, South Africa Info [14] released figures regarding the annual economic growth. It showed an average economic growth rate of 3.5% from September 1999 to June 2005. "Despite recent strikes, higher interest rates and inflation figures, the Bureau for Economic Research has come out with an upbeat forecast of 5% Gross Domestic Product (GDP) growth for South Africa's economy in 2007, supported by strong fixed investment, continued employment growth and consumers' ability to cope with "a more challenging macroeconomic environment"" [15]. The South African economy is therefore growing.

An example of a typical South African average daily load profile can be seen in the following figure. It is noticeable that the peak energy demand is between 18:00 and 20:00. This is illustrated in Figure 1-5 [16].

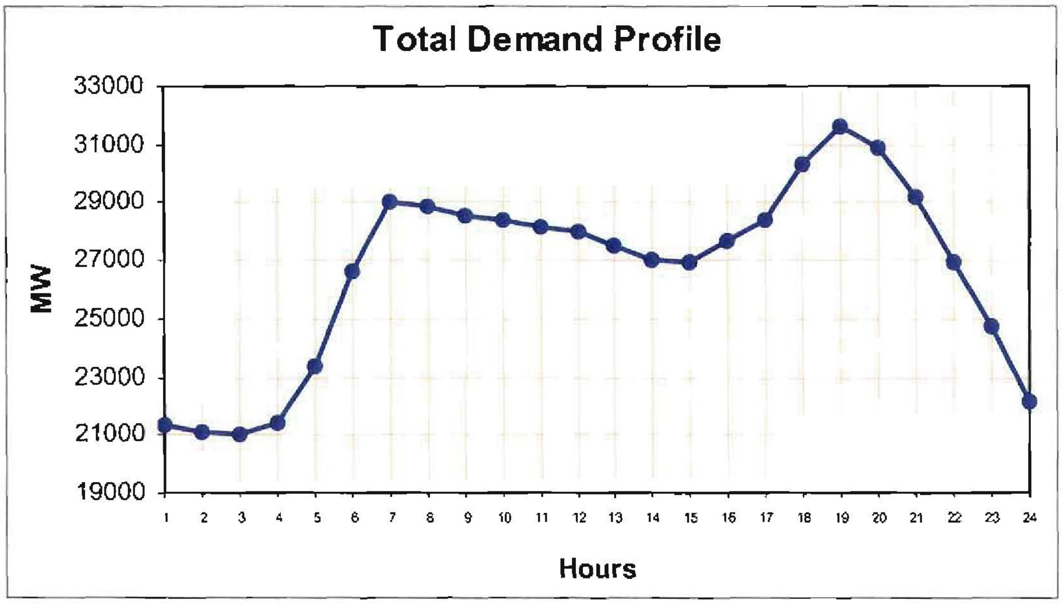


Figure 1-5 Example of a total demand daily profile [15]

Early predictions stated that Eskom, the local electricity supplier in South Africa, which produces 60% of the electricity in Africa [17], would not be able to provide electricity for its country's demand, see Figure 1-6. The figure also shows the maximum demand of the country in. Even though Eskom lifted their peak-time tariffs considerably, the demand is still growing and other strategies of saving power have been implemented by Eskom.

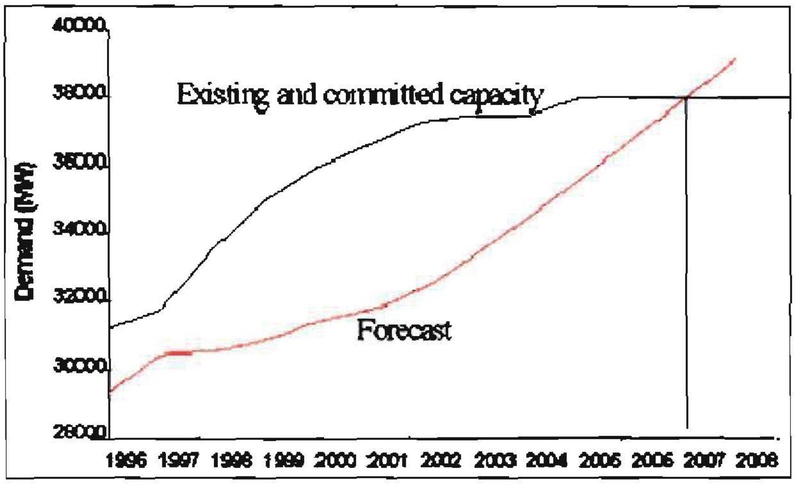


Figure 1-6 Eskom Capacity Status and Maximum Demand Forecast made in 2000 [21]

On several occasions in 2007, Eskom was forced to exercise a strategy called load shedding. This prevents the electricity reserve margin from reaching critical low levels and therefore endangering network stability. Load shedding is defined as the removal of pre-selected customer demand from a power system, as a result of the occurrence of an abnormal condition, in an effort to maintain the integrity of the system and minimise overall customer outages [18].

A physical description of load shedding is as follows: "*A strategy that consists of a given sequence of feeder disconnections, minimising total load curtailment while taking into account load dynamic characteristics*" [19]. Eskom spokesperson Fani Zulu said after load shedding took place: "*There would be enough electricity to meet the national demand if consumers used electricity sparingly.*"[20].

From the above stated facts it is safe to conclude that South Africa's energy, and with more focus, its electricity demand is rapidly increasing [22]. Speaking at a seminar on the world energy situation, presented in Johannesburg in January 2004, Eskom General Manager Strategist Andrew Etzinger said that the South African electricity demand is expected to grow by 1,200 MW per year due to the expected economic growth over the next 20 years [23].

1.2. ESKOM Solutions to Energy Supply Problem

1.2.1 Introduction

As further increases in demand are expected in the future, the load profile will also show an increase in demand during morning and evening peak electrical demand times. If the base load also continues to increase, as it has done over the past few years, it will become more difficult to counteract the increased electricity demand during peak demand periods as this makes load shifting strategies less viable[24] [25].

One way of addressing the increased demand experienced during peak times would be to build additional power stations. These stations typically require low capital investment, but demand high running costs, e.g. pumped water storage, systems and gas turbines. It is estimated that a gas turbine's operation costs is R1.60/kW, compared to Eskom's average of below 16c/kW [26]. The drawback to this idea is that the additional power stations would only be required during peak times, and will thus be idle for the rest of the time. Consumers would then have to bear the investment costs [27].

Further expansions in generation capacity will also place additional strains on the transmission and distribution network [28]. It is estimated that R107 billion would be required between 2005 and 2009 to solve the electricity problem and meet the country's growing electricity needs [29].

The then Minister of Mineral and Energy (DME), Dr. P.N. Maduna, set forth a new vision for energy in his budget speech on 21 May 1997. He identified opportunities to restructure and consolidate the State's assets in the industry. During the same period, maximum value would be gained from them. This contributed amongst other issues to the development of the White Paper on Energy Policy [30] [31].

In 1998, the White Paper on Energy Policy was published. The white paper had mainly five objectives [32]. These are:

- Increasing access to affordable energy services
- Improving energy governance
- Stimulating economic development
- Managing energy-related environmental impacts
- Securing supply through diversity

These objectives might lead to a further increase in consumer demand. Increased access to affordable electricity will also increase consumer electricity demand, especially in the residential sector. Economic growth will also result in increased electricity expenditure.

1.2.2 Corrective Measures Taken by Eskom

Costing

One way to limit the use of electrical energy is to alter the pricing structure applied to the various industries. Eskom introduced the time-of-use pricing structure tariffs. Eskom increased electricity cost during the high-peak periods and lowered the costs during the off-peak periods. The implementation of these structures encourages Eskom's clients to pay more attention to their power profiles. One of the main objectives of these time-of-use pricing structures is to reduce peak time electricity demand by motivating electricity use during the less expensive off-peak times [22].

Various tariff structures are provided by Eskom. Each is tailor-made according to the needs of the customer. The tariff structures are primarily grouped into three non-municipal classes, namely: urban-, residential- and rural tariffs [33]. The mining and industrial sectors are placed in the urban tariff structure.

Time-Of-Use (TOU) examples can be seen in the table below:

URBAN TARIFFS			
NightSave	**MegaFlex**	**MiniFlex**	**BusinessRate**
Electricity tariff for urban customers with an NMD from 25 kVA	TOU electricity tariff for urban customers with an NMD from 1 MVA that are able to shift load	TOU electricity tariff for urban customers with an NMD from 25 kVA up to 5 MVA	Electricity tariff for small businesses, governmental institutions or similar supplies in urban areas with an NMD up to 100 kVA

RESIDENTIAL TARIFFS			
HomePowerBulk	**HomePowerStandard**	**HomeLight**	
Electricity tariff for residential bulk supplies, typically sectional title developments and multiple housing units, in urban areas connected prior to 1 January 2004	Electricity tariff for medium-usage to high-usage residential customers, churches, schools,halls, old age homes or similar supplies in urban areas with an NMD up to 100 kVA	Electricity tariff for single-phase, low-usage residential supplies in urban areas, but can also be applied to churches, schools, halls or similar supplies with low usage residential customers in urban areas	

RURAL TARIFFS			
NightSave Rural	**RuraFlex**	**LandRate**	
Electricity tariff for high load factor rural customers with an NMD from 25 kVA with a supply voltage ≤ 22 kV (or 33 kV where designated by Eskom as rural)	TOU electricity tariff for rural customers with dual-phase and three-phase supplies with an NMD from 25 kVA with a supply voltage ≤ 22 kV (or 33 kV where designated by Eskom as rural)	Electricity tariff for rural customers with an NMD up to 100 kVA with a supply voltage of ≤ 500V	

Table 1-1 Different Eskom Tariffs

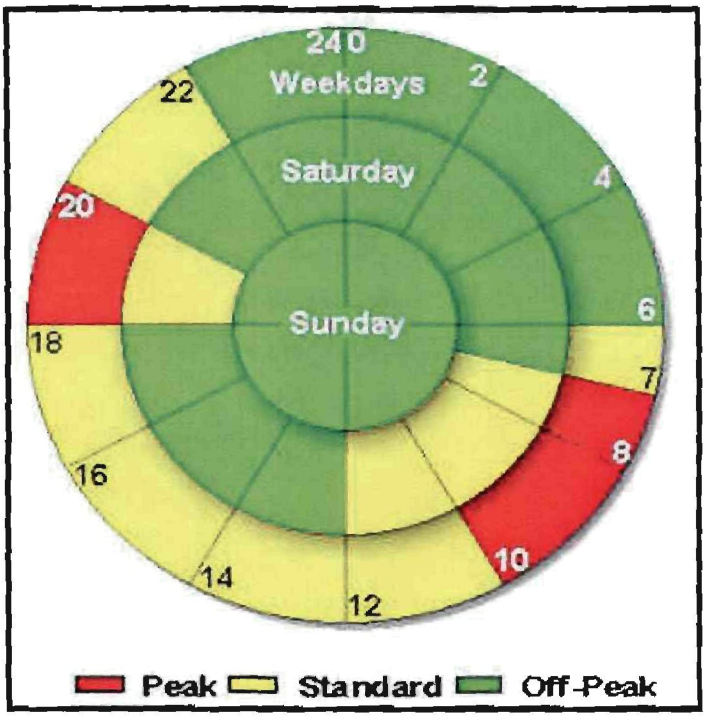
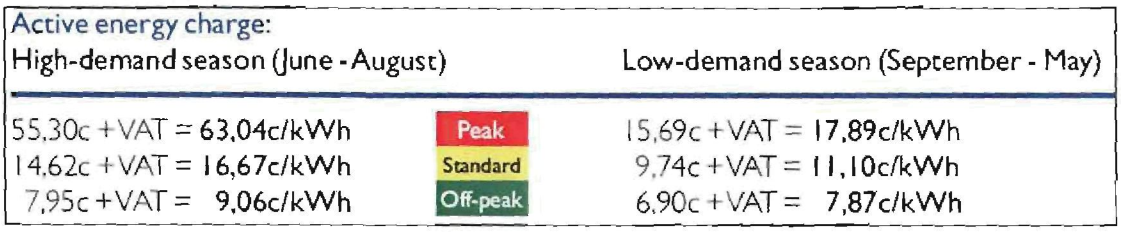


Figure 1-7 Megaflex – Variable pricing structures chart [33]



Active energy charge: High-demand season (June - August)		Low-demand season (September - May)
55,30c +VAT = 63,04c/kWh	Peak	15,69c +VAT = 17,89c/kWh
14,62c +VAT = 16,67c/kWh	Standard	9,74c +VAT = 11,10c/kWh
7,95c +VAT = 9,06c/kWh	Off-peak	6,90c +VAT = 7,87c/kWh

Figure 1-8 Tariffs for Megaflex [34]

The above figures illustrates Eskom's peak, standard and off-peak periods. There are effectively two peak periods, a morning peak period and an evening peak period. Pricing variations between peak and off-peak periods are large and is part of the Eskom initiative to create awareness with its clients to be sensitive of the daily electricity demand profile. Tariffs during the winter season, which runs from June to August, are also much higher than those of the summer season, which runs from September to May. The 2006/7 winter month's tariffs are up by 9.6% from 2005/6 the Megaflex tariffs.

Demand Side Management

To ensure a stable and reliable electricity market, a balance between the electricity supply and demand is a necessary factor [35]. Another one of the strategies mentioned earlier, is to minimise the peak energy demand by focussing on reducing the energy load in peak times, as well as creating a society which is more energy conscious and conserving throughout the day.

A strategy that complies with this theory is called Demand Side Management (DSM). Demand Side Management is a power saving initiative implemented by South Africa's primary energy provider, Eskom. DSM is defined as joint control of electricity supply and electricity demand. It also includes a broad range of tools for changing electricity load shape [21].

Objectives of this strategy include:

- Reducing price volatility/flattening spot prices
- Improving system security and reducing the risk of black-outs
- Reducing network congestion
- Delaying construction of additional generation, and/or grid and network upgrading
- Reducing greenhouse gas emissions, and
- Improving market efficiency by enhancing consumers' ability to respond to changing prices [21]

Demand side management interventions can generally be broken down into four broad subcategories. These are (1) strategic load growth; (2) load shifting; (3) interuptibility; and (4) Energy Efficiency interventions [35].

The first subcategory, namely strategic load growth, can be defined as increasing an energy demand profile uniformly to a higher average level. This intervention is normally utilised when there is an excess in electricity capacity [36].

The other alternatives can be utilised when a shortage of generating capacity occur. When the electric demand is moved from peak times to lesser demand periods, it can be described as load shifting. When uniformly reducing the demand curve, it is called energy efficiency [36].

Eskom's DSM programme is aimed at reducing the national peak-power demand, thereby postponing the immediate need for additional power generation capacity [37].

Rather than waiting on the construction of a new power station, Eskom is offering a business opportunity to Energy Service Companies (ESCOs), to assist in the attempt to save power. ESCOs are companies that develop, install and finance projects designed to improve the daily electrical load profile of a specific user. It is the ESCO's responsibility to make sure that the Eskom client reduces its electrical usage during the evening peak time [38].

Eskom developed a system where they are willing to fund DSM project implementations done by ESCOs who aid in the reduction of the electrical load during the Eskom morning and evening peak period, as well as the efficient use of electrical power during the rest of the day. By saving electrical power throughout the day, Eskom is building a virtual power station.

The mining industry is of importance to the local economy and is always trying to increase production. With growing production, growing electricity demands will also occur, as current electrical mining applications will be expanded. Figure 1-9 shows a typical hourly profile of a mine's pumping power usage. By using different strategies and optimisation procedures, an optimised profile as illustrated by the yellow line on Figure 1-9 can be achieved. Thus load is removed from the evening peak period.

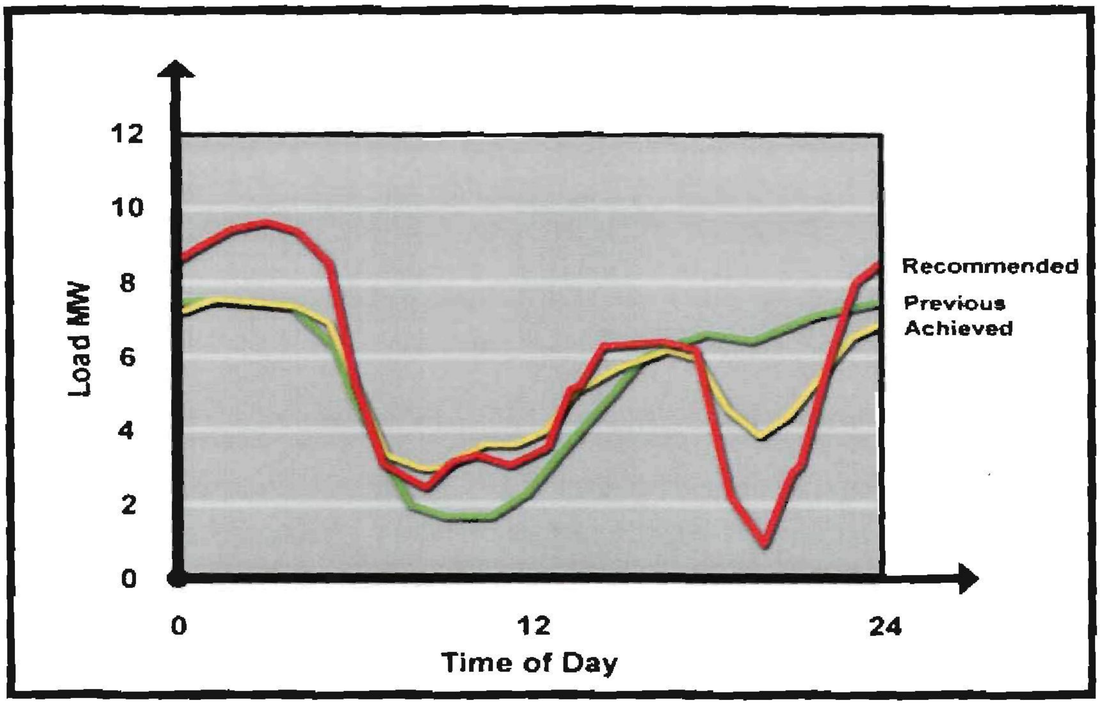


Figure 1-9 Daily electricity profile for a typical mine showing the proposed DSM intervention profile, achieved DSM profile and profile without DSM intervention (2003) [39]

DSM interventions can therefore be used to manipulate the daily electricity consumption profile, thereby reducing electricity costs. Both Eskom and the mines benefit from this exercise. Millions of rands have been saved through successfully implemented DSM programmes and many more will be saved by using such strategies.

A single example of the cost and electricity savings being realised through DSM, is the optimisation of the Clearwater Pumping System at AngloGold Ashanti's Kopanang goldmine.

DSM has achieved a sustainable load shift of 2.5 MW out of the evening peak time. In the process, the mine has saved close to R900 000 on their energy bill. The unrealised further potential load shift (and energy savings) will be addressed in the next version of REMS.

The technology is novel. Its application in the next five years could lead to a 300 MW load shift and more than R50 million / year savings in the deep mine sector [40].

Quite a few DSM projects have already been implemented in South African mines. Some of these projects make use of load shift, where electricity is shifted out of the daily peak times. As can be seen in the above example, clear water pumping systems use storage dams to store water to be used on different times of day, thus pumping during Eskom's off-peak periods, rather than in the peak periods [40].

Other DSM projects use load reduction, where load is reduced during daily peak times. Reduced load is not necessarily moved to other time periods. It may comprise strategies for more efficient use of electricity and the reduction of waste (e.g. reduction of leaks in a compressed air system). This principle can be used when energy can not be stored using other means. Compressed air can not effectively be stored as kinetic energy to be used later, due the fact that there is not much energy storage potential for compressed air. Thus, compressed air usage is reduced to a minimum during Eskom peak periods, resulting in the operation of fewer compressors during these periods and reducing the electric demand.

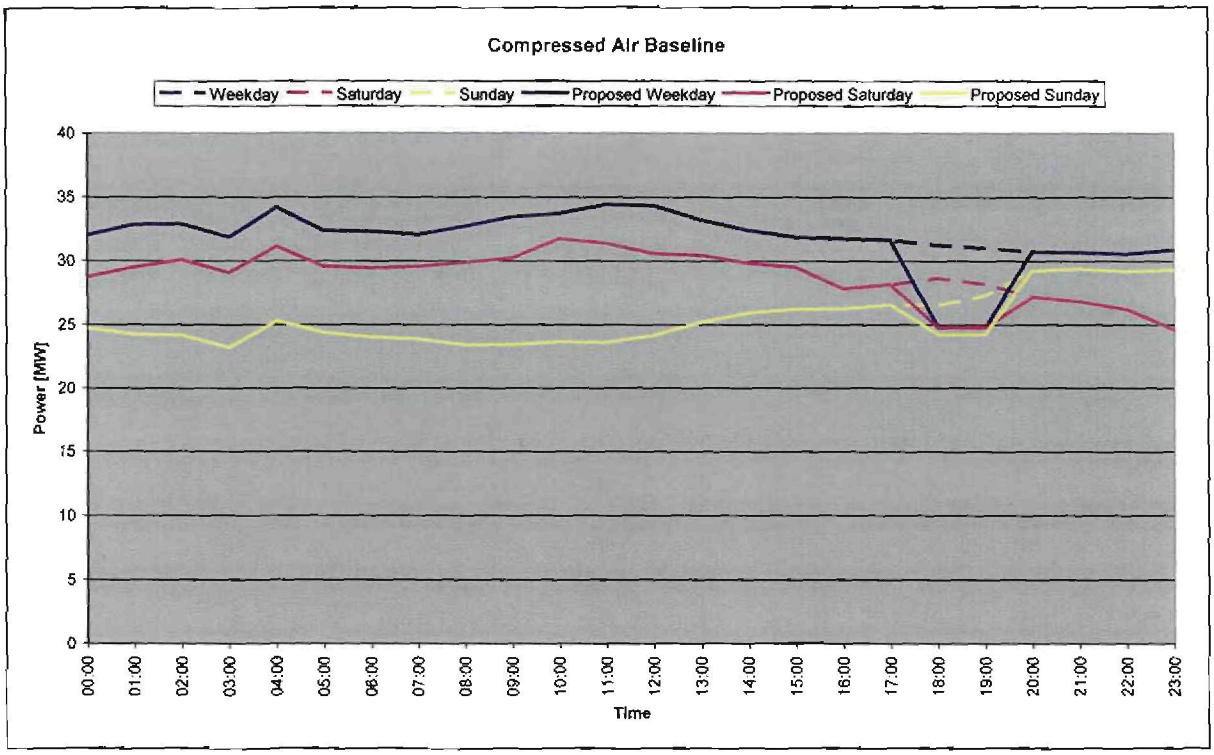


Figure 1-10 Case study of West Wits compressed air usage load profile

Figure 1-10 shows a load reduction baseline for compressed air at West Wits compressed air ring. It can be seen that a saving of 6.4 MW can be achieved during

Eskom's peak demand time. This also concludes to a electricity cost saving of close to a million rand per year.

Electricity baseline was constructed using historical data recorded on the mine and verified by North West University's Measurement and Verification (M&V) team. The cost saving is determined by first calculating the electricity cost associated with the baseline and then secondly calculating the electricity cost associated with the actual reduced electricity profile. The difference between these costs is the cost saving achieved through the load reduction intervention.

Eskom put more pressure on electricity consumers to reduce electricity consumption during both peak and off-peak times. On Friday 25 January 2008, Eskom instructed large mining companies to reduce electricity consumption to a minimum level, only allowing electricity for emergency applications. Surely this will motivate the mining industry to be more conscious towards using electricity more wisely.

1.3. Demand Side Management Applications in Mining Industry

Compressed Air in the Mining Industry

There is a considerable amount of mines in South Africa. Mining in South Africa consumes 17.6% of all electricity generated [41]. Compressed air is an essential component for mining applications used for production. Therefore, a substantial opportunity for load reduction exists in this field.

Compressors in the mining industry are large power users. Where compressed air rings are used, installed capacities of multiple times the size of single shafts exists. Good load-shedding possibilities exist when analysing these systems.

It should always be remembered that the compressors are an intricate part of the mine's production. When compressors are stopped, pressure will drop and an array of problems will start to occur. Loading boxes, which holds ore, may start to open and lose their loads if the compressed air pressure drops too low. Other problems, such as a lack of proper agitation, insufficient drilling, as well as insufficient box-hole ventilation, can all contribute to not only production losses, but also unnecessary breakdowns.

Compressed air rings have the advantage of a larger base load than those found at a single mine shaft. A large amount of air is always available, even if the air demand on one of the shafts surpasses its own installed capacity. If there is surplus air at one of the shafts, air can be distributed to other shafts on the same ring.

Although compressed air rings have the potential to shed large amounts of energy during peak times, they also pose their own difficulties. Because of the longer distances between the shafts, larger losses in pressure occur. The specific air needs of all the shafts on the ring are also of critical importance. Opportunities for wasting air and thus power, occur quite often.

Compressor blow-offs can be heard on many occasions throughout the day, which means that too many compressors are operating simultaneously. Blow-offs occur when the compressed air system pressure exceeds the maximum allowable pressure limit of a compressor. A safety valve then releases compressed air to reduce the internal system pressure. This prevents reverse-flow into the compressor, protecting the compressor from mechanical damage caused by surge. This is an indication that an unnecessary surplus of compressed air is being generated and frequently being released into the atmosphere. Electricity is therefore wasted. Controlling the air distribution to the individual shafts can also be a problem.

By switching off a number of compressors during peak energy demand times, a large energy load reduction can be achieved. This system can also be controlled effectively by using a proper air compressor management system. It implements the use of compressor guide vanes and guide vane controllers to effectively control the air supply to the system to meet the exact air demands of the shafts on the ring. By implementing a real-time energy management system in conjunction with the above, accurate control of the compressed air system can be done.

1.4. Research Objectives

The main objective of this study is to identify DSM opportunities on large compressed air rings, specifically in the South African mining industry. These opportunities will be investigated to determine their DSM potential. Thereafter an optimised above ground compressed air simulation model will be developed and verified using real-time testing data.

A case study will be used to predict, verify and optimise a generic compressed air model for the West Wits compressed air ring, which will reduce the electricity demand in peak demand times, as well as saving money for the consumer. The investigation and system implementation should be done in such a way that it does not interfere with the mine's operations and production.

1.5. Outline of this Document

A brief overview of each chapter is given below.

Chapter 1

This chapter focuses on the possibilities of a growing electricity demand, particularly in South Africa and the effects of it on the local power supply. The current effects of an electricity supply shortfall are also investigated and discussed. Background is given on possible countermeasures to prevent an electricity shortage in South Africa.

One of the countermeasures, dubbed Demand Side Management (DSM), is discussed in detail as well as the companies that form part of the initiative. A further look into the applications of DSM is also done, completed by a discussion on the research objectives of this particular study. The implementation of DSM on compressed air rings in the mining industry is also briefly explained and the outcomes of this study summarised.

Chapter 2

A chapter dedicated to identifying DSM potential at a mine's compressed air system, as well as discussing compressed air and it's uses in the mining industry. Background on various types of compressors, used in the mining industry, is also examined. Different compressed air setups and layouts are investigated and the effect thereof on DSM evaluated.

The focus area of DSM on compressed air rings is also discussed, as well as the importance of an above ground compressed air simulation to assist in the correct and safe predictions of changes in such a system. This chapter summarises DSM on a mine's compressed air system.

Chapter 3

Chapter 3 summarises the basic needs for an above ground compressed air simulation and discusses the development of such a program in detail. Explanations on each of the equations and formulas used are given and the details of the different variables in the simulation are tabled and clarified.

There is also a subsection that is dedicated to verify the results that are obtained from the simulation model. This verification process uses real-time test results from a case study done on a compressed air ring and serves as an accuracy measurement of the model.

Chapter 4

In this section, various control strategies of DSM on compressed air rings are investigated, as well as the possible effects thereof on the compressed air system's nature and establishment. An optimised control strategy will be designed and a verification study, consisting of tests conducted on part of the West Wits compressed air ring, will be illustrated.

Chapter 5

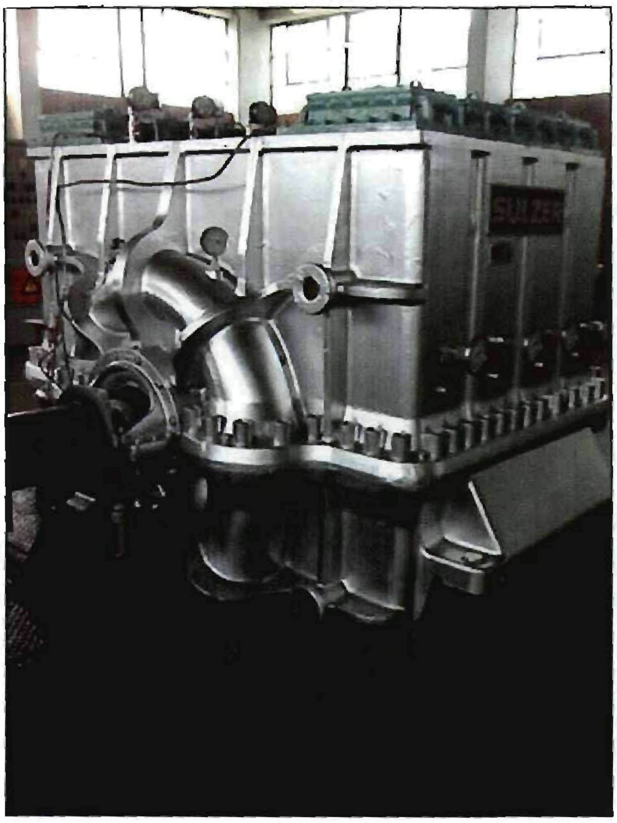
The case studies consist of various evaluated compressed air rings. Various tests were conducted and documented. The data regarding these tests as well as the effects of these tests on the compressed air system and the compressed air equipment are discussed in detail in this report.

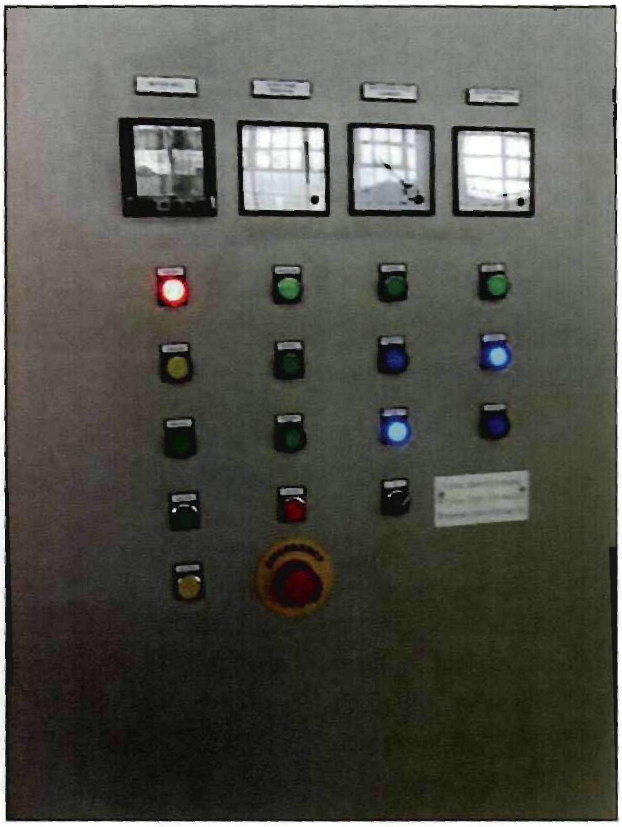
This section also helps to further verify the proposed optimised control strategy and the real-time results of the actual tests conducted on this system. The energy and capital savings of such a project is also shown, as well as the success of a fully automated compressed air management system.

Chapter 6

This chapter concludes the study and will discuss the effects of the proposed optimised control strategy on not only the South African electrical energy supplier, Eskom, but also on compressed air mining systems. The environmental impact will also be discussed briefly. Recommendations for further related studies will also be discussed.

CHAPTER 2: Compressed Air Systems in the South African Mining Industry





Compressed air is an integral part of the mining environment. It is also one of the largest electrical energy users on the mine. This chapter focuses on finding potential on compressed air networks in the mining environment.

2. Chapter 2: Compressed Air Systems in the South African Mining Industry

2.1. *Introduction*

As stated in Chapter 1, compressed air is an important part of almost any mining setup. A compressed air system is the traditional means used to supply energy for underground mining equipment. Converting electrical power into mechanical power by compressing air is probably the most expensive and least efficient utility in the mining industry [42].

Compressed air systems can be divided into two categories:

Low Pressure Systems

The typical pressure for such a system ranges between 50 kPa and 200 kPa. They are mainly used in the mining industry for ventilation, flotation cells and in process tanks. The low pressure compressed air is supplied by a device called a fan or a blower [42].

A blower device is in itself a compressor of air, although the physical properties differ from those of a high pressure compressor. High pressure machines are usually centrifugal of nature and make use of large blades on a single shaft, called an impeller.

The blades are arranged in a circle and rotate in a shell, called a volute. The volute's shape is one of expansion, which causes an expansion of the flow entering and exiting the control system. This causes the flow velocity of the air to decrease, resulting in an immediate pressure rise.

The rotational speed of the impeller used in a fan, are far less than the rotational speed of the impeller used in a high pressure compressor [42].

High Pressure Systems

High pressure compressors typically raise the pressure of the air flowing through the compressor to around 700 kPa, although this may vary between different products.

There are three different types of high pressure systems:

- Centrifugal – Compresses air via radial flow through the compressor. Most commonly used machine.
- Axial – Flow passes through the compressor in an axial fashion.
- Piston type – These are constant displacement machines and operate in a similar fashion as a reciprocating engine.

High pressure compressors are of high importance in the mining industry, as it is the requirement of various equipment used underground.

2.2. Use of Compressed air in the Mining Environment

Compressed air is used for a variety of applications which includes the following:

Rock Drilling

Rock drills are mainly hydro-, electric- or pneumatic powered. In the South African mining industry, the norm is pneumatic drilling. These machines are the primary air users during the production period of a day. Rock drills usually require a pressure of close to 500 kPa and the capacity of air that they use can be seen in the table 2-1.

The highest amount of air is demanded during the drilling shifts, thus requiring a large supply from the compressors which also causes high power usage.

Figure 2-1 An example of a rock drill

Diamond Drills

Diamond drills require relatively high operating air-supply pressures and are mainly used for further stope (horizontal passage and mining levels) expansion drilling. When analysing a mine's compressed air system, it is important to realise that diamond drills are used throughout the day and are not bound to the normal drilling shift.

Agitation

Compressed air is also used for agitation in backfill dams and plants. Agitation systems are usually open ended tubes in the bottom of a backfill dam, through which compressed air flows in such a way that no settlement of the backfill can occur.

Mechanical Ore Loaders

These machines use a constant supply of air at a pre-designed pressure to operate sufficiently for production use. Ore loaders are used to load ore into loading boxes or onto conveyors.

Loading Boxes

Loading boxes carry ore and unload by means of a hatch at the bottom of the box that opens and closes by means of compressed air pressure cylinders. If the system pressure drops too low, the loading box hatch opens up and drops the load. The hatch will close when the compressed air pressure increases.

Refuge Bays

Refuge bays are of extreme importance in the mining industry, as they are required by law to provide a safe haven for shaft mining personnel in case of a gas leak, fire or any hazard of the sort underground. These bays are pressurised chambers in which mining personnel can seek sanctuary in case of hazardous conditions. By pressurising the refuge bay, harmful gasses and fire can be kept out, as flow always occur from a high pressure to a low pressure. Compressed air is used to pressurise the system.

Pneumatic Pumps

In most cases, pneumatic pumps are stationary pumps used to pump out excessive water from the stopes into large underground dams. They are pneumatically driven machines, but are not widely used in the South African mining industry.

Air Leaks

Air leaks can be caused by poor maintenance, old age of pipes, dents, knocks, rock falls on the pipe work, as well as any other open end in the pipe network not utilising compressed air in the manner it was destined for. In other words compressed air that is being wasted without the knowledge of the users or deliberately. Air leaks causes pressure drops in the system and compressors must deliver extra compressed air into the system to overcome the pressure drops.

The table below illustrates a list of typical compressed air users in the mining industry and the mass (in kilograms) of compressed air that they use to operate per second:

Pneumatic Equipment	**Air Usage (kg/s)**
Rock Drills (Jackhammer)	0.060
Mechanical Loaders	0.137
Diamond Drill	0.090
5 mm Diameter Leak	0.030
10 mm Diameter Leak	0.120
Loading Boxes	Irregular compressed air release during loading actions, reliant on pressure
Pneumatic pumps	Irregular compressed air release during loading actions, reliant on pressure
Refuge Bays	Irregular compressed air release during loading actions, reliant on pressure
Agitators	Vary between 0.1 – 0.3

Table 2-1 Typical compressed air users and their compressed air usage [42]

Now that the underground applications have been discussed, the networks that supply compressed air will be investigated.

2.3. Compressed Air Networks

A compressed air network can be defined as a system that supplies and delivers compressed air to active mining shaft/s for various applications.

There are mainly two types of systems that supply compressed air:

- Standalone systems
- Compressed air rings

Standalone Systems

When a shaft draws its air straight from the compressor delivery via a piping system and no other shaft is receiving air from the same compressor house, it is called a standalone system. This system is less complex than a compressed air ring and usually has a very predictable nature.

Changes in the system also occur rather rapidly, because of the smaller volume that the system retains. Finding leaks and doing maintenance on the system are also more simplified than on a compressed air ring.

The figure below illustrates a typical standalone system.

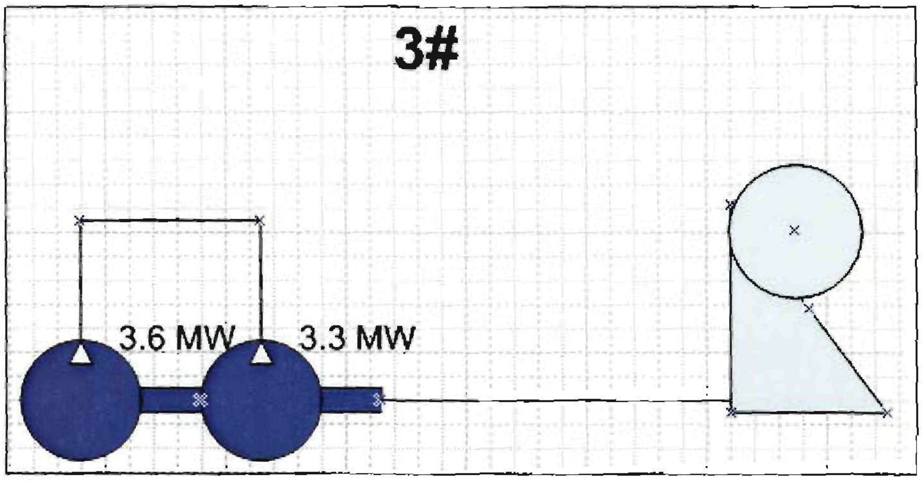


Figure 2-2 Air reticulation system of President Steyn 3#

Compressed Air Ring

The main idea of a compressed air ring is to have various compressors continuously supplying a pressurised compressed air grid with the necessary volumes of air, so that more than one shaft can extract compressed air from it. In essence, it is one compressed air piping system, connecting multiple shafts and compressor houses.

The effects of changes in these systems are usually experienced in a delayed fashion, because of the higher volume of compressed air that circulates through the system. Maintenance on such a system can sometimes be cumbersome, as these systems can be intricate in their own right. Each system has got its own characteristics and acts accordingly.

A compressed air ring has the following advantages:

- If a shaft's air demand exceeds those of its own compressor house's supply, it will be able to draw extra compressed air from the grid.
- A centralised compressor house might be able to supply enough air for multiple shafts, thus not needing to establish extra compressors at each shaft.
- Eases maintenance, because when maintenance is done on a specific shaft's compressors, air can be supplied from another shaft's system.
- A larger array of options is available to the entire ring.

As there are many advantages to a compressed air ring, disadvantages are inevitable. These include:

- Large possible pressure drops throughout the system, depending on the status of the pipes and the flow velocity through the pipes.
- The diversity of the system can also affect the system air pressure in a negative way less control can be exercised over such a system.
- Maintenance can be a hassle, as these systems can be intricate and cover large areas, thus many leaks can occur. Leak detection is labour intensive. Furthermore, many pipe areas are difficult to access and fix.
- Ineffective use of air by one of the shafts on the ring can hamper the other shafts on the ring and cause a lower overall pressure in the grid.

2.4. Potential for DSM Implementation on Compressed Air Ring

Several large compressors are usually used to supply compressed air to a compressed air ring. This ensures that the system keeps up with the high compressed air demand of a ring feed system. As a compressed air ring allows a greater number of compressed air users distributed over a large area, compressed air leaks and wastage are more likely.

There are various factors why compressors are not always being operated efficiently. On most mines centralised blasting is being implemented. This means that the mine operates according to a fixed mining schedule, following a traditional daily cycle of drilling, blasting and cleaning.

This also has the effect that the air demand will vary throughout a 24-hour profile, having peak compressed air usage periods and low compressed air usage periods. During the low demand period, less compressed air is needed and the norm should be to operate compressors according to the demand.

Current trends show that this is not the case on many mines and this opens up a window of opportunity for power saving projects. By implementing a proper control strategy on a mine's compressed air system, large power savings can be realised, not only in the Eskom peak period, but also throughout the day, as energy efficiency can also be utilised in such a project.

For such a project to realise, a simulation model of the above ground compressed air network is important and should be developed, followed by a relevant case study to verify the model. Such a study will be used to determine the compressed air usage during specific periods of the day and will also help to determine if there are major air leakages. It might also prove useful in identifying other unexplained factors that reduce air pressure (e.g. inefficient piping layouts).

2.5. Need for a New Simulation Model for Compressed Air Systems

A simulation model for the compressed air system will assist in predicting system pressures and pressure losses on different locations in the system, due to different compressed air mass flow inputs, frictional losses, losses due to the flow velocity and turbulent flow.

Such a system will help in correctly determining the amount of compressors to operate. It will also be able to determine the number of compressed air the operating machines should deliver into the system as controlled by the guide vanes.

By accurately predicting these values, valuable decisions can be made in approaching the case study and its outcomes. With the sometimes unpredictable nature of compressors and the run-down status that some of these machines might be in, careful and precisely planned tests are of extreme importance.

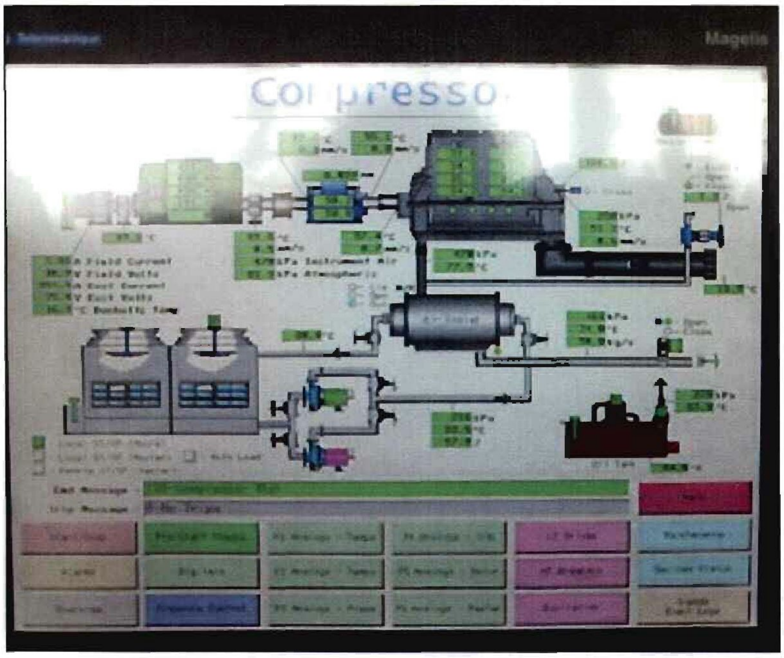
2.6. Conclusion

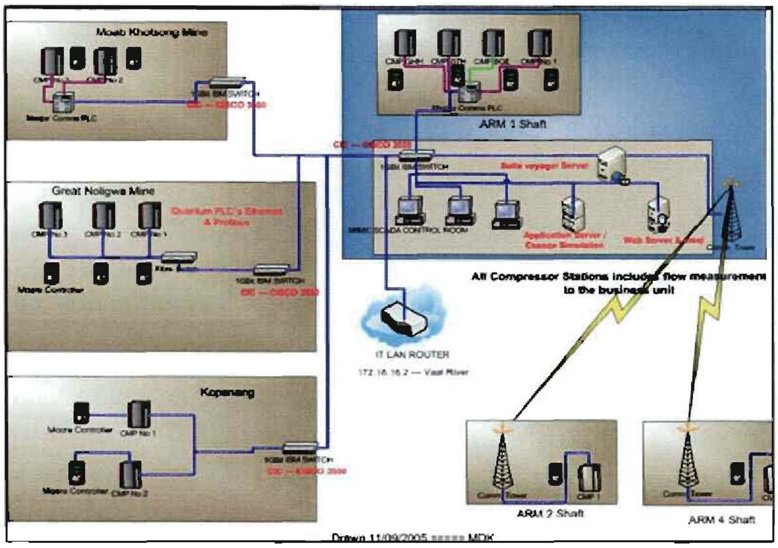
In conclusion, it is found that fair DSM potential exists in the compressed air sector of the mining industry. This is not only due to the large power draining nature of large centrifugal, axial and piston compressors, but also the ineffective way that compressed air systems are being managed in the mining industry.

Compressors are very expensive equipment and the unnecessary starting and stopping of such equipment might lead to costly breakdowns. By controlling the compressed air demand and/or the supply, compressors can be operated on lighter loads or switched off during specified times of the day.

This constitutes huge power savings. It is also necessary to create a simulation that will assist in predicting important aspects of the system, as well as to be used in the design of the control software that will be used for the optimum control strategy.

CHAPTER 3: New Simulation Model for Compressed air





In this chapter a compressed air surface network simulation is developed to predict test results and assist in the development of an optimised control strategy.

3. Chapter 3: New Simulation Model for Compressed Air

3.1. Introduction

Now that the need for a compressed air simulation has been established, the development of such a system can be described. Such a simulation must be fairly accurate so that safe predictions can be made regarding a certain compressed air system. A model can be developed in many ways, but for the purpose and application of this study it was decided to follow the detailed procedure as seen below:

- Start with a review on compressed air and its own unique properties.
- Investigating pressure losses of compressed air in single and multi-pipe systems. This is an important aspect to consider as it directly influences the accuracy of the simulation model.
- Investigating the use of compressed air in the mining industry was also of critical importance, as this also affects many of the properties of compressed air, as well as the outcome of the simulation. An example of this is that the previous statement can help to determine which variables are available in reality. It will also help to determine which variables are measured accurately or at all, as well as which variables will have to be predicted to have useful answers.
- To verify this system, real-time test results would have to be acquired and compared to the simulation results. This will point out errors in the simulation, from where fine-tuning can be started.
- Finally, when a fairly accurate above ground compressed air simulation is constructed, it can be used to predict the physical effects of different DSM strategies on a compressed air ring feed system.

3.2. Development of an Above Ground Pressure Simulation Model

3.2.1 Introduction

In this section the explanation of the development process will be structured in the same way in which it has been mathematically calculated. A short explanation follows each calculation to clarify each step. This section explains the simulation methods of a simple compressed air system with one inflow and two outflows.

The simulation will be used to predict pressure drops in the system and it enables the user to accurately plan testing and avoid a situation where the system pressure falls too low and production losses occur. The simulation will also be used in the development of REMS CM to make accurate predictions of the amount of compressors needed to operate safely within production and safety constraints.

3.2.2 Assumptions

This simulation was evaluated as a steady-state simulation of the compressed air system and not as a dynamic one. This means that a stagnant scenario will be used and all the unknown values in the system will be calculated according to the steady state inputs used.

Although mass flow rates are being used, only the immediate effect thereof will be used in this program. It has been constructed to accommodate the compressed air ring between Tau Tona and Savuka, as well as other similar compressed air systems, consisting out of one inflow of air and two outflow points.

Mass flows are constantly fluctuating and it will be assumed that the demand will satisfy the need for each shaft exactly, because of the effective use of guide vane control. The mass flow values of the compressed air exiting the system will also be specified equally to the delivery mass flow value.

The system does not make use of an automatic variable inlet guide vane control function, but rather makes use of the user's knowledge to predict an actual inlet flow value, as well as the rated delivery pressure of the compressor. In other words: for the simulation model, a mass flow value will be a predicted input from the user, which is supposedly then the same as the flow directed into the system by the guide vanes.

The discharge pressure of the compressor will also be a realistic, predicted value. The mass flow value and discharge pressure value can also be acquired from the specific compressor's diagrams. It should be noted that the valve openings and the mass flow through the valve, used in the simulation, were adjusted in such a manner that the pressure immediately downstream from the valve would realistically reflect the true pressure of the system.

3.3. Simulation Process

For the simulation to deliver the necessary output data, certain input data will be required. These data is listed in the following table:

Input Variable	**Description**	**Unit**
P1	Delivery pressure of the compressor/s	kPa
D1 - D7	All the pipe diameters throughout the system	m
T1	Temperature of the delivered compressed air	°C
cfm	Also known as cubic feet per minute Necessary to calculate the mass flow	cfm
L1, L3, L5, L7	Distances between different nodes in the system	m
ValvePercentageOpen	The valve opening expressed as percentage open	%

Table 3-1 Input variables to compressed air system simulation model

Values that are fixed in the simulation are the following:

Fixed Value	**Description**	**Unit**
eStaal	Average roughness of the piping, dependant on the material type used	mm

Table 3-2 Fixed values

Other variables that can be found in the calculations below are the following

Other Variables	**Description**	**Unit**
ρ	Density	kg/m^3
Q	Volume flow	m^3/s
m-dot	Mass flow	kg/s
μ	Viscosity	kg/m.s
h_x	Enthalpy	kJ/kg
A	Area	m^2
Vel	Velocity	m/s
Re_x	Reynold's number	Constant
f	Friction factor	Constant
P_{lx}	Pressure loss (line)	kPa
P_x	Pressure	kPa
K_x	K factor	Constant
h_{vernou}, $h_{verbreed}$	Head loss	m

By evaluating the values in the previous table, the following process will be followed:

Equation 1 calculates the density of the atmospheric air before going into the compressor intake:

$$\rho_0 = \rho(\text{'Air'}, T = T_1, P = 86) \tag{1}$$

Equation 2 calculates the volume flow rate from the given cfm value:

$$Q = cfm \cdot 0.0004719474 \tag{2}$$

Equation 3 calculates the mass flow through the compressors. This value is a key factor, as it is the total kg/s that will be used throughout the whole system:

$$\dot{m}_1 = \rho_0 \cdot Q \tag{3}$$

Equations 4, 5 and 6, respectively calculate the density, viscosity and enthalpy of the air after exiting the compressor:

$$\rho_1 = \rho\,(\,'\mathrm{Air}_{ha}'\,,\,T = T_1\,,\,P = P_1\,)$$

$$\mu_1 = \mathbf{Visc}\,(\,'\mathrm{Air}_{ha}'\,,\,T = T_1\,,\,P = P_1\,)$$

$$h_1 = \mathbf{h}\,(\,'\mathrm{Air}_{ha}'\,,\,T = T_1\,,\,P = P_1\,)$$

(4), (5), (6)

Equations 7 and 8 calculate the area of the piping through which the air flow after the compressor outlet and use it in the next equation to acquire the flow velocity:

$$A_1 = \frac{\pi \cdot D_1^{\,2}}{4}$$

$$\mathrm{Vel}_1 = \frac{\dot{m}_1}{\rho_1 \cdot A_1}$$

(7), (8)

Equation 9 calculates the Reynolds number for use in the friction factor equation:

$$\mathrm{Re}_{air,1} = \frac{4 \cdot \dot{m}_1}{\pi \cdot D_1 \cdot \mu_1} \tag{9}$$

In this case the Reynolds number is always high, because of the nature of the flow which is turbulent and not laminar.

Because of turbulent flow, Equation 10 is valid to calculate the friction factor:

$$f_1 = \frac{0.25}{\log^2 \left[\frac{e_{Staal}}{3.7 \cdot D_1} + \frac{5.74}{Re_{air,1}^{\ 0.9}} \right]} \tag{10}$$

The result of Equation 10 is then used in Equation 11 to determine what the pressure loss will be because of the friction and flow velocity:

$$P_{l,1} = \frac{f_1 \cdot \frac{L_1}{D_1} \cdot \frac{\rho_1 \cdot Vel_1^{\ 2}}{2}}{1000} \tag{11}$$

Equation 12 is the pressure at Node 2. This pressure is given by subtracting the pressure loss in Equation 11 from the pressure at Node 1.

$$P_2 = P_1 - P_{l,1} \tag{12}$$

Equations 13, 14 and 15 show that a constant enthalpy was assumed for this simulation:

$$\begin{aligned} h_2 &= h_1 \\ h_1 &= h_{valve} \\ h_3 &= h_2 \end{aligned} \qquad (13), (14), (15)$$

Equation 16 calculates the compressed air temperature at Node 2:

$$T_2 = T\,(\,'Air_{ha}'\,,h = h_2\,,P = P_2\,) \tag{16}$$

Equations 17 and 18 deliver the area of the pipe at Node 2:

$$D_1 = D_2$$

$$A_2 = \frac{\pi \cdot D_2^2}{4} \qquad (17), (18)$$

Equations 19 and 20 deliver the opening of the valve as a percentage open value:

$$\text{ValvePercentageOpen} = \frac{D_{valve}}{D_2} \cdot 100$$

$$A_{valve} = \frac{\pi \cdot D_{valve}^2}{4} \qquad (19), (20)$$

Equation 21, the K-factor is a result of the narrowing from the valve inlet to the centre:

$$K_1 = \frac{0.5 \cdot \left[1 - \left(\frac{D_{valve}}{D_2} \right)^2 \cdot \sqrt{\sin(90)} \right]}{\left[\frac{D_{valve}}{D_2} \right]^4} \qquad (21)$$

Equation 22, the new density of the compressed air at Node 2:

$$\rho_2 = \rho(\text{'Air'}, T = T_2, P = P_2) \qquad (22)$$

In Equation 23 it is accepted that the flow through the valve will be the same as the flow that will be delivered to the one shaft. This value is smaller than the initial inflow, because of the split off of the air to the other shaft, just before the valve:

$$\dot{m}_2 = \dot{m}_7 \qquad (23)$$

Equation 24 calculates the velocity of the air, flowing into the valve. This value will be used to determine the head loss in the valve itself. This head loss can be seen in Equation 25:

$$Vel_2 = \frac{\dot{m}_2}{\rho_2 \cdot A_2}$$

$$h_{vernou} = K_1 \cdot \frac{Vel_2^{\ 2}}{2}$$

(24), (25)

Equations 26 and 27 supply the K-factor for where the air exits the wider valve exit from the smallest diameter in the centre of the valve:

$$A_3 = \frac{\pi \cdot D_3^{\ 2}}{4}$$

$$K_2 = \frac{\left[1 - \left(\frac{D_{valve}}{D_3}\right)^2\right]^2}{\frac{D_{valve}}{D_3}}$$

(26), (27)

Equation 28 is the head loss through the valve exit:

$$h_{verbreed} = K_2 \cdot \frac{Vel_{valve}^{\ 2}}{2}$$

(28)

The pressure in the centre of the valve through the narrowest opening can be calculated from Equations 29, 30 and 31:

$$T_{valve} = T\left('Air_{ha}', h = h_{valve}, P = P_{valve}\right)$$

$$\rho_{valve} = \rho\left('Air', T = T_{valve}, P = P_{valve}\right)$$

$$P_{valve} = P_2 - \frac{\rho_2 \cdot 9.81 \cdot h_{vernou}}{1000}$$

(29). (30), (31)

The head loss in Equations 25 and 28 is used, together with the temperature and density that is received from Equations 32 and 33, to determine the pressure loss over the whole valve in Equation 34:

$$T_3 = \mathbf{T}(\text{'Air}_{ha}\text{'}, h = h_3, P = P_3)$$

$$\rho_3 = \rho(\text{'Air'}, T = T_3, P = P_3)$$

$$P_{valve} = \frac{P_2 \cdot A_2 - (\rho_{valve} \cdot Vel_{valve}^2 \cdot A_{valve} - \rho_2 \cdot Vel_2^2 \cdot A_2)}{A_{valve}}$$

$$P_3 = P_{valve} + \frac{\rho_{valve} \cdot 9.81 \cdot h_{verbreed}}{1000}$$

(32), (33), (34), (35)

Out of the above 4 equations, the flow velocity at Node 3 at the exit of the valve can be determined by Equation 36. This is a simple mass flow balance through the valve which calculates the exit flow velocity of the compressed air out of the valve.

$$P_3 = \frac{P_{valve} \cdot A_{valve} - (\rho_3 \cdot Vel_3^2 \cdot A_3 - \rho_{valve} \cdot Vel_{valve}^2 \cdot A_{valve})}{A_3}$$

(36)

Equation 37 calculates the viscosity of the flow at Node 3, whereas Equation 38 calculates the mass flow at the exit of the valve:

$$\mu_3 = \mathbf{Visc}(\text{'Air}_{ha}\text{'}, T = T_3, P = P_3)$$

$$Vel_3 = \frac{\dot{m}_3}{\rho_3 \cdot A_3}$$

(37), (38)

A new Reynolds number is calculated in Equation 39, which is used in Equation 40 to determine the friction factor for the following pipe:

$$Re_{air,3} = \frac{4 \cdot \dot{m}_3}{\pi \cdot D_3 \cdot \mu_3}$$

$$f_3 = \frac{0.25}{\mathbf{log}^2\left[\frac{e_{Staal}}{3.7 \cdot D_3} + \frac{5.74}{Re_{air,3}^{0.9}}\right]}$$

(39), (40)

Equation 41 calculates the pressure loss in the next section, which is then used to calculate the pressure at Node 4, using Equation 42:

$$P_{L,3} = \frac{f_3 \cdot \frac{L_3}{D_3} \cdot \frac{\rho_3 \cdot Vel_3^{\ 2}}{2}}{1000}$$

$$P_4 = P_3 - P_{L,3}$$

(41), (42)

The next list of equations follow the same manner of calculations as previously discussed to calculate the pressure losses over the pipe from Node 5 to 6, as well as give the pressure at Node 6:

$$\rho_5 = \rho_3$$

$$Q_5 = cfm_5 \cdot 0.0004719474$$

$$\dot{m}_5 = \rho_5 \cdot Q_5$$

$$P_5 = P_2$$

$$h_5 = h_2$$

$$T_5 = \mathbf{T}\ (\text{'Air}_{ha}\text{'}\ , h = h_5\ , P = P_5\ )$$

$$\mu_5 = \mathbf{Visc}\ (\text{'Air}_{ha}\text{'}\ , T = T_5\ , P = P_5\ )$$

$$A_5 = \frac{\pi \cdot D_5^{\ 2}}{4}$$

$$Vel_5 = \frac{\dot{m}_5}{\rho_5 \cdot A_5}$$

$$Re_{air,5} = \frac{4 \cdot \dot{m}_5}{\pi \cdot D_5 \cdot \mu_5}$$

$$f_5 = \frac{0.25}{\mathbf{log}^{\ 2}\left[\frac{e_{Staal}}{3.7 \cdot D_5} + \frac{5.74}{Re_{air,5}^{\ 0.9}}\right]}$$

$$P_{l,5} = \frac{f_5 \cdot \frac{L_5}{D_5} \cdot \frac{\rho_5 \cdot Vel_5^{\ 2}}{2}}{1000}$$

$$P_6 = P_5 - P_{l,5}$$

(43)-(55)

The following list of equations is a repeat of the pressure loss equations, but this time only for the final stretch of piping to the second shaft at Node 8:

$$\rho_7 = \rho_3$$

$$Q_7 = cfm_8 \cdot 0.0004719474$$

$$\dot{m}_7 = \rho_7 \cdot Q_7$$

$$P_7 = P_3$$

$$h_7 = h_2$$

$$T_7 = \mathbf{T}\left('Air_{ha}', h = h_7, P = P_7\right)$$

$$\mu_7 = \mathbf{Visc}\left('Air_{ha}', T = T_7, P = P_7\right)$$

$$A_7 = \frac{\pi \cdot D_7^{\ 2}}{4}$$

$$Vel_7 = \frac{\dot{m}_7}{\rho_7 \cdot A_7}$$

$$Re_{air,7} = \frac{4 \cdot \dot{m}_7}{\pi \cdot D_7 \cdot \mu_7}$$

$$f_7 = \frac{0.25}{\mathbf{log}^2\left[\frac{e_{Staal}}{3.7 \cdot D_7} + \frac{5.74}{Re_{air,7}^{\ 0.9}}\right]}$$

$$P_{l,7} = \frac{f_7 \cdot \frac{L_7}{D_7} \cdot \frac{\rho_7 \cdot Vel_7^{\ 2}}{2}}{1000}$$

$$P_8 = P_4 - P_{l,7}$$

(56)-(68)

By utilising the steps above, the pressures for the different nodes can be found [43] [44]. For these values to be correct, it is important to specify the correct input values.

3.4. Verification and Optimisation of the Simulation Model

For verification purposes, real-time testing was carried out at the Tau Tona and Savuka sections of Anglogold Ashanti's West Wits gold mine complex. The testing was conducted to draw up a comparison between the Tau Tona system and shaft pressures to the mass of compressed air delivered to the system by its compressors. It will also be used to verify an optimised control strategy later on in this thesis.

Testing Procedure

For testing purposes, the West Wits compressed air ring was divided into two parts by means of a valve near Mponeng. The valve isolates Mponeng and leaves Savuka and Tau Tona on the remaining compressed air ring. Testing was conducted on both separated sections, but for the verification of the simulation, only the Tau Tona and Savuka complex results were used. See Figure 3-2 later on in this section.

Different testing scenarios were observed over a three day period. The results were documented. The valves between Tau Tona and Savuka were left open for the duration of the tests, as the first day of testing showed that Tau Tona is always exporting air to Savuka. Separating these two shafts will result in Savuka starting up another 2 compressors to sufficiently supply the shaft with compressed air.

An illustration of the various shifts on the West Wits section can be seen below. It is important to note, that the tests were not done during peak drilling periods. Peak drilling periods usually require high pressures and the need for compressed air is at its absolute maximum. This constitutes that the maximum amount of compressors must also always be available for use. Therefore testing during this period will not deliver any major power savings and can cause production loss or worse, loss of life.

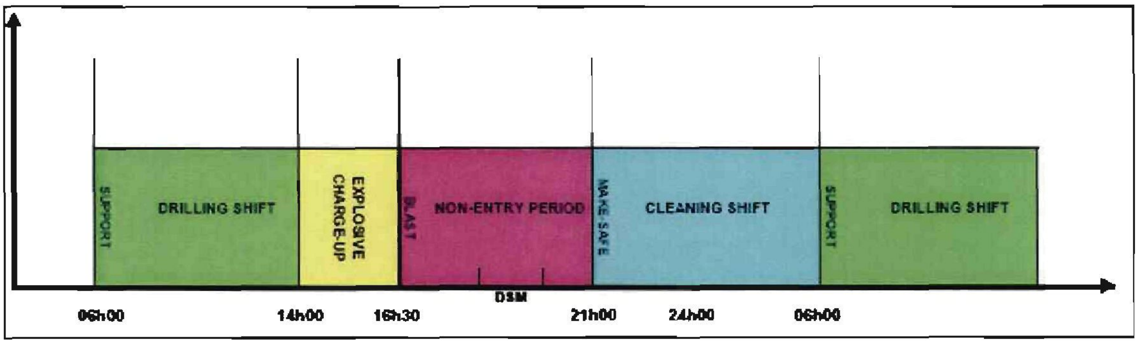


Figure 3-1 An illustration of a typical mining schedule over a 24-hour period [1]

As stated in earlier chapters, the period after the drilling period is where the least amount of compressed air is required in the mine. After blasting there is a waiting period to let dangerous gasses clear. It is during this period, usually from

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[1] *Personal communication – Mr. J van der Bijl (Pr.Eng), Technical Manager, HVAC International*

16:00 - 21:00, that the opportunity exists for power-saving tests. No production should be influenced and there is no person in the shaft that can suffer from any problems that might occur due to a lack of compressed air pressure.

The following table states the various compressors and their installed capacities for each of the two applicable mines:

	Model	Drive Power (kW)	Suction Volume (cfm)	Mass Flow (Kg/s)	Compressor Efficiency
Tau Tona	**Sulzer**	5 900	40 000	19	63
	Sulzer	5 900	40 000	19	64
Savuka	**BTH**	3 766	25 000	11	52
	BTH	3 766	25 000	11	45
	BB	4 030	25 000	11	52
	BB	4 030	25 000	11	50
	BB	4 030	25 000	11	50
	Sulzer	4 800	30 000	14	59

Table 3-3 Compressors available at Tau Tona and Savuka

Savuka's compressors are inefficient. The reasons for this are the mechanical state of the machines due to their old age and prolonged use. Therefore these compressors use more electricity (than newer, more efficient compressors) to produce the required compressed air. As can be seen in the table below, by operating more efficient machines, fewer machines can be used in total to achieve the desired results. Delivering the equivalent compressed air to the shafts, Scenario 1 proves more efficient as it uses 15.9 MW while Scenario 2 uses 18.5 MW.

	Operated Compressors Scenario 1	**Operated Compressors Scenario 2**
Tau Tona	2	1
Savuka	2	4
Total Operating MW (estimated.)	15,9	18.5

Table 3-4 It is more energy efficient to operate Scenario 1 as opposed to Scenario 2

The essence of the testing was to throttle back the two above ground valves at the Tau Tona shaft to slowly induce a downstream pressure of 340 kPa, measured twenty-odd meters from the valves. Two pressure indicators were installed at Tau Tona's two above ground compressed air lines for this purpose.

It is important to realise that a downstream pressure of 340 kPa is chosen for specific reasons. Loading boxes, as well as the agitation of backfill at West Wits, cannot function properly at pressures lower than 300 kPa. The chosen pressure set point is a conservative one and therefore should not cause any hassles.

A measurement of the ring pressure is received from a pressure transmitter near Tau Tona shaft, upstream from the two above ground valves. The ring pressure can be seen on Tau Tona's SCADA interface. Savuka's above ground valve was at a fixed open position. Savuka's above ground pressure was also measured and logged from their SCADA. These values where constantly monitored and logged every 5 minutes.

A schematic layout of the remaining compressed air ring, after the separation from Mponeng, can be seen below:

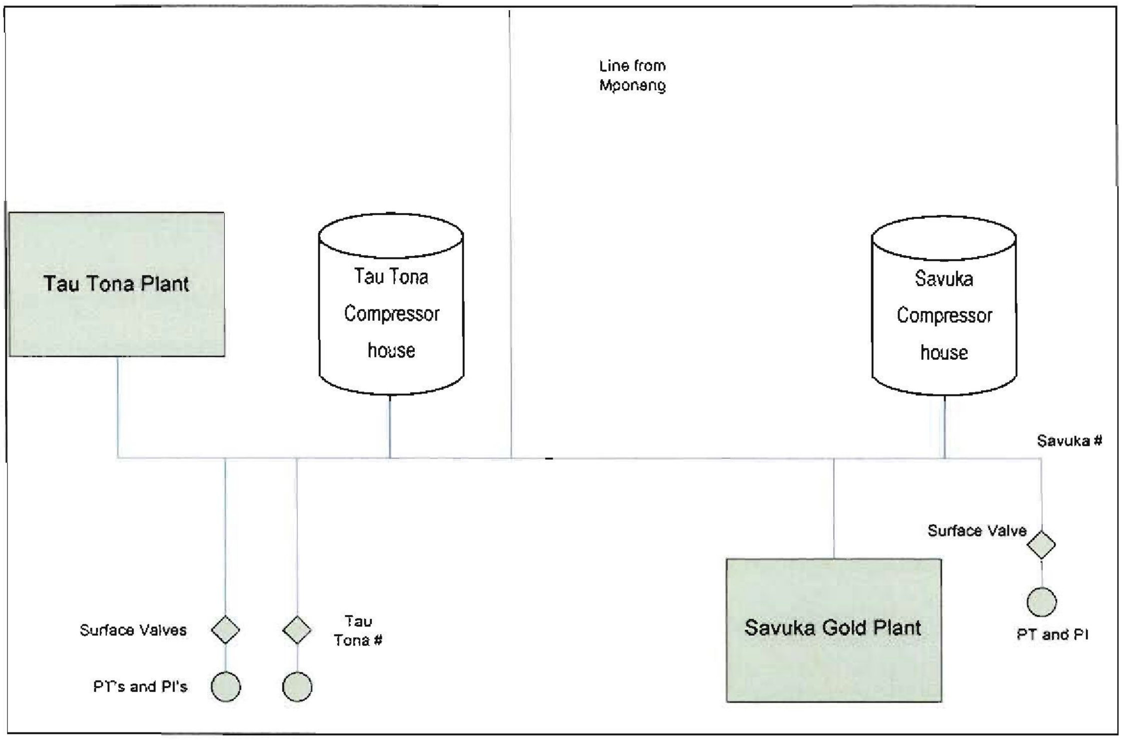

Figure 3-2 Testing layout of Savuka and Tau Tona as well as their gold plants

Testing Schedule

Throttling back of Tau Tona's two above ground valves started at just before 18:00. The valves were throttled back in increments until the downstream above ground pressure at Tau Tona dropped close to 320 kPa.

In the process, the Tau Tona compressors' Moore controllers' set points were lowered to close to 440 kPa. A Moore controller is a well-proven compressor control device, utilising tested features to protect a compressor against surges while simultaneously optimising the efficiency and intake airflow of the compressor. As the valves were throttled back, the upstream pressure rose. The compressors' Moore controllers adapted the inlet guide vanes to deliver the exact mass of compressed air to sustain the desired pressure.

By lowering the compressed air supply necessary to sustain the desired system pressure (using guide vane control), strain on the compressor motors is reduced and compressed air is delivered easier than on full demand. Thus requiring less power from the electric motor to drive the compressor and saving electricity.

It is important to note that the piping network used for the compressed air network at the West Wits section is steel. An average pipe roughness parameter value of e=0.00005 was used for the simulation. This value is a realistic approximate used for steel pipes found in a compressed air network.

The figure below shows a summary of the test results:

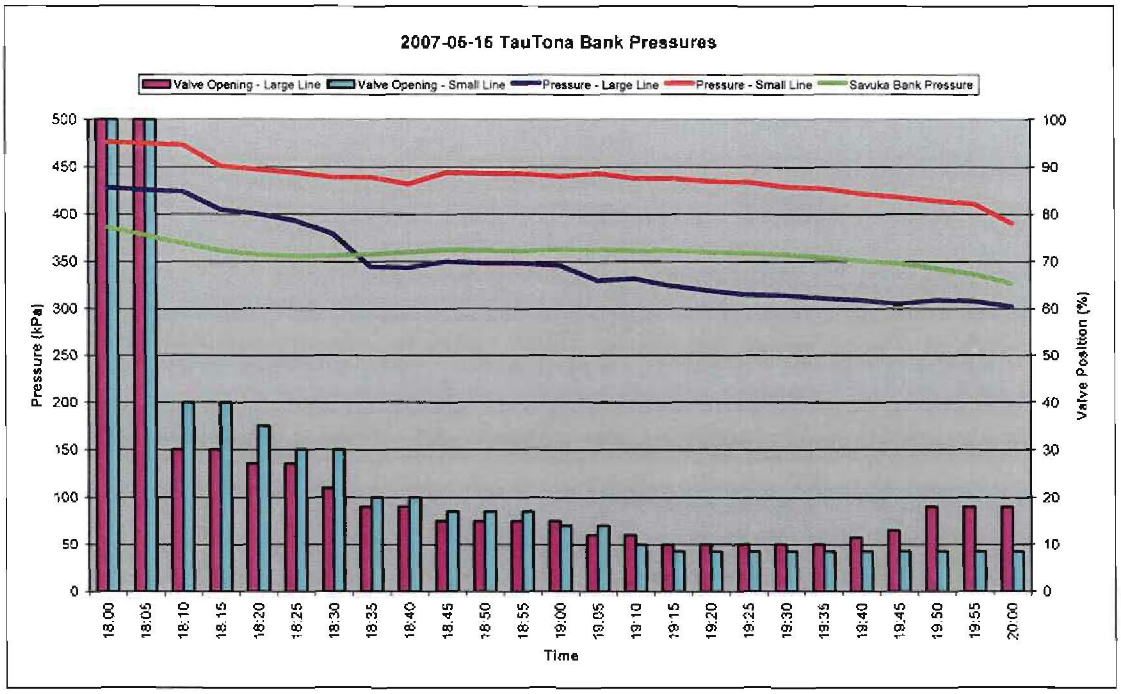

Figure 3-3 Air pressures Tau Tona bank, valve opening percentages, Savuka bank pressure[2]

As can be seen in the previous figure, pressures slowly decreased at Tau Tona's two compressed air lines over the two-hour period from 18:00 until 20:00, as the valves were throttled back. It was later discovered that there were complications on one of the Tau Tona compressed air lines, resulting in its higher pressure shown as the red line in the figure.

The blue line in Figure 3-3 more accurately resembles and affects the downstream pressure at Tau Tona and will be used as the average Tau Tona above ground pressure in the simulation process. As can be seen, Savuka's pressure profile, illustrated in green, also showed a slow negative tendency, but smoothed out to close to 340 kPa.

---

[2] Pressure scale on left and valve position scale on right of graph are not linearly related

The following figure illustrates the percentage openings of the guide vanes over the two hour period of testing. As a lower ring pressure was required, the compressors' inlet guide vanes had cut back accordingly.

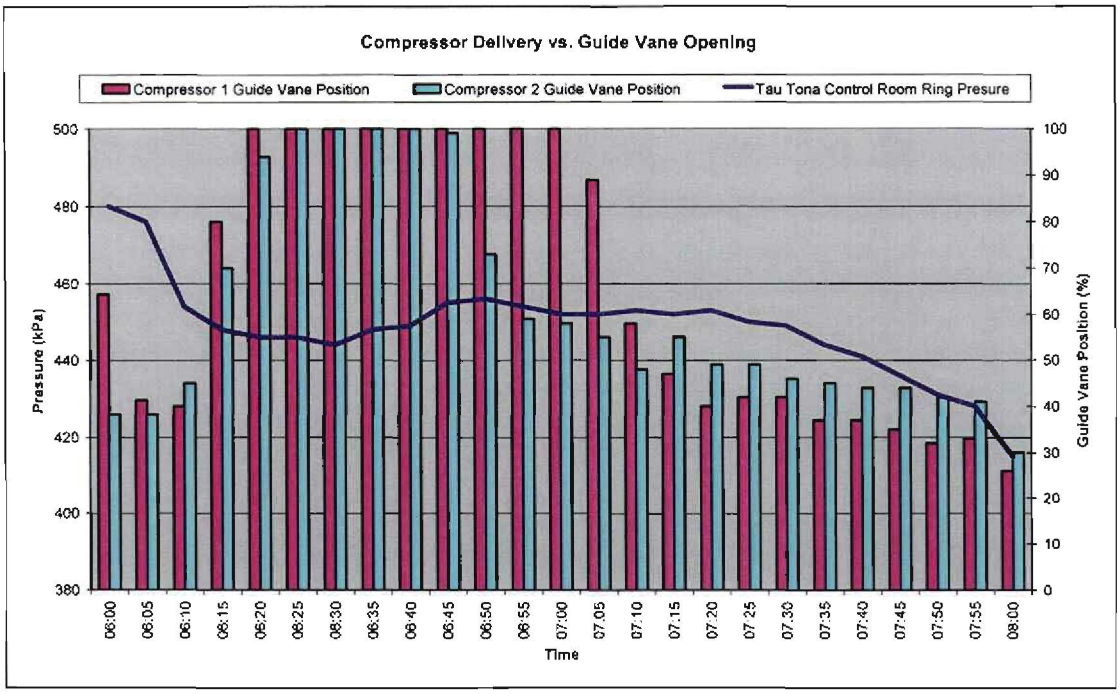

Figure 3-4 Inlet vanes vs Ring pressure guide[3]

The figure illustrates that the ring pressure is not directly dependent on the compressors' delivery values. Ring pressure is more dependent on the direct compressed air usage of each independent shaft, as well as the backpressure created when closing valves downstream.

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[3] Pressure scale on left and guide vane position scale on right of graph are not linearly related

The ideal settings for this system to be able to function properly are tabled below. Note that the large compressed air line at Tau Tona had the most influence on the downstream pressure, whereas the valve on the small compressed air line wasn't operating reliably and thus not tabled.

Mine	**Tau Tona**	**Savuka**
Pressure set point @ Above ground valves (kPa)	330	300
Pressure set point @ Moore controller (kPa)	400 – 460	N/A
Above ground valve opened (%)	15 – 20	20 - 100
Guide vane opening Automatic Control (%)	30 – 40	100
Amount of compressors operating	2	1 to 2

Table 3-5 Optimum settings as tested

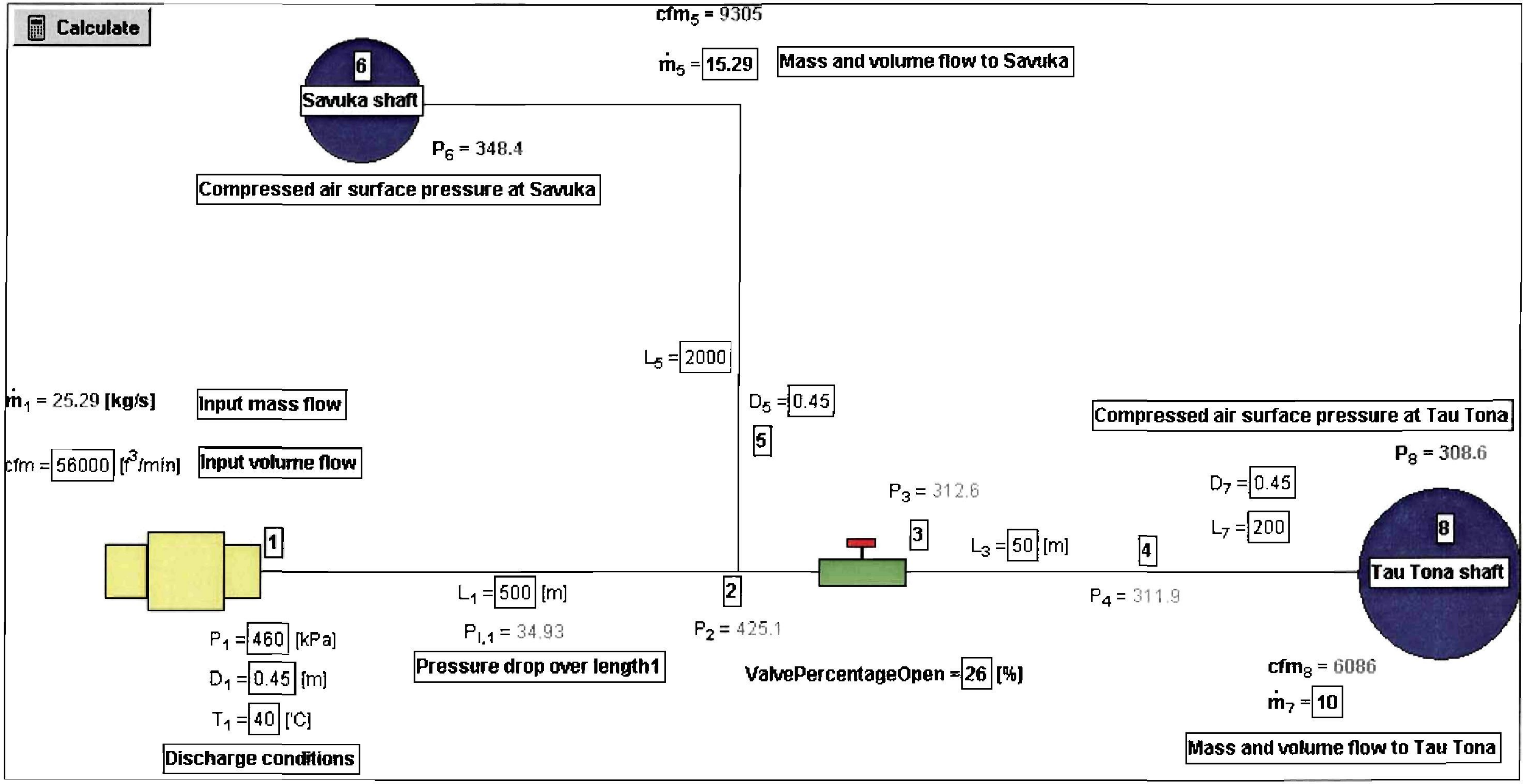
Simulation of the Procedure

A simulation was drawn up in the mathematical analysis program, dubbed Engineering Equation Solver (EES), to physically resemble the compressed air system layout between Savuka and Tau Tona. Simulation of the underground compressed air will not be part of the initial simulation model.

It must be added that, only a basic layout was compiled for the simulation. The total amount of bends and other flow restrictions could not be accurately quantified and it was thus taken into account that a slight, constant deviation of pressure loss was going to be imminent throughout the system.

By inserting longer pipe lengths than those actually used between the shafts, the extra pressure loss due to bends and other restrictions could be brought into account. The effect thereof on the accuracy of the simulation results will be discussed later on in this section.

The basic layout with all the variables can be seen in the Figure 3-5. All the input variables are noted in the figure. All the other values are output values calculated using the input variables, as well as using the calculation process explained earlier in this chapter.



cfm_5 = 9305

$\dot{m}_5$ = 15.29

P_6 = 348.4

L_5 = 2000

$\dot{m}_1$ = 25.29 [kg/s]

cfm = 56000 [f^3/min]

D_5 = 0.45

P_3 = 312.6

P_8 = 308.6

D_7 = 0.45

L_7 = 200

L_3 = 50 [m]

L_1 = 500 [m]

P_4 = 311.9

P_1 = 460 [kPa]

$P_{l,1}$ = 34.93

P_2 = 425.1

D_1 = 0.45 [m]

T_1 = 40 ['C]

ValvePercentageOpen = 26 [%]

cfm_8 = 6086

$\dot{m}_7$ = 10

Figure 3-5 Screenshot of the above ground simulation

Verification Procedure

To verify the accuracy of the simulation, the same input values as those of the plotted curve in Figure 3-4 will be used. Any variance in the results will be explained later.

Time	Valve Opening	Compressor Discharge Pressure	Ring Pressure Actual	Ring Simulated Value	Tau Tona Above ground Pressure	Tau Tona Simulated Value	Savuka Above ground Pressure	Savuka Simulated Value
18:00	100	490	480	**475**	428	**432**	386	**409**
18:05	100	490	476	**470**	426	**425**	378	**409**
18:10	30	470	454	**449**	424	**418**	369.5	**384**
18:15	30	465	448	**445**	405	**396**	361.7	**377**
18:20	27	460	446	**439**	400	**391**	357.5	**371**
18:25	27	460	446	**434**	393	**385**	355.6	**371**
18:30	22	460	444	**434**	379	**372**	356	**371**
18:35	18	465	448	**443**	344	**337**	357.3	**377**
18:40	18	465	449	**443**	343	**336**	359.7	**377**
18:45	15	470	455	**449**	350	**344**	362.1	**384**
18:50	15	470	456	**449**	348	**343**	361.7	**384**
18:55	15	470	454	**446**	348	**343**	360.9	**384**
19:00	15	470	452	**444**	346	**341**	362.4	**384**
19:05	12	470	452	**444**	330	**322**	362.1	**384**
19:10	12	470	453	**444**	332	**324**	361.4	**384**
19:15	10	470	452	**444**	324	**317**	361.7	**384**
19:20	10	470	453	**444**	319	**312**	360	**384**
19:25	10	465	450	**440**	315	**308**	358.7	**377**
19:30	10	465	449	**440**	314	**307**	357	**377**
19:35	10	460	444	**438**	311	**304**	354.4	**371**
19:40	11.5	460	441	**436**	309	**302**	351	**371**
19:45	13	460	436	**430**	305	**300**	348	**371**
19:50	18	445	431	**423**	309	**303**	342.9	**351**
19:55	18	440	428	**418**	308	**302**	336.5	**345**
20:00	18	430	415	**407**	302	**299**	327	**331**

Table 3-6 Actual pressures versus simulated pressures

Actual Ring Pressure versus Simulated Ring Pressure

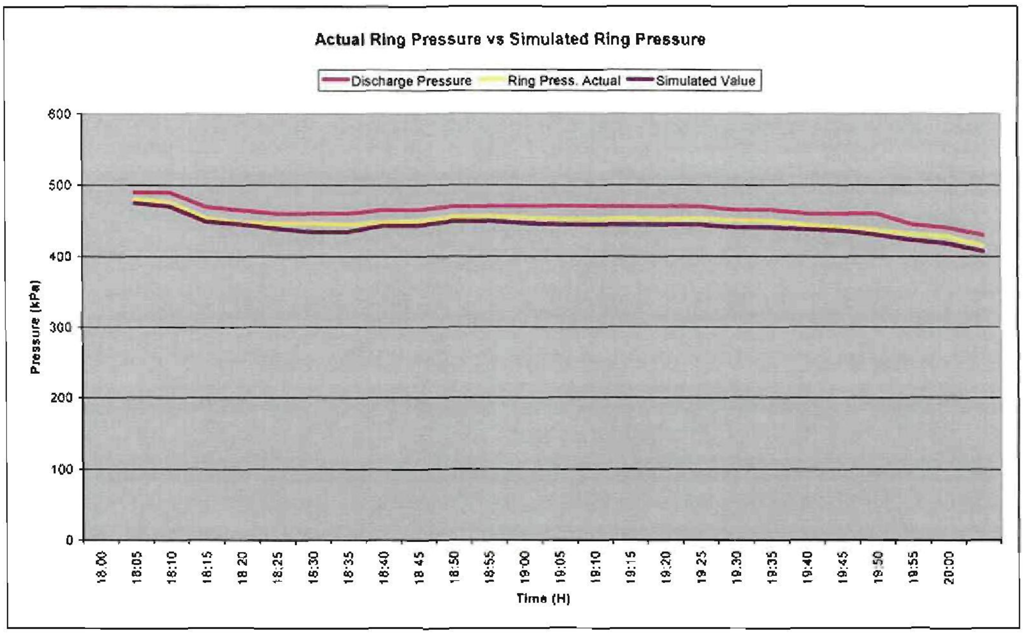


Figure 3-6 Actual ring pressure at Tau Tona versus simulation predictions

Statistically analysing the data delivers the following R-value:

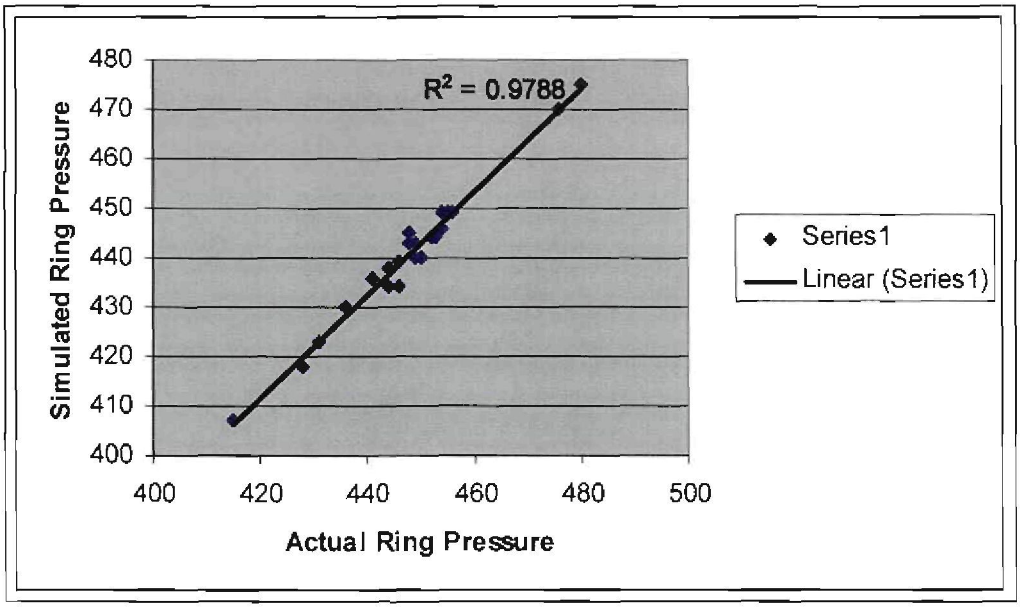


Figure 3-7 Correlation of simulated ring pressure with actual ring pressure

$R^2 = 0.9788$

Conclusion

By evaluating the first section of the simulation, it can be seen that an expected pressure drop with regards to the flow and friction losses is followed by the simulated trend. The pressure at the compressor discharge is only slightly higher than the other two trends.

The small variation between the actual ring pressure and the simulated ring pressure is due to the fact that distance of the compressed air line, between the compressor house and the ring pressure measurement point, might vary slightly.

It is important to notice that the simulated trend follows the actual trend quite closely and reflects that the pressure losses in the first piping section could most probably be due to friction and the flow velocity of the compressed air in the column.

No erratic pressure drops occur, mainly due to the relatively short distance of the pipe line towards the above ground pressure measurement location. The absence of any valves or other restrictions in the particular section is also a contributing factor.

Actual Tau Tona Above Ground Pressure vs. Simulated Above Ground Pressure

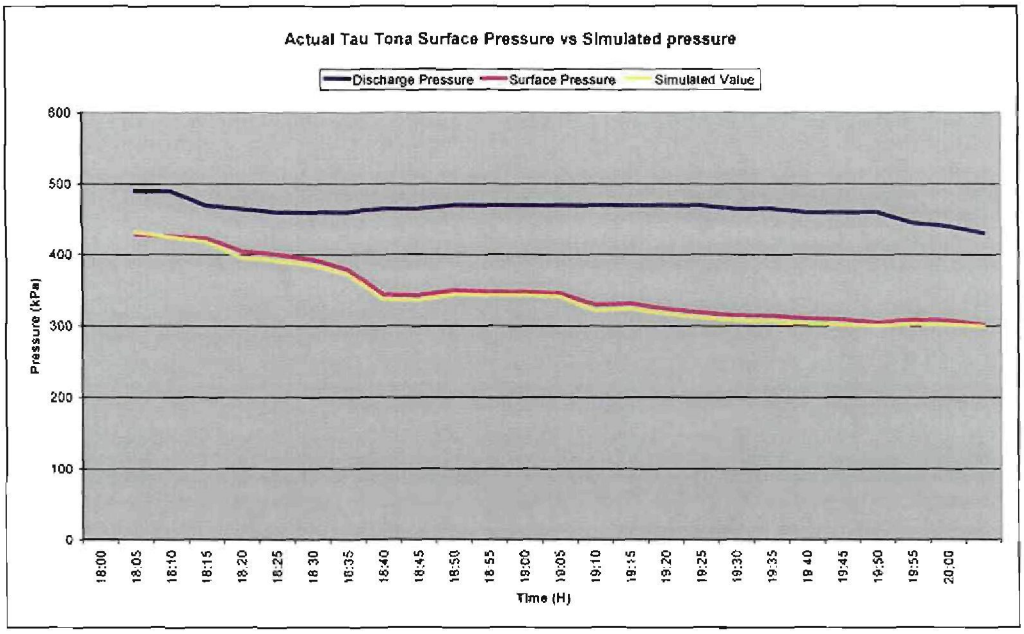


Figure 3-8 Actual Tau Tona above ground pressure just after the above ground valve versus the simulation predictions of ring pressure

Statistically analysing the data delivers the following R-value:

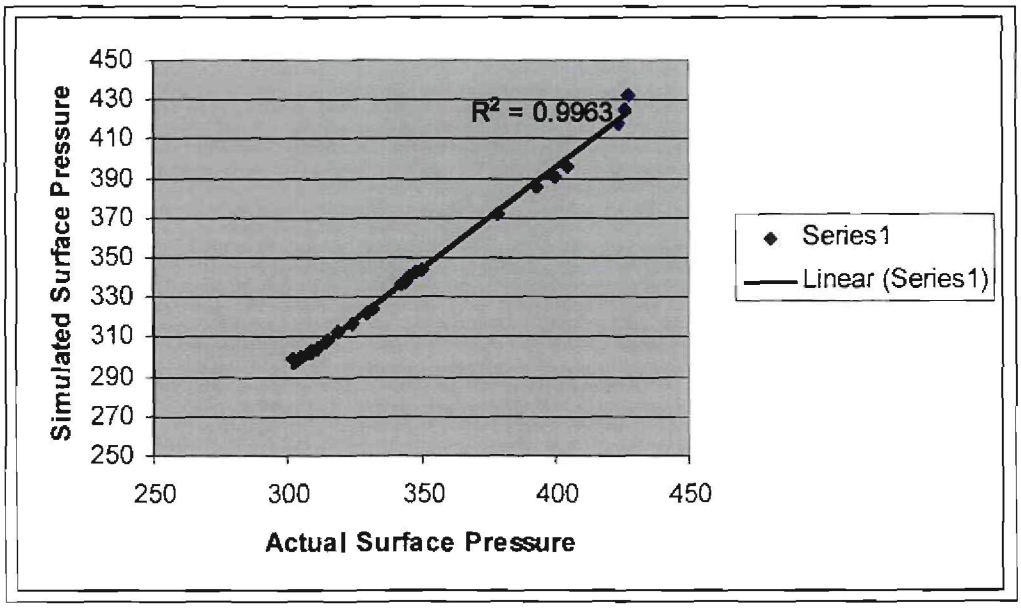


Figure 3-9 Correlation of simulated above ground pressure with actual above ground pressure

$R^2 = 0.9963$

Conclusion

Although a pressure drop is induced by the sheer distance of the above ground valve from the compressor discharge, the very evident pressure drop is more related to the actual throttling close of the valve. It should be kept in mind that the measurement point is immediately downstream from the above ground valve and is directly affected by the valve's position, thus the more visible drop in pressure.

The compressors' discharge pressure set point was also lowered during the whole process, causing the compressors' guide vanes start closing and thus delivering less air into the system. By lowering the demand, a system pressure drop also occurs, due to less air pressurising the compressed air piping network as a whole.

Again a slight variation is visible between the actual above ground pressure and the simulated value. This can be contributed to the following factors:

- The precise distance of the measuring point from the compressor house.
- Possible variation in the valve loss characteristics of the physical and simulated valve. This can be verified at the manufacturer of the valve.
- Variation in the precise flow velocity of the compressed air flowing through the system, or more specifically the valve.

Due to the above ground valve being gradually throttled back to 10% open and the discharge pressure set point being lowered to 430 kPa, the downstream pressure showed a pressure decrease from 428 kPa to 302 kPa.

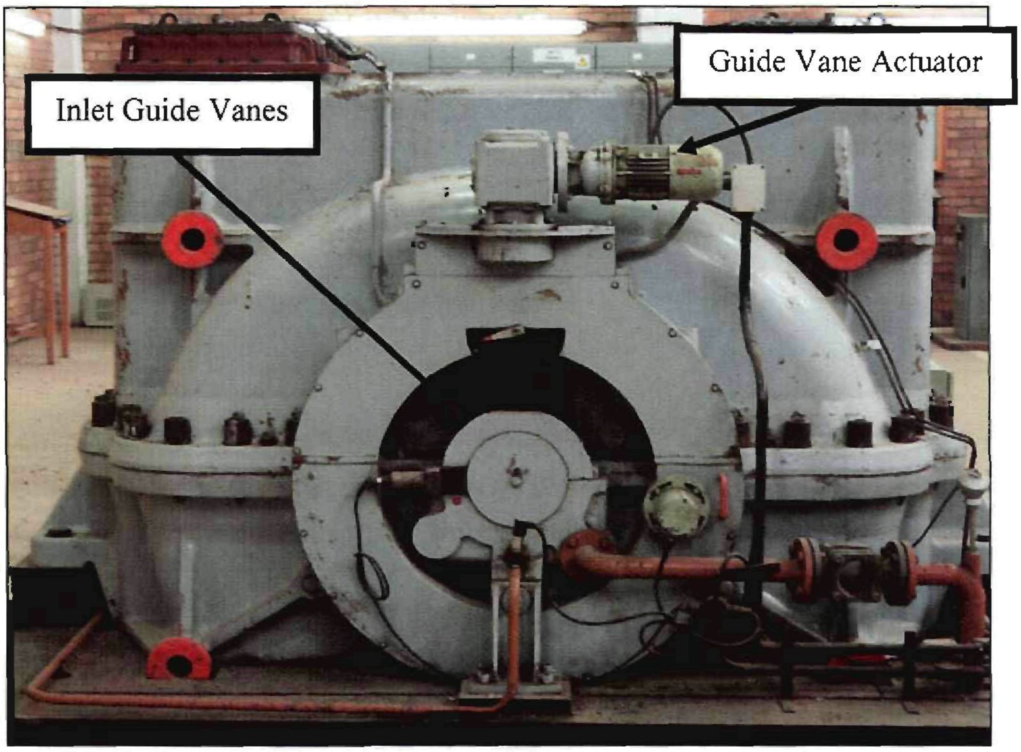


Figure 3-10 Front view of a Sulzer compressor. Note the inlet guide vane control in the centre[4]

Actual Savuka Above Ground Pressure vs. the Simulated Savuka Pressure

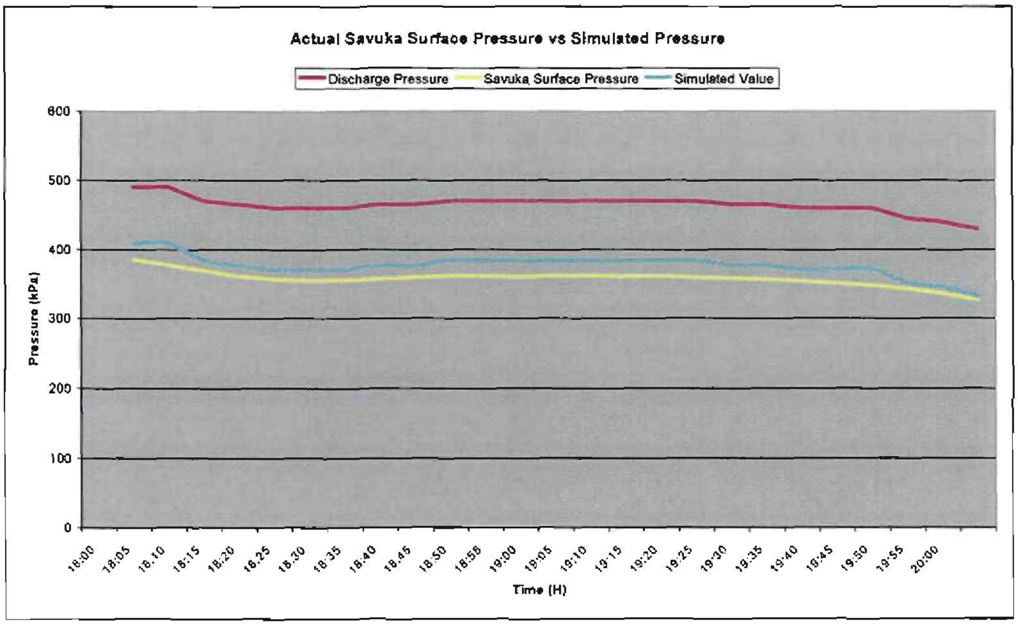


Figure 3-11 Above ground pressure at Savuka versus the simulate Savuka above ground pressure

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[4] *Personal communication – Mr. A. Garbers, CIC Engineer, Anglogold Ashanti*

Statistically analysing the data delivers the following R-value:

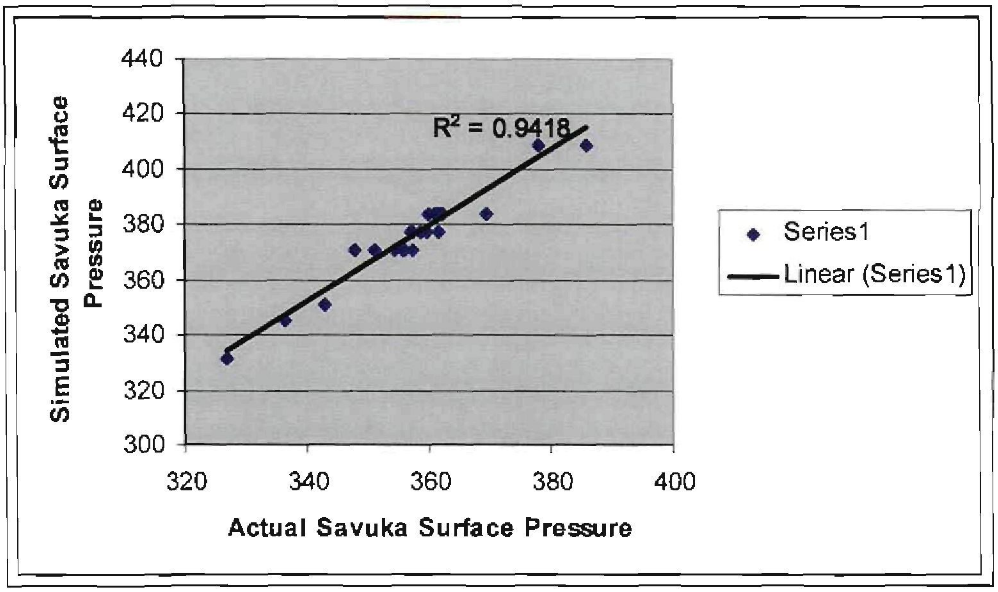


Figure 3-12 Correlation of simulated Savuka above ground pressure with actual Savuka above ground pressure

$R^2 = 0.9418$

Conclusion

Savuka shaft does possess a compressor house, but since no air is being exported to Tau Tona and due to the overall efficiency of the compressors being a great deal lower than those found at Tau Tona, only the nett inflow of the compressed air at Savuka was used.

The true Savuka shaft above ground pressure profile is on average a 100 kPa lower than the compressor discharge pressure at Tau Tona. Contributing to this is the fact that the Savuka shaft is situated close to 1500 meters away from the compressor discharge at Tau Tona mine.

It can also be owed to the fact that other types of pressure losses occur than those caused by friction and flow velocity. The trend of the Savuka pressure baseline also differs slightly from the actual profile and can be explained by the following reasons:

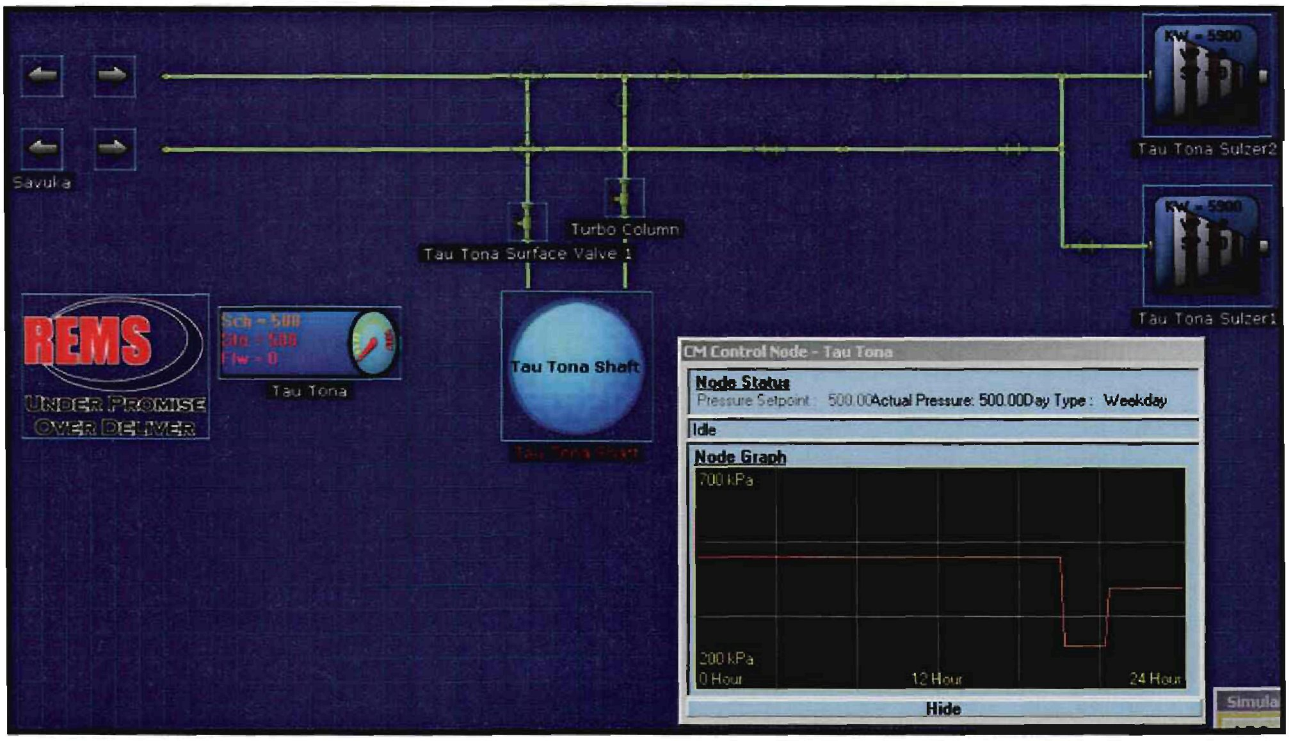
- The total flow splits into two different directions just before the above ground valves at Tau Tona shaft. It also has the effect that a smaller amount of air continues to flow to Savuka from the Tau Tona compressor house and it is hard to quantify the exact amount of air continuing through the line at any stage.
- There are an unknown number of bends and other flow restrictions evident in the compressed air line from Tau Tona to Savuka and this could lead to a deviation of the projected pressure profile from the actual pressure profile.
- The profile is not identically the same and this is due to constantly varying flow to the shafts which is not illustrated in the simulation. Constant flow (steady-state flow) values were used for the simulation, thus no erratic fluctuations took place over the time period.

3.5. Conclusion

The above illustrated scenarios showed a narrow resemblance between the trends of testing results and the trends of the simulated results. It can be concluded that the simulation model is fairly accurate and can be used to predict pressure drops, possible valve openings and flow balances for multi-pipe compressed air networks.

Systems comprising of one nett inflow of compressed air and two or more outflows can be simulated and the results used to aid in the safe control of such compressed air networks. This function will be explained in more facets in Chapter 4, where it will assist in the development of an optimised control philosophy for a compressed air network.

CHAPTER 4: Developing Control Strategies



CM Control Node - Tau Tona

Node Status

Pressure Setpoint : 500.00 Actual Pressure: 500.00 Day Type : Weekday

Idle

Node Graph

Various control strategies can be followed to achieve power saving results on compressed air systems. This chapter explains some of the control variations and also the development of an optimised control strategy for saving large amounts of electrical energy on compressed air rings.

4. Chapter 4: Developing Control Strategies

4.1. Introduction

In an industry where compressed air has been used in such a large array of applications, different control strategies had a certainty of developing. Successful recent DSM interventions prove that electricity can be utilised more efficiently than in the past. This has been shown in various mining applications already.

Throughout the years, different products and initiatives came onto the scene providing solutions for the efficient use of electricity. This is also the case for compressed air technologies. In the following chapters, some of these solutions will be explained and compared to each other.

Financial Implications of Power Saving in the Compressed Air Environment

Southern Africa's sole energy provider, Eskom, charges its clients by using various types of tariff plans. In the mining industry, a tariff plan called Eskom Megaflex is mainly used for electricity charges. Peak periods, as per the Megaflex tariffs, are between 7:00 and 10:00 on a weekday morning and between 18:00 and 20:00 on a weekday evening.

By using the Megaflex pricing structure, a short summary is given in Table 4-1. Cost savings for various compressor capacities are listed. These savings were calculated for a yearly period. The 40-hour week saving was calculated by working in an annual three-week shutdown period and the 168hour week was calculated from the assumption that continuous operation took place.

A simple calculation for calculating electrical savings can be used:

$$ECY = MC \cdot \frac{1}{MotEff} \cdot h \cdot d \cdot w \cdot \frac{R}{kWh} \tag{69}$$

ECY: Electricity Cost per Year [R/year]

MC: Motor power [kw]

MotEff: Motor efficiency = 0.9

h: Operated Hours per day = 24 [hours/day]

d: Number of operation days per typical week = 7 [days/week]

w: Number of weeks per year operated [weeks/year]

R/kWh: Standard Tariff rate

Compressor Capacity			**Annual Potential Savings (R)**	
kW	**liters/s**	**Cfm**	**40hr/week**	**168hr/week**
18	55	110	1,704	4,118
90	250	500	8,520	23,590
160	500	1000	15,146	41,937
315	1000	2000	29,818	82,563

Table 4-1 Potential savings from various capacity compressors [45]

As can be seen in Table 4-1, large energy savings, resulting in large financial savings can be realised when the optimum compressor is used for supplying air to a system. Over-specifying compressed air delivery results in air wastage and thus electrical energy wastage.

4.2. Comparison of different control strategies

4.2.1 Air Receivers

An air receiver is usually a large underground excavation, which can be totally sealed off and charged during periods of low compressed air demand. To determine if an underground air receiver would be economically viable, the following factors have to be taken into account:

1.) A large underground excavation must already exist and it must be able to be completely sealed off from the outside. No leaks must be able to occur and usually cement plugs are used as a sealing method.

2.) It should be identified as a high- or a low pressure receiver. High pressure receivers are more functional, but more expensive, since booster compressors are used for extra pressurisation of the system.

Advantages of such a system include the following:

- Air can be stored for peak usage times and this can eliminate the need for an extra compressor during peak shifts.
- Less pressure losses are the order of the day, as a surplus of compressed air has been saved.
- Sometimes not a costly exercise.
- Storage capacity can be a buffer for any momentary fluctuations in the air flow and pressure.

Disadvantages of such a system include the following:

- Large area needed in the beginning. Not always available.
- Regular leak detection on the receiver must be conducted.
- High pressure units might be potentially dangerous.
- Because of the large capacity of the main columns, the air receiver size might be negligible.

4.2.2 Supply Side Control

Another strategy for effective energy control in a compressed air system is to purposefully control the amount of compressed air which is delivered into the system by the compressors.

Compressors usually deliver a specific amount of compressed air at a specified pressure. The compressed air mass flow does not vary much on a standard centrifugal compressor, as the rotational speed stays constant for the duration of delivery.

When, however, guide vane control is used, the mass flow of compressed air through the compressor can be varied. There are however, dangers regarding this concept. The main concern for any operator of a compressor is a phenomenon called surge.

Surge

A definition for surge in a compressor is given by Eric Hore of Moore system controls: "*Surge is a phenomenon associated with axial and centrifugal compressors. It occurs when, for any given speed, guide vane angle or inlet valve position, flow in the system decreases sufficiently to cause momentary flow reversal in the compressor.*

Flow reversal occurs at an instant when the pressure developed by the compressor no longer exceeds the pressure in the downstream system. This is an unstable condition, which triggers self-oscillation between flow and pressure, resulting in erratic compressor capacity.

Surge appears as rapid pulsations in the flow and discharge pressure, which invariably causes damage to the compressor, associated piping and upsets to the process. Anti-surge and capacity controls are the main elements of compressor control." [46]

Surge Prevention

Anti-surge prevents surge by maintaining a safe minimum flow through the compressor. This is accomplished by manipulating a blow-off or recycle valve. The capacity control is generally based on a pressure (suction or discharge) or flow, by manipulating a suction or discharge valve, guide vanes or even the rotational speed of the compressor.

During steady-state operation, the capacity control of the compressor (discharge pressure, suction pressure or flow control) can conflict with the anti-surge control, since each attempts to vary the flow through the compressor in contrary directions. Therefore, the control system must also decouple the capacity control with the anti-surge control to avoid possible instability.

An instrument, called a Moore controller, can be used for this application. Moore Process Controls has developed a well-proven compressor control algorithm, utilising tested features to protect a compressor against surges while simultaneously optimising the efficiency of the compressor.

This algorithm had been successfully implemented on multistage blowers with multiple side-streams as well as single stage booster compressors, air compressors, multistage high compression ratio compressors (with pressure ratios greater than 30, meaning delivery pressure 30 times greater than the inlet pressure), multistage propylene and ethylene refrigerant cooling compressors with side streams.

Features of the compressor control algorithm include:

- Anti-surge control.
- Static control line.
- Dynamic control line.
- Safety line.
- Adaptive gain.
- Surge detector and counter.
- Capacity control.
- Decoupling of anti-surge and capacity control.
- Automatic start-up and shutdown sequences.
- Load-sharing (if required).

Compressor Characteristic Curve

A compressor-characteristic curve serves to illustrate a specific compressor's safe operational characteristics. It is easily identified by an exponentially decreasing curve over the x-axis, called the surge limit line. Surge occurs when a compressor is operated in the area above this line.

The figure below illustrates a typical compressor curve, as well as the characteristics of different guide vane positions.

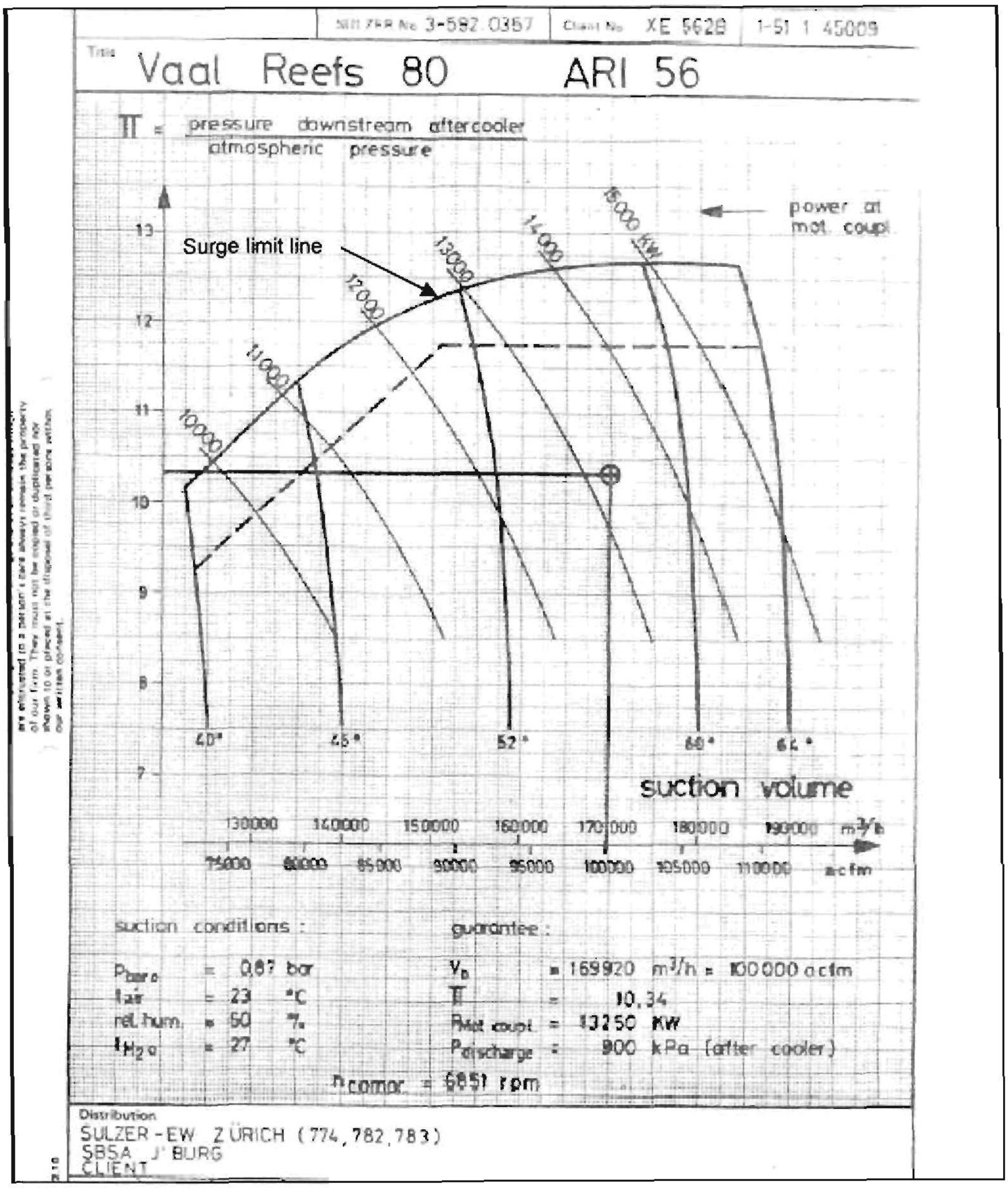


Figure 4-1 A compressor curve of a Sulzer compressor. Note the variable guide vane openings 40% - 64% and their characteristic lines |47|

As mentioned on the previous page, the Moore controller is equipped to control a compressor's characteristics within 7% - 8% of the surge limit line, by using the abovementioned methods. It is not uncommon to control compressor functionality as close as 5% of the surge limit line. This artificial line is called the surge control line.

If the compressor should be operated in the area above the surge limit line, the compressor will go into surge and if this continues for almost any given time, the compressor will sustain considerable damage.

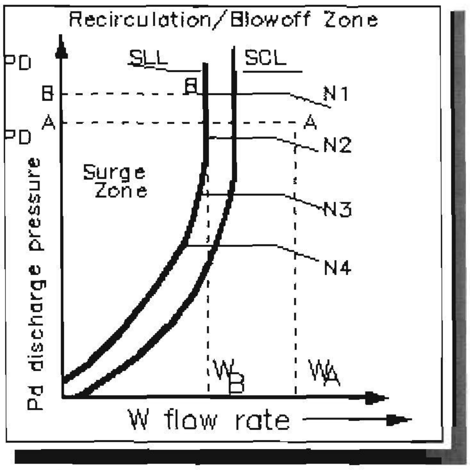


Figure 4-2 Illustration of a surge limit line (left) and a surge control line (right). Note the same profile, only about 7% - 8% to the right [48]

Load Sharing

Compressed air systems usually vary in the number and types of compressors used, the physical layout of the system and the amount of compressed air applications drawing air from the system. Each compressor will also differ from each other and this might also pose as a problem when optimal guide vane control is of significance.

All the abovementioned factors can cause compressors to operate inefficiently, cancelling out the positive effect that guide vane control might have on the compressor delivery. To prevent this from happening, a method called load sharing can be used.

Load sharing is the process where compressors in the same system, operating in parallel, sharing the same or different characteristics, are operated to equally bear the necessary load. By effectively sharing load, compressors can be operated safely from the surge limit line.

Using clever techniques and evaluating each compressor's characteristics and establishing a load-sharing line, load sharing can be successfully implemented. This method is a safe way of ensuring that all of the related compressors reach their surge control lines simultaneously.

Various methods of establishing load sharing can be used:

- Variable speed drives on the compressor.
- Management of the intake volume of the compressor, i.e. suction valve and the guide vane control.

Of the mentioned methods, guide vane control is probably the most widely used in the common trade. All of these methods can be used to actively setup each compressor to operate under proportionally equal loads, as well as not crossing the crucial surge limit line.

Example of Supply Side Control

By using a guide vane controller, i.e. a Moore controller, a pre-specified pressure profile can be followed by the compressor. A 24-hour profile can be inserted in a control system and the Moore controller will adapt the compressor delivery accordingly.

The pre-specified pressure will be measured from a common point in the system. The Moore controller will aptly control the inlet guide vanes or the suction valve in such a way, that the compressor delivers just enough compressed air to sustain the longed pressure at the measuring point.

The following case study, reference [48], was done on the Vaal River Operations of mining house Anglogold Ashanti. This case study shows the effective use of inlet guide vane control to accurately match the demand of the system's applications by sustaining a predetermined pressure profile.

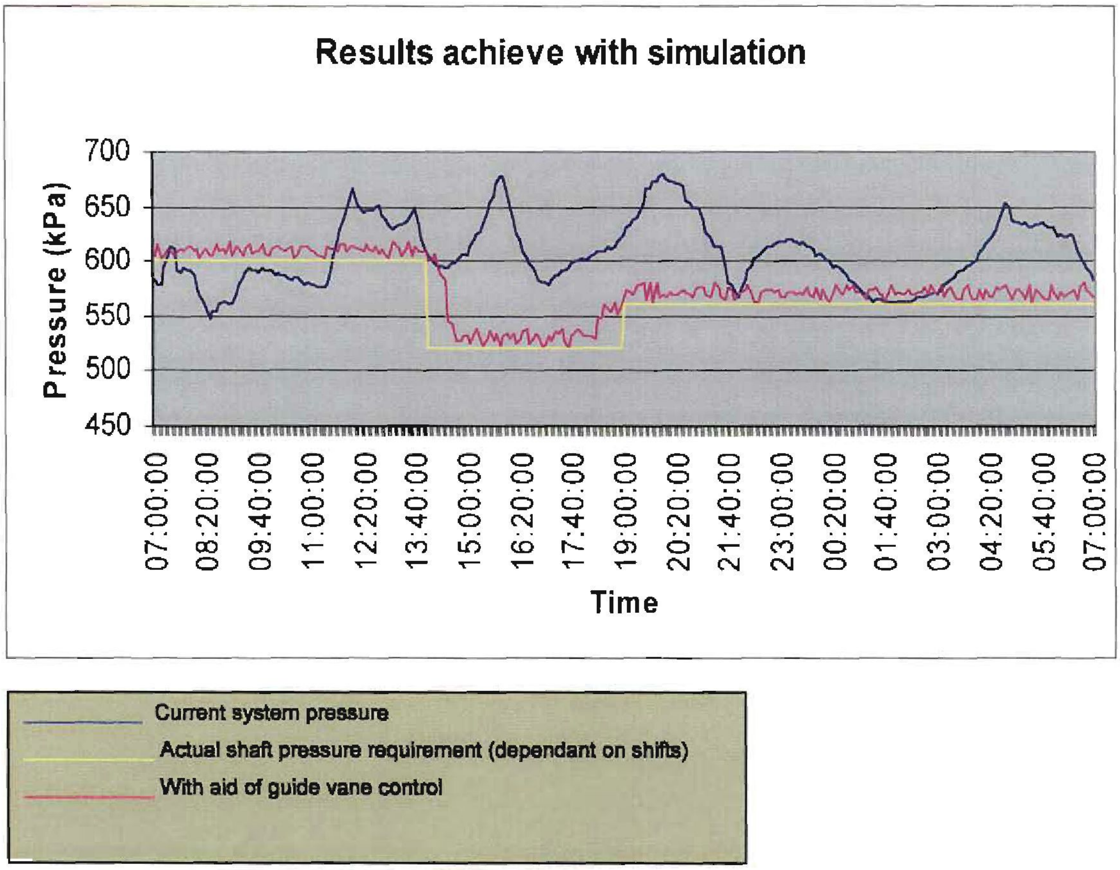


Figure 4-3 An illustration of the accuracy of following a pressure profile by using guide vane control [48]

Figure 4-4 gives a good indication of the close proximity that a pressure profile can be followed by using a proper guide vane control system. The yellow line indicates the pre-inserted pressure profile over the 24-hour period. The system pressure, at the time of testing, is shown and in pink, is shown in blue. The controlled pressure profile is shown in pink.

Guide vane control, via a Moore vane controller, is a very accurate and safe way of controlling system pressure according to the system's compressed air demand. By changing pressure set points throughout the day to various pressure points, guide vane control can optimally reduce load on the compressors and save power in the process. The average electrical savings throughout a 24-hour period can be seen in the following table:

Time per Day	Average Electrical Power Savings
07:30 – 14:00	2.79 MW
14:00 – 07:30	9.90 MW

Table 4-2 Average electrical savings on the Vaalriver compressed air ring

4.2.3 Demand Side Control

Another strategy is to actively control the compressed air demand of the system. For guide vane control to effectively cut back on guide vane openings and reducing load, an above ground upstream pressure build-up is required.

Various techniques can be applied and mainly two will be discussed in this section:

- Above ground air control systems
- Underground-air control systems

Above ground Air Control Systems

Above ground air control systems are usually identified by above ground air control valves at each shaft, controlling the amount of air flowing downstream. When a valve is throttled closed, compressed air mass flow down the shaft is minimised and a build-up occurs in the above ground compressed air piping system.

The upstream pressure raises enough to trigger the guide vane controller to counter the effect and minimise the inlet guide vane angles. Minimising these angles will allow just enough compressed air to enter the system to drop the rising pressure to the desired set point and sustaining it.

To types of valves are ordinarily used for this application:

- Above ground control valves
- Pressure sustaining valves

Above Ground Control Valves

An above ground control valve is inherently a normal manual valve with an actuator fitted to the valve handle. The valve opening position can automatically be controlled via a SCADA and PLC system, so that only the desired amount of compressed air can be supplied to the users downstream.

The valve receives a position from the controller and acts accordingly. All communications to and from these automatic devices usually takes place through the use of fibre optic cables, single- or multi-pair copper wiring or radio links.

Pressure Sustaining Valves

Pressure sustaining valves consist out of a valve, fitted with an actuator and 2 pressure transmitters: one upstream and one downstream. The actuator at the valve is controlled via the use of a PLC, which receives its set points from the SCADA or a central controller, in the form of a pressure set point. By comparing the downstream pressure to the set point, the valve will automatically adjust its position to deliver the preferred downstream pressure.

An advantage of an above ground air control system is that it is an inexpensive way of minimising air flow downstream, although not always the most effective way. If there are many air users or leakages underground, an above ground control valve would probably be fully open to allow maximum compressed air to flow to the users and minimise pressure loss. This would mean no pressure build-up and most likely no extra savings on the compressors.

Figure 4-5 illustrates the automatic above ground air control system that is being implemented at the West Wits Gold mining section of Anglogold Ashanti. Manual testing was conducted beforehand and it was found that between 18:00 and 20:00, the valves on the surface at each shaft could be throttled back considerably, constituting into a considerable upstream pressure build up and thus also energy savings.

The above ground control strategy in Figure 4-5 shows a central control room from where pressure set points are sent out to the various PLCs at each shaft. The PLCs give the necessary signals to the actuators at each of the pressure sustaining valves and they then deliver enough compressed air at the correct pressure. All pressure, temperature and flow instruments are shown as balloon tabs and are necessary for air balances and proper control.

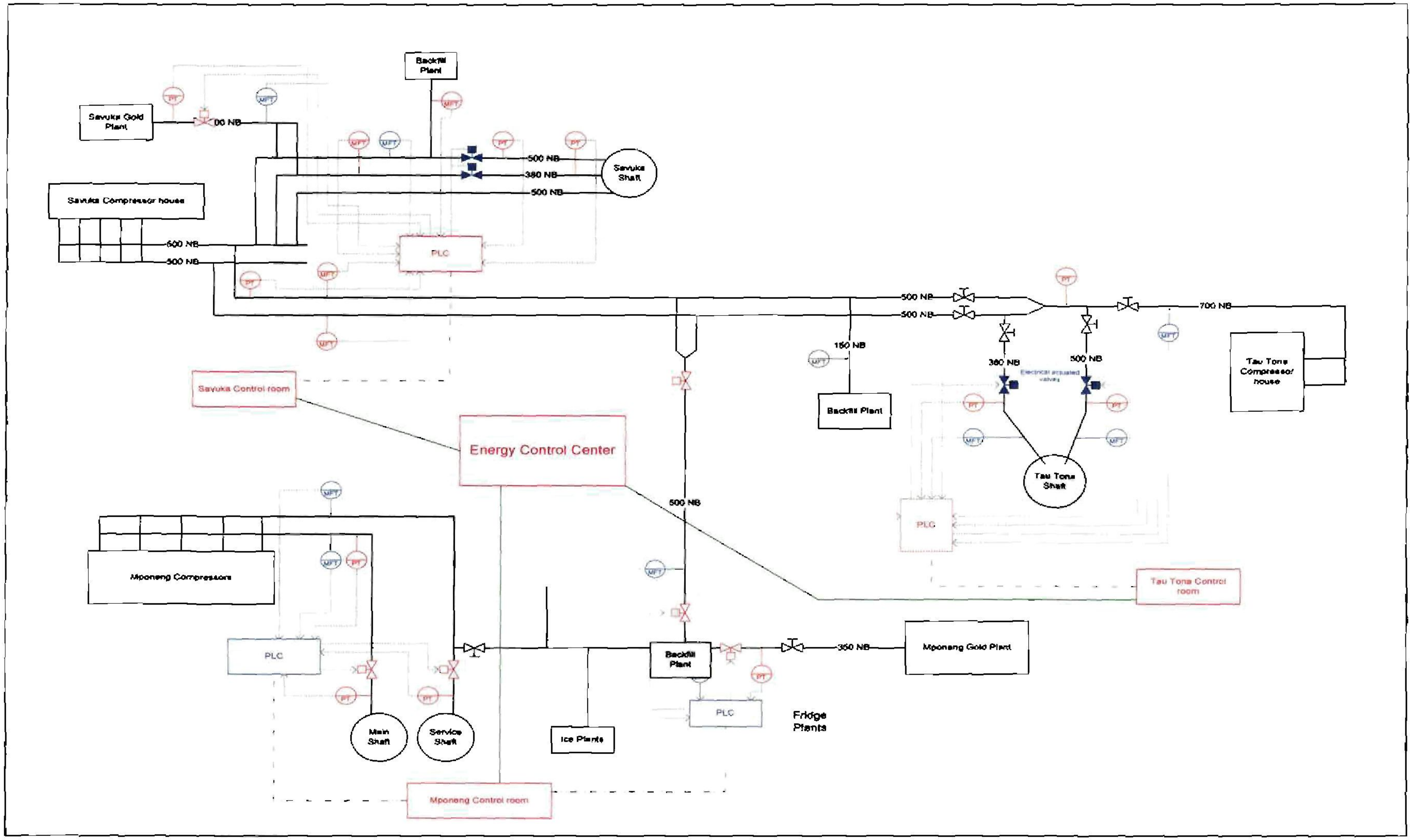


Figure 4-4 A typical above ground control system which will be implemented at West Wits compressed air ring[5][6]

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[5] *Personal communication – Mr. P.L. du Toit, Turbo Machinery Manager, Anglogold Ashanti and Mr. A. Garbers, CIC Engineer, Anglogold Ashanti*

[6] *Nominal Bore (NB) indicates internal pipe diameter*

Underground-air control Systems

Another form of demand side control is underground-air control. Underground-air control is the most efficient way of causing an upstream pressure build-up. It comprises of control/pressure sustaining valves on each underground level, only allowing the exact amount of air to pass through to the level. If no air is needed, the valve can be closed off, causing no air wastage.

Each of these valves is operated in the same way as the above ground control valves in the previous section. A PLC at the valve receives information from a PLC on the surface and operates the valve accordingly. The valves can also be controlled by valve position or by pressure set points.

The screenshot below is from the REMS CM$^{©}$ energy management controller used at Kopanang gold mine near Orkney, in the North West province in South Africa. It can be seen that there are 4 main above ground valves and 39 sub-level valves. Each valve receives a position set point from the main controller and acts accordingly. Red crosses show closed valves and blue arrows show active mining levels.

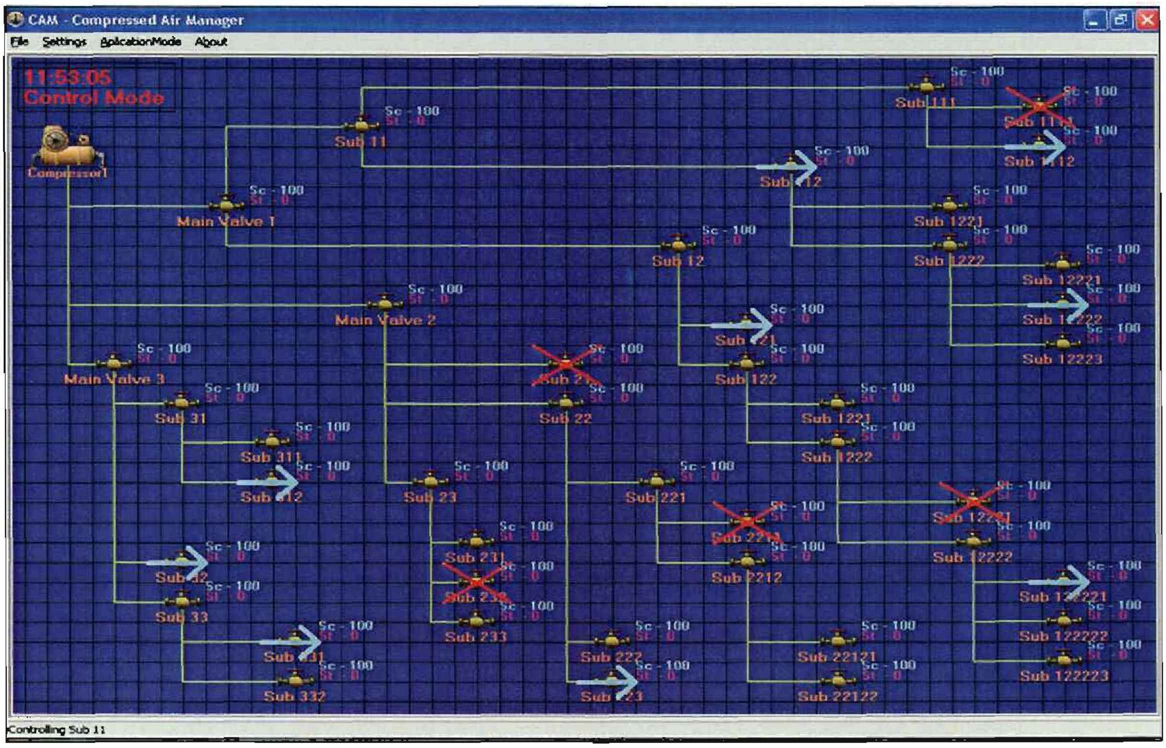


Figure 4-5 A screenshot of the REMS CM© underground-air controller at Kopanang mine

The next figure shows the underground system layout of Tau Tona gold mine, near Carletonville, in the North West province South Africa. The levels show control valves, pressure and flow transmitters, as well as the compressed air network towards each level and vertical shafts.

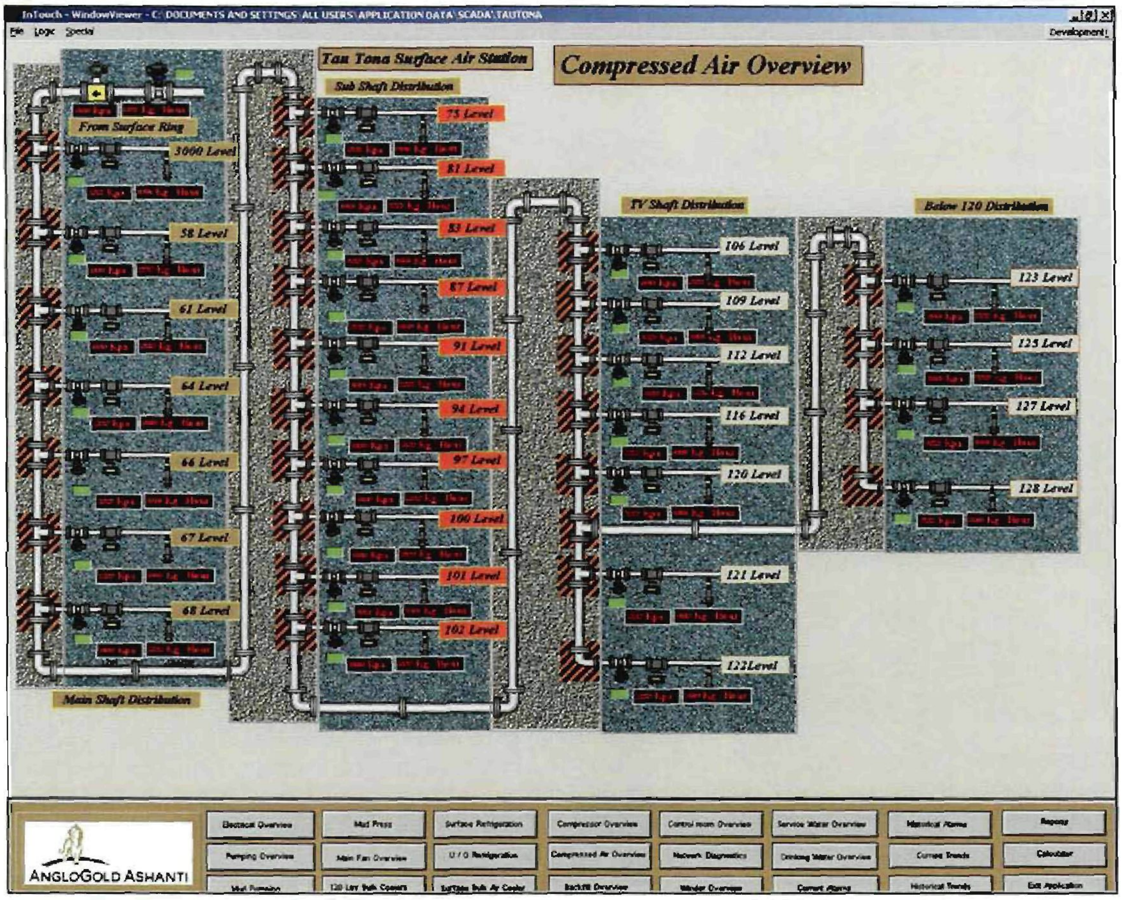


Figure 4-6 Tau Tona gold mine's underground air reticulation system

The main difference between above ground air control and underground control is the fact that above ground air control causes less air to flow down the shaft to all the levels, even those who are in need of air. This causes a lower overall pressure underground and could cause difficulties for certain underground compressed air applications.

By using underground control, all levels requiring air will always have sufficient air and those levels that are wasting air can be closed down. This will cause the necessary upstream pressure build ups, without the risk of having too little compressed air flow to critical equipment.

Leak Detection and Recommended Air Pressures

Leak detection and finding the recommended pressures for specific applications during different times of day, are probably two of the cheapest ways of saving energy in the compressed air environment. All that is needed is a dedicated compressed air supervisor who can regularly inspect the compressed air piping network for leakages, as well as someone who can determine the minimum or optimal air pressures for compressed air applications in the shaft during different times of day.

Leakages in the compressed air network are a very common problem in the mining industry. Negligence in maintaining these pipes is the main cause of naturally-caused leakages. The other form of leakages is those that are the result of mining personnel that leave the compressed air drill connection points or manual section valves open. Theft and purposeful damages to these connection points are also sometimes causes for leakages.

Except for the fact that air columns might be leaking air, other applications can also be causing headaches. Faulty valves, poorly boxed-up flanges, worn seals or gaskets are also prime candidates for unnecessary pressure losses. Agitation also uses a lot of compressed air and determining the correct sizes or baffling the feed lines can also minimise compressed air loss.

By determining the correct pressures for applications throughout the day, large energy savings can be initiated. For instance, during certain periods of the day, no drilling takes place. Less air is obviously needed and because of the low pressure needed by other applications the total air pressure can be lowered by 100 kPa to 200 kPa. By doing so, fewer compressors can be operated and those operating can be set to deliver only enough air to sustain the lowered pressure set point.

This will cause reasonable power savings and all that is needed is a preset pressure schedule over a 24-hour profile. By implementing uniform, structured leak detection inspections and determining the correct pressures for applications throughout the day, fair amounts of energy can be saved without any expensive infrastructure upgrades.

4.3. Optimised Control Strategy

This section discusses a generic, optimised control strategy, which was found through evaluating various factors, including those discussed in the previous section. As not all mining operations are the same, many factors play part in the construction of such a system. Some of these include:

- Operating shifts
- Physical layout of the mine
- Type and amount of compressors
- Status of current compressors
- Existing infrastructure
- Type and amount of compressed air users

Another factor that is important for such a system is that production should not be influenced at all costs. Any unnecessary drop in the system pressure could result in rock-drills not operating optimally or loading boxes not opening and closing quickly enough. Both of these will cause production losses.

Agitation is also a factor that can be influenced by having a too low system pressure. When agitators are not operating efficiently, backfill will harden and backfill plants can be clogged up. This causes increased maintenance and cleaning up sessions, which wastes man-hours and money.

Safety can also be influenced by a system pressure being too low, as it is required by law that refuge bays in the shaft are always to be pressurised. If a fire starts somewhere in the shaft, refuge bays are a worker's only escape. Without having a high enough pressure in the refuge bay, fire and gas can intrude into the chamber of the refuge bay with tragic consequences.

Main Optimising Solution

After evaluation of the above, it was found that the heart of the solution was to sustain minimum pressure during all periods of the daily mining schedule. An optimised solution should always supply just enough compressed air to the system, so that the minimum required pressure would be satisfied. This will amount to the most energy efficient solution.

The optimum control strategy was configured by following the above stated principle and combining many of the control strategies discussed earlier in the chapter. It was found to theoretically be the most accurate, safe and sustainable control strategy for efficiently controlling a compressed air ring and gaining large energy savings.

4.3.1 Optimised Control Strategy Design

The main design parameters of control are the following:

- Central control system – Command system
- Compressor discharge capacity control – Supply side control
- System above ground pressure control – Demand side control
- Compressor selection

Central Control System – Command System

Before combining the different strategies, it is important to realise that a central control system is of extreme importance. Without a brain the body would not function. A central control system should be in charge to change the system variables over a 24-hour profile, so that the rest of the system can adapt to the commands.

Such a control system should be of a robust nature, however easy to use. The system will receive information regarding the system pressures, temperatures and flows and taking that info into account will make informed decisions. It is important for the system to always operate within the safe parameters set by the components' limitations.

The control system will give commands to PLCs in the system, which safely controls various components in the system.

The following PLCs will receive commands to adapt:

- PLCs at compressor control panels (Guide vane control and switching on/off of compressors)
- PLCs at above ground and/or underground station control valves

The compressor control system will change the desired pressures of the system by adhering to a pressure profile entered beforehand by the user. The control system will change pressure set points at selected nodes in the compressed air ring. Upon changing these set points, the rest of the control will react to the changes required and manage the amount of air accordingly. The rest of the control will be discussed hereafter.

Compressor discharge capacity control – Supply side control

As discussed earlier in this chapter, demand side control is the control of inlet guide vanes or inlet suction valves, to manage the amount of compressed air flowing into the system through the compressors. It was decided to use the more accurate means of a Moore guide vane controller for the control system, as it was a safe and accurate way of controlling the compressed air flow. These controllers will control the compressor discharge pressure, according to a given pressure set point.

System Above Ground Pressure Control – Demand side control

Depending on the amount of underground leakages and compressed air users, the type of demand side control (above ground or underground control) will be tailored. If the amount of leakages and underground compressed air users are relatively low or if the required air pressure underground is not required to be high, above ground air control valves can be used to limit the amount of air flowing down the shaft. In many cases it will be sufficient to only use above ground air control valves to manage the compressed air flow.

If the number of underground leakages and/or amount of compressed air users is too high, underground-air control systems will be more effective in controlling and isolating underground stations' air supply. In summary, if the underground pressure is important, underground control would be the better option, otherwise above ground air control would be sufficient. Above ground and underground station control valves receive pressure set points from the control system and adjust accordingly.

Compressor Scheduling

Compressor scheduling is an important part of the optimised control strategy. By incorporating a system, much like a task scheduler, but only for prioritising compressors, it can be ensured that the most efficient compressors will always be operated. Operation of the most efficient compressors is important, as an inefficient compressor consumes more electric energy to supply the same amount of compressed air as a more efficient machine.

The control system will have an integrated compressor scheduling subdivision in the Compressor Manager (CM) controller. This system will operate by enabling the user to enter the various compressors into a table, categorising them according to their efficiency. When all the compressors' guide vanes are at minimum opening, the control system senses that there is an opportunity to switch off a compressor. The controller will then make use of the compressor scheduling sheet to determine which one of the compressors is the most inefficient and then switch off the specified machine.

If the guide vane openings are still at a minimum, the control system will again make use of the compressor scheduling sheet to switch of machine that is now the most inefficient. This system also operates in reverse and if the guide vanes of the compressors currently operating are at a maximum opening, the controller will firstly check for the availability of compressors and then switch on the next more efficient compressor from the compressor scheduling sheet.

4.3.2 Characteristics of Optimised Control Strategy

The above-stated optimised control strategy can be explained in the form of a normal functional analysis flow diagram and a table containing all of the functional parameters. These parameters explain the different logical blocks in the flow diagram and illustrate how they should be followed in the functional analysis flow diagram.

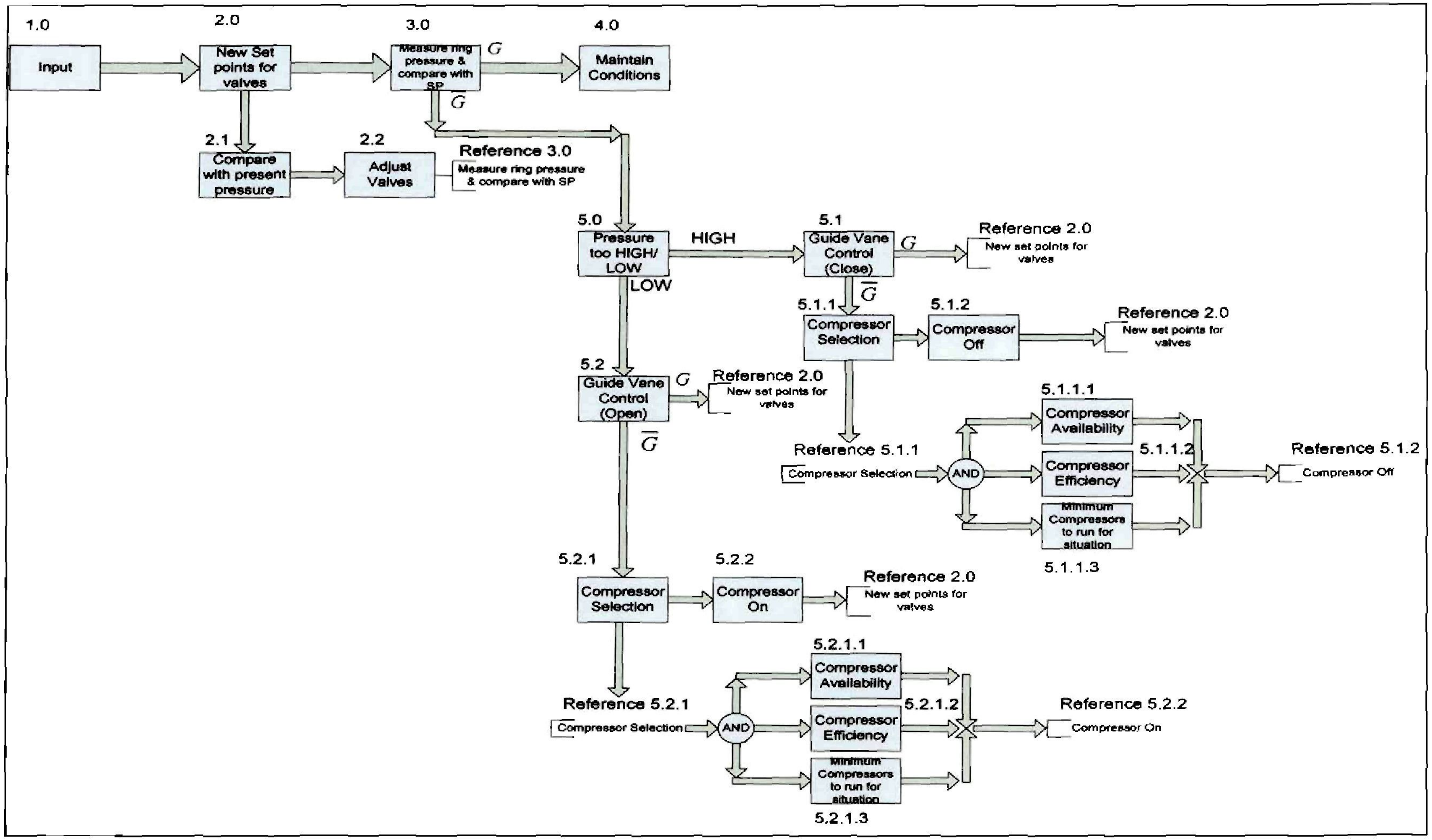


Figure 4-7 Functional analysis flow diagram of the optimised control strategy

FUNCTION	FUNCTIONAL PARAMETER
1.0- Input	Current Pressure, Time and Pressure against Time profiles as well as compressor scheduling data.
2.0 - New set points for valves	Data from Pressure against Time profile sent to pressure sustaining valves at stations.
2.1 - Compare with Present Pressure	Measured Pressure at station must be equal to Pressure on profile at given Time.
2.2 -Adjust valves	If 2.1 not satisfied, valve will automatically adjust accordingly.
3.0 - Measure ring pressure & compare with set points	Measured Pressure at current 3 ring positions must be equal to Pressure against Time profile at given Time.
4.0 -Maintain conditions	If 3.0 satisfied maintain condition and repeat functions 1.0-3.0.
5.0 -Pressure too high/low	If 3.0 not satisfied, continue to function 5.1 (High) or 5.2 (Low).
5.1 - Guide vane control (close)	Measured pressure higher than Profile Pressure at given time.
5.1.1 -Compressor scheduling	Following three steps are explanatory.
5.1.1.1 - Compressor availability	Check which compressors are available at given moment and flag them as available.
5.1.1.2 - Compressor efficiency	All compressors will be listed according to their efficiency ratings and will be used when flagged as available. The most efficient compressors will be the most regularly operated machines.
5.1.1.3 -Minimum compressors to run for situation	Predetermined setting to acknowledge minimum number of compressors for necessary air demand.
5.1.2 - Compressor off	Choose appropriate compressor to be switched off, according to above 3 functions.

FUNCTION	FUNCTIONAL PARAMETER
5.2 - Guide vane control (open)	Measured pressure higher than Profile Pressure at given time.
5.2.1 -Compressor scheduling	Following three steps are explanatory.
5.2.1.1 -Compressor availability	Check which compressors are available at given moment and flag them as available.
5.2.1.2 -Compressor efficiency	All compressors will be listed according to their efficiency ratings and will be used when flagged as available. The most efficient compressors will be the most regularly operated machines.
5.2.1.3 -Minimum compressors to run for situation	Predetermined setting to acknowledge minimum number of compressors for necessary air demand.
5.2.2 -Compressor on	Choose appropriate compressor to be switched on.

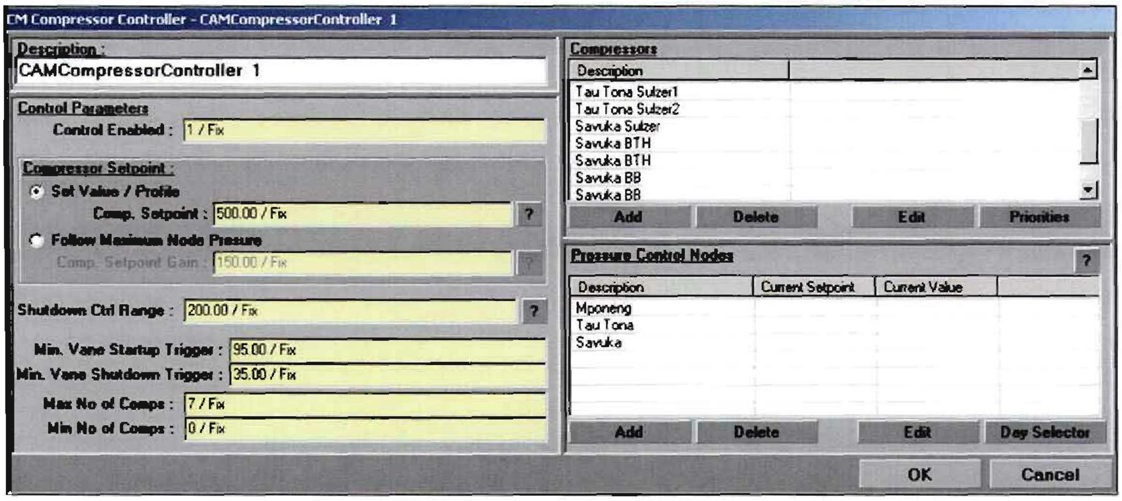
Table 4-3 Functional parameters explaining the functional analysis flow diagram

4.4. Verification of Optimised Control Strategy

4.4.1 Introduction to the Case Study

Testing was done on the Tau Tona and Savuka sections of the West Wits compressed air ring as explained in Section 3.3 – Simulation Process. The tests were conducted to verify the previously discussed above ground compressed air simulation model, as well as the optimised control strategy defined in the previous section. All of the testing was done manually and incorporated every aspect of the proposed control strategy.

As can be seen in Chapter 3, Tau Tona and Savuka were isolated from Mponeng mine and were regarded as a ring on their own. All the compressors in this specified ring were evaluated for their installed capacities and compressor efficiencies. A compressor scheduling table, as illustrated in Figure 4-9, was then drawn up and the compressors were prioritised according to their efficiencies.



Description : CAMCompressorController 1

Control Parameters

Control Enabled : 1 / Fix

Compressor Setpoint :

● Set Value / Profile

Comp. Setpoint : 500.00 / Fix

○ Follow Maximum Node Pressure

Comp. Setpoint Gain : 150.00 / Fix

Shutdown Ctrl Range : 200.00 / Fix

Min. Vane Startup Trigger : 95.00 / Fix

Min. Vane Shutdown Trigger : 35.00 / Fix

Max No of Comps : 7 / Fix

Min No of Comps : 0 / Fix

Compressors

Description	
Tau Tona Sulzer1	
Tau Tona Sulzer2	
Savuka Sulzer	
Savuka BTH	
Savuka BTH	
Savuka BB	
Savuka BB	

Pressure Control Nodes

Description	Current Setpoint	Current Value	
Mponeng			
Tau Tona			
Savuka			

Figure 4-8 REMS CM compressor scheduling sheet – Priority 1 compressor at top

Optimum Amount of Operating Compressors

The optimised control strategy states that only the optimum amount of compressors must be operating during the selected period. Compressed air demand is the main deciding factor when choosing the correct amount of compressors to sustain the required pressure in the ring. When a lower pressure is needed, less mass flow can be delivered to sustain the desired pressure.

When testing commenced, 4 to 5 compressors in the ring were operational from the previous shift. As the drilling shift came to an end and the downstream users reduced, the system pressure started to rise and an opportunity to initiate the control philosophy occurred. Blasting occurs during the testing period from 15:00 until 20:00 and little compressed air is used during this shift.

Implementation of the Control Strategy

As discussed in Section 3.3 – Simulation Process, many system variables were changed several minutes before 18:00. The first variable that was changed was the number of operating compressors. The compressor scheduling list was evaluated and the number of operating compressors was gradually decreased from 5 to 4. As the pressure was still much too high, another compressor was taken offload. It was found that 3 compressors, with the aid of guide vane control, were sufficient to sustain the required downstream pressure of 340 kPa.

The next step, after establishing the optimum amount of compressors for the efficient operation of the system, was to lower the pressure set point of the guide vane controllers to a value that will result in a 320 kPa pressure in the shaft. The Moore controllers automatically adjust the positions of the inlet guide vanes to accommodate the variances in the system pressure and prevent surge.

Although the required pressure in the shaft could be 320 kPa, the Moore controller set point will most probably be a relatively higher value. The reason for this is that there are flow and friction pressure losses in the pipe networks leading to the shaft. This was proven during this particular testing. It was found that the pressure delivered at the compressor discharge for sustaining a downstream pressure of 320 kPa, was 430 - 440 kPa.

Step 3 was to throttle the valve positions of the above ground valves. Throttling of the above ground valves at Tau Tona was implemented successfully during the testing, as Tau Tona does not suffer from many leakages in the downstream area. After establishing an optimum valve position for the Tau Tona above ground valves, it was used as a specific set point for the control philosophy.

Savuka's above ground valve was fully open during the testing, since there are many leaks in this mine, which already resulted in a minimum downstream pressure. Further closing of the Savuka above ground valve would have resulted in a too large pressure drop downstream. It can be noted that the Savuka compressor that was chosen for the control philosophy also makes use of guide vane control, but because of the high compressed air demand at Savuka, it was also operating on full load.

In summary, the settings that were found to form the most ideal circumstances for the implementation of the proposed optimised control strategy were:

Tau Tona – Savuka **Control Settings for Eskom peak demand period (18:00- 20:00)**	
Pressure Set points – Above Ground Valves	320 kPa / 18% open
Pressure Set points - Moore Controller	440 kPa
Compressor Scheduling	Tau Tona - Sulzer 1
	Tau Tona - Sulzer 2
	Savuka - Sulzer

Table 4-4 Ideal peak-time set points for the Tau Tona-Savuka section

The above settings were identified through a gradual process. It is a setting which is just enough to not influence any production or cause safety concerns on, or in the shaft area of the Tau Tona – Savuka section of West Wits. The settings may vary slightly for this specific section, depending on the amount of leakages and compressed air users that might occur.

Tau Tona and Savuka each operate at slightly different pressures over a 24-hour period. For the above stated control philosophy to be effective, an optimised pressure profile over a 24-hour period must be followed by the system settings and hardware. The optimum pressure profile that was established for the Tau Tona-Savuka complex through testing can be seen in Figure 4-10 on the next page.

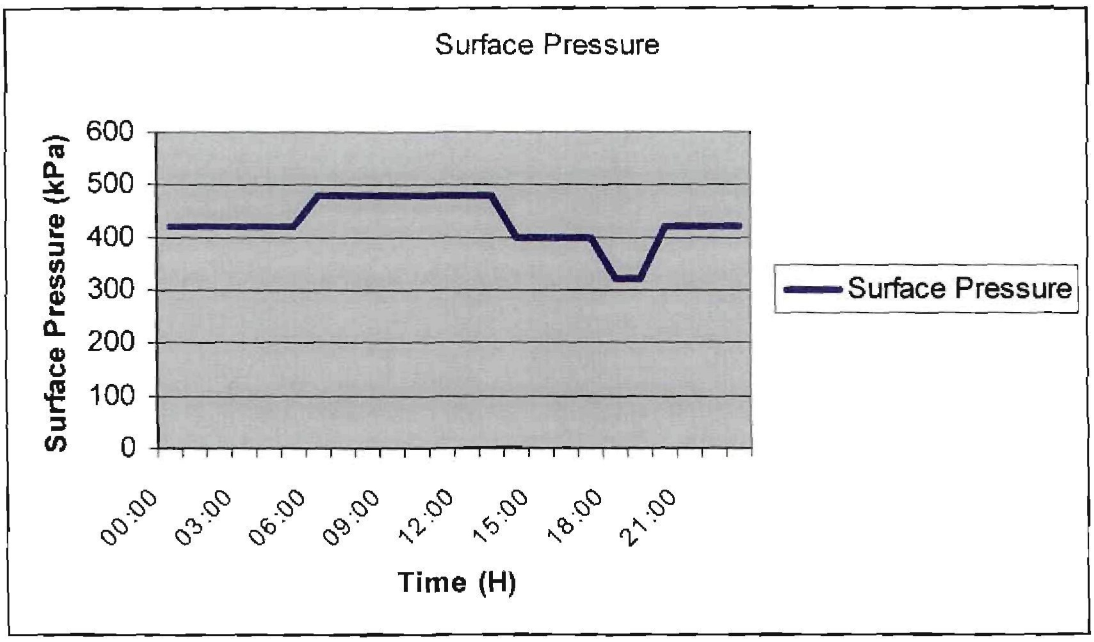


Figure 4-9 Proposed pressure profile for Tau Tona – Savuka complex over 24-hours

When one plots the data of the pressure delivered by the compressors, measured at the specific positions where the pressure set points are of importance, it becomes visible that the strategy is fairly accurate. The following figure illustrates the real-time test pressures following the pressure set points closely.

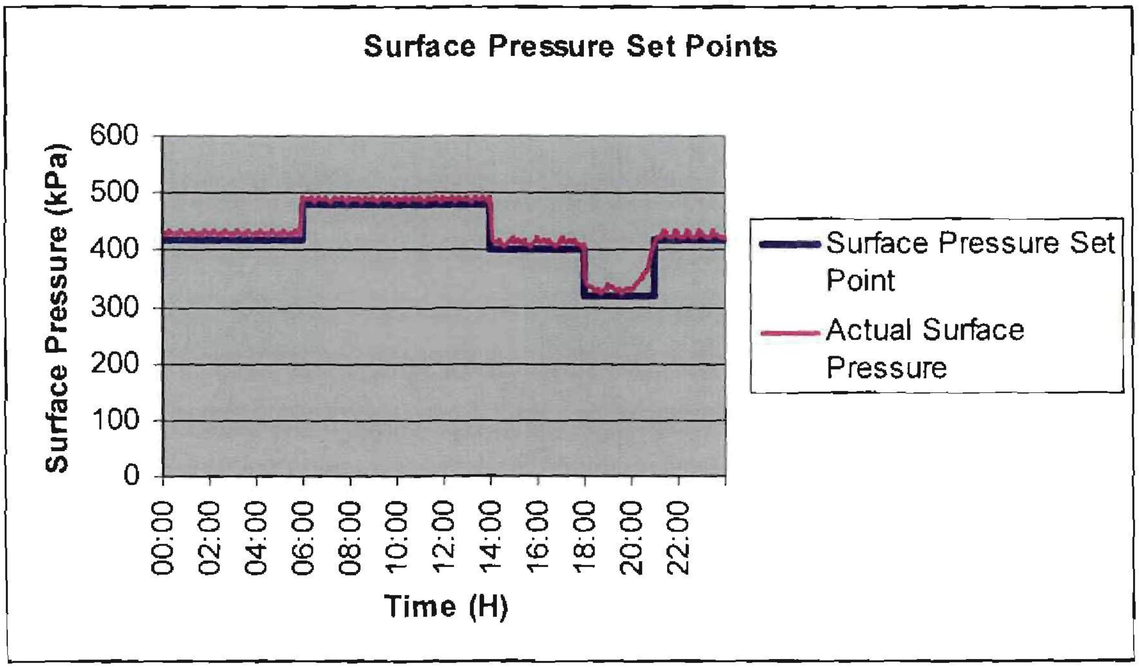


Figure 4-10 Optimised control strategy (as explained above) following tested optimised pressure profile

The same process can be successfully followed and implemented on various other compressed air rings. The settings need only be adjusted to fit the needs of the specific compressed air ring. Other shafts might use higher or even lower pressure set points. Some compressed air rings won't use above ground control valves, but will rather opt for underground control valves. But inherently, the same strategy can be used to create the same results.

Power Savings

The most energy efficient way of operating the compressors is when the exact compressed air demand is met in a compressed air ring. In comparison to a setup where the compressed air is over-supplied, delivering just enough compressed air constitutes large electrical energy savings. No compressed air will be wasted and therefore no unnecessary energy wastage occurs.

In the graph below, an illustration of the control strategy's power saving capabilities, specifically in the Eskom evening peak period (18:00 – 20:00), is shown. Note that this period is also the main focus area of Demand Side Management, although energy efficiency is also possible during the rest of the day, following the same procedure.

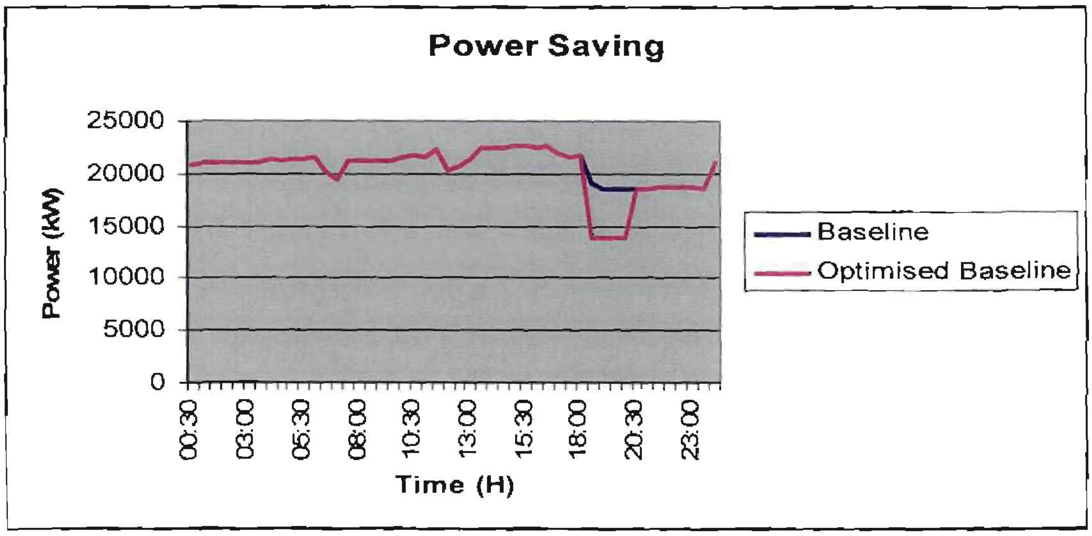


Figure 4-11 Illustration of peak-clipping. Energy is taken out of the Eskom evening peak period (18:00 – 20:00) [7]

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[7] *Personal communication – JJ van der Westhuizen, Energy Administrator, Anglogold Ashanti*

A summary of the control settings and the power savings is given in the following two tables. All of these results where realised through the implementation of the optimised control strategy and control settings, which in their own regard were derived from testing.

Reduction of power over peak demand period (18:00 – 20:00) is calculated by subtracting the new optimised power profile from the baseline power profile (developed from historic data). This reduction in power can be translated to cost savings using the Eskom Megaflex tariff rate.

Control	Time Initiated	Time Ended	Settings
Pressure Set points – Above Ground Valves	17:50	20:00	320 kPa / 18% open
Pressure Set points - Moore Controller	17:50	20:00	440 kPa
Compressor Scheduling			Tau Tona - Sulzer 1
	17:50	20:00	Tau Tona - Sulzer 2
			Savuka - Sulzer

Table 4-5 Control settings for the control of the Tau Tona – Savuka complex compressed air ring

Estimated savings (18:00 – 20:00)	
Electrical load reduction (MW)	4.77
Energy (GJ) per annum	8,929.44
Financial (R/c) per annum (estimated)	644,215.00

Table 4-6 Savings achieved during the verification tests

4.5. Conclusion

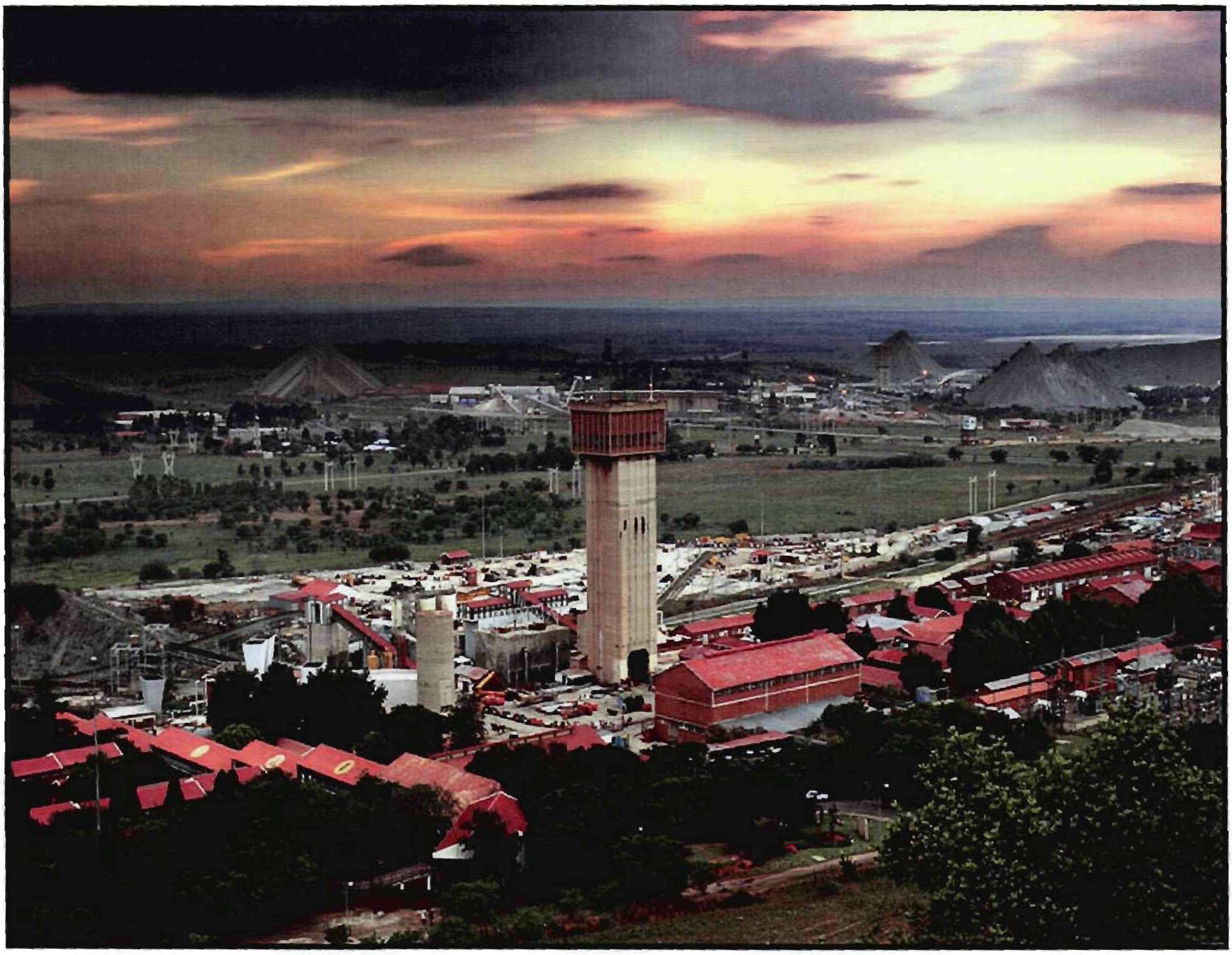
It was proven in practice that there are many different control strategies for compressed air systems in the mining and industrial industries. Most of them can be effectively used to manage compressed air flow in compressed air rings. Each of these control strategies has positive and negative aspects and by finding a combination between many or all of them, positive aspects can be enhanced and negative aspects eliminated.

As seen earlier in the chapter, it was concluded that the ideal control strategy would be one that incorporates various aspects of all the strategies, namely; supply side control, demand side control, having an automatic central control system and having a compressor selection scheduler. These four features make it possible to allow for very precise management of a compressed air ring.

It is important to have all safety interlocks built-in in any automatic compressor control system, as all of these signals must be positive before the electric control panels at each compressor can give the go-ahead for the start of any compressor. Moore-controllers are also very important in the prevention of compressor surge. The control system should always operate within all safety constraints.

A control system has been created, following the theory as discussed above, as well as manual testing of which the results were discussed in Chapter 3 – New Simulation Model for Compressed Air. The control system is a real-time energy management system and is designed to save energy by only causing the system to deliver the necessary amount of compressed air to the compressed air ring. This control system is implemented on various rings and will be discussed in the next chapter.

CHAPTER 5: Application of Control Strategy



To further verify the value of the optimised control strategy, case studies have been tested. In this chapter 4 different compressed air rings are evaluated and real-time testing conducted.

5. Chapter 5: Application of Control Strategy

5.1. Introduction

In Chapter 4 an optimised control strategy for operating compressed air rings in general was investigated, developed and verified through practical tests conducted on the West Wits compressed air ring. West Wits is a large compressed air ring and testing on this ring showed that the results of using the proposed control strategy on this specific ring were sustainable and accurate.

In this chapter, various other large compressed air rings will be examined and the effects of implementing the proposed control strategy on them will be discussed. Although different in character, they should deliver the same desired results, which are sustainable power savings. The compressed air rings that will come under discussion are the following:

- Kloof 1# / 3# gold mining complex (Goldfields mine)
- Kloof 4# / 7# gold mining complex (Goldfields mine)
- Rustenburg Platinum ring (AngloPlat)
- Vaalriver compressed air ring (Anglogold Ashanti)

All of the above mines make use of compressed air rings which incorporate and combine many compressors, linked together with intricate pipe networks which also consist of various valves, T-pieces, bends and many other equipment. These above ground networks were investigated in detail and the proposed control strategy was set up for each of them individually.

It is important to notice that the optimised control strategy on all of the following case studies were tested manually, incorporating the principles that were build in the REMS CM© automatic compressed air control system. The automatic system was finalised after real-time testing. The interface and operation of the system can be found in Appendix A. The REMS CM© automatic control system operates the compressed air system in exactly the same manner as the manual operation during the tests.

5.2. Application 1: Kloof 1# / 3# Gold Mining Complex

5.2.1 Introduction

Kloof Main shaft is part of Goldfields' gold mines located in the North West province of South Africa.

5.2.2 Site Details

Kloof Main shaft is located near Westonaria off the N12, en route to Potchefstroom from Johannesburg in South Africa.

Figure 5-1 Google Earth view of Kloof Main# [8]

5.2.3 System Details

Kloof Main# is also linked with Kloof 3#. There are two compressors located at 3# and eleven at Main#.

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[8] *Courtesy Google Earth*

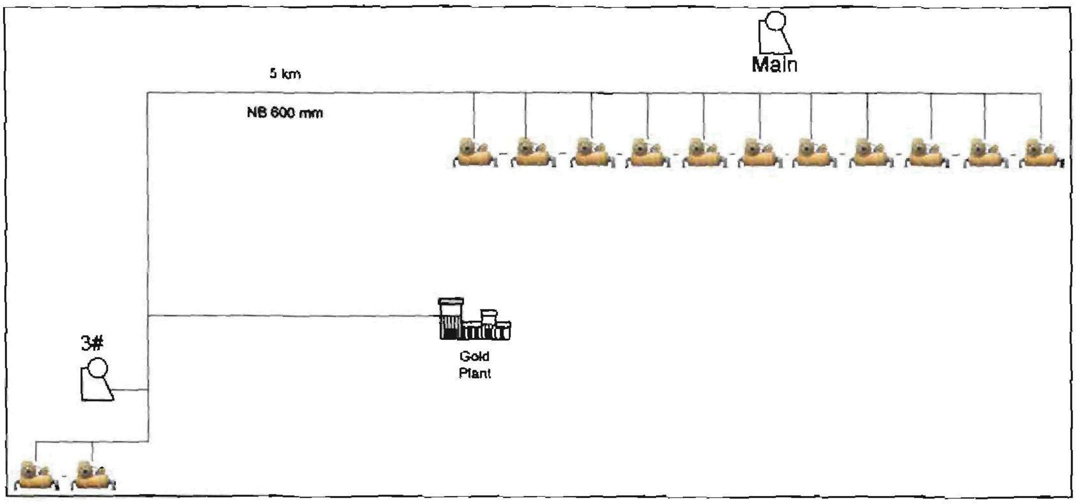

Figure 5-2 Layout of the compressed air system

Kloof 1#, or Main# as it is also known, is connected to Kloof 3# and supplements 3#'s compressed air needs throughout a 24-hour profile. In the event of isolating the column between these two shafts, 3#'s compressors will not have enough capacity to sustain a high-enough compressed air pressure for drilling and loading. Currently, 3# is under further development and is in dire need of compressed air during a 24-hour period. It is thus important that the column be kept open throughout the entire period.

Kloof 1#'s compressed air system consists out of the following compressors:

- 2 x 4.5MW centrifugal machines
- 2 x 4.2MW centrifugal machines
- 2 x 2.8MW centrifugal machines
- 2 x 2.5MW centrifugal machines
- 3 x 0.65MW piston-type machines

Kloof 3#'s compressed air system consists out of the following compressors:

- 1 x 4.2MW centrifugal machines
- 1 x 4.5MW centrifugal machines

It must be added that the two compressors at 3# were not tampered with for any testing. Thus, the baseline was formulated for 1# only.

A previous visit to Kloof 1# resulted in the following baseline with an average electrical power load of 22.87 MW during Eskom's evening peak period (18:00 - 20:00). The baseline below was constructed from a month's data. The month stretched from 20 June 2006 to 20 July 2006. This is illustrated in the figure below:

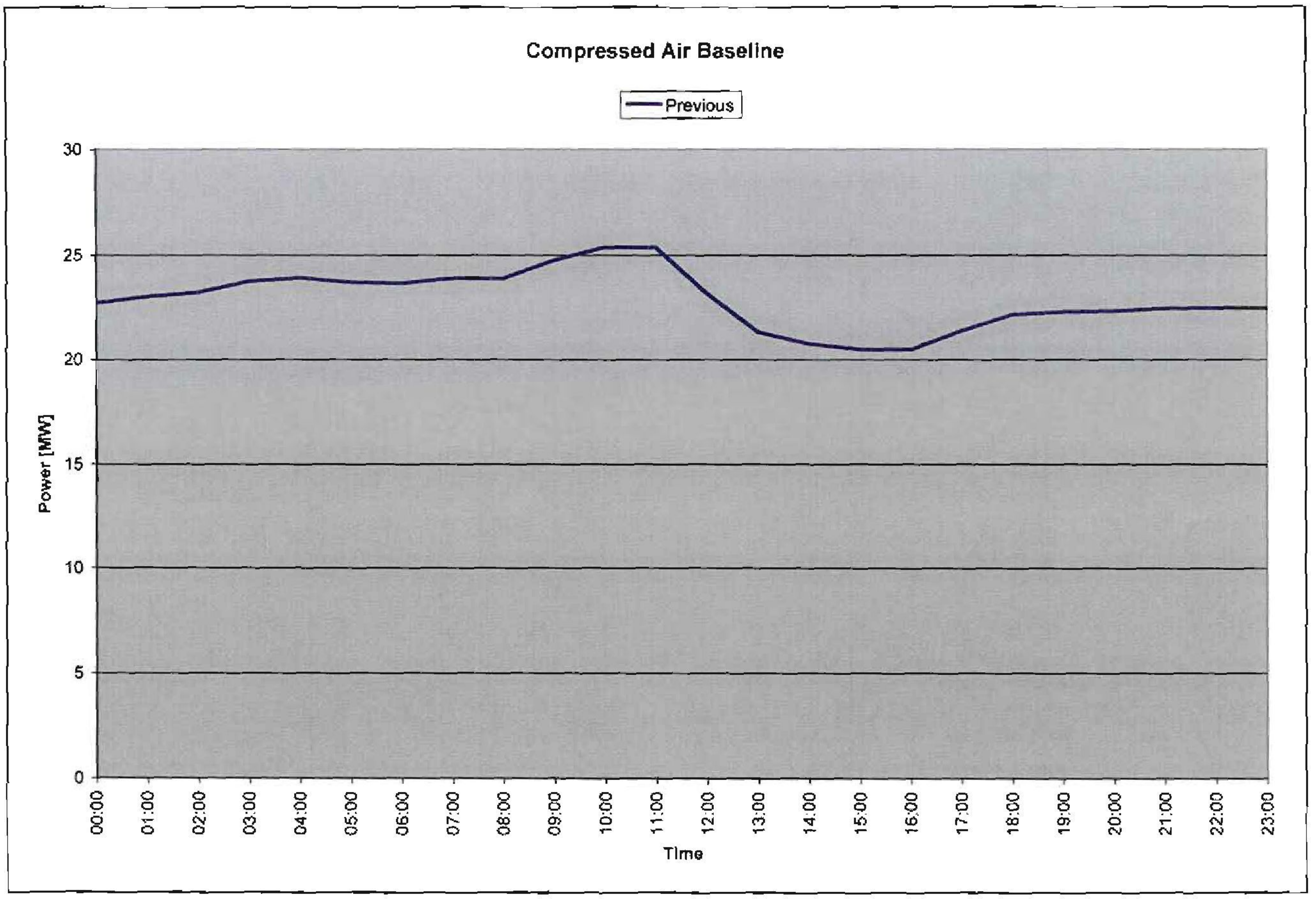

Figure 5-3 Kloof 1# baseline

5.2.4 Testing and Results

Testing was done over a seven-day period from 20 February to 27 February 2007. In essence, by lowering the overall delivery pressure of the compressors on 1#, operating the most effective compressors, as well as benefiting from the available guide vane control on two of the compressors at 1#, the overall load was reduced.

The constraints for the test were the following:

- No less than 400 kPa compressed air pressure on 2 sub shaft.
- No less than 420 kPa compressed air pressure above ground for the gold plant.
- There should be no complaints of low compressed air pressure from 3# personnel.

To be true to these constraints a combination of the following compressors was used. They are also the most efficient machines that were available during the testing period:

- Compressor no.6 (Demag) – 2.8 MW
- Compressor no.7 (Demag) – 4.2 MW
- Compressor no.8 (Demag) – 4.5 MW
- Compressor no.9 (Demag) – 4.2 MW
- Compressor no.12 (Sulzer) – 4.5 MW

Compressors 8 and 9 also made use of guide vane control to assist in maintaining the correct pressure. The guide vane angles were opened at 31% and 54% respectively for these two compressors during the testing period.

By operating only the above-stated compressors and utilising the current available guide vane control, an average electrical power profile, as shown in Figure 5-4, was achieved. It must be noted that this was achieved whilst still operating within the pressure constraints.

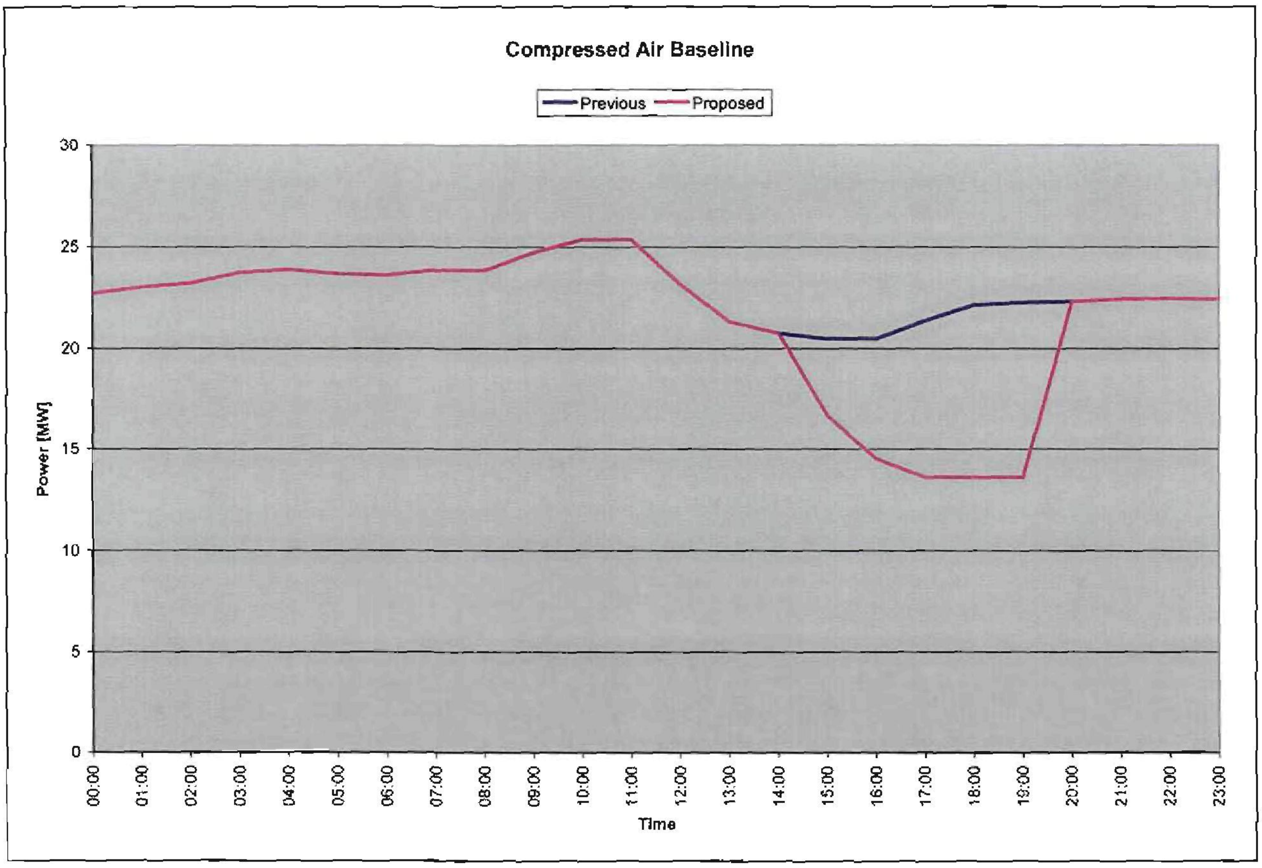

Figure 5-4 Proposed power saving profile

The demand side control strategy was not implemented on the Kloof 1# / 3# complex, as it was already operating on a minimum amount of compressors to sustain its minimum underground pressure of 400 kPa. Throttling an above ground valve would cause further pressure losses.

No underground valves were available for the testing purposes. It must be added that underground control valves would cause extra savings to be realised, as this would isolate areas of compressed air wastage and thus minimise the compressed air demand.

5.2.5 Summary and Conclusion

Testing on the Kloof 1# / 3# complex was conducted over a seven-workday period which stretched from 20-27 February 2007. By evaluating the system over a seven-workday period, an accurate average electrical baseline for a typical mining workday was determined. An average power saving of **9.2MW** was achieved during the

Eskom evening peak period (18:00 – 20:00), compared to the previously acquired baseline.

The results were achieved whilst being true to the above stated constraints. The performed tests proved that the optimised control strategy discussed earlier in this thesis could also effectively be rolled out on the Kloof 1# / 3# complex compressed air ring. The various savings are listed in the table below:

Estimated savings (18:00 – 20:00)	
Electrical load reduction (MW)	9.2
Energy (GJ) per annum	17,222.40
Financial (R/c) per annum (estimated)	1,242,212.00

Table 5-1 Savings for the proposed control

The following table is a summary of the necessary infrastructure required to realise the tested DSM potential automatically on Kloof Main#, as well as for the other case studies to follow:

Kloof Main infrastructure upgrades
Control Room and Communications
Description
Central PLC Equipment
Supervisory Software
Remote Communications Hardware
PLC and SCADA Engineering
Installation and Commissioning
Compressor Control Systems
Description
New PLC Installation
PLC Upgrading

Kloof Main infrastructure upgrades
Compressor Power Metering
Description
Power Monitoring Hardware
Shaft Air Consumption
Description
Kloof Main# Valve, Compressed Air Monitoring

Table 5-2 Infrastructure breakdown for Kloof 1# compressed air system [9]

5.3. *Application 2: Kloof 4# / 7# Complex*

5.3.1 Overview

The Kloof 7# compressed air system consists of seven compressors in total:

- 4 x centrifugal compressors
- 3 x piston type compressors used for emergencies.

Kloof 7# supplements Kloof 4# with compressed air via a subterranean link on 23 underground level. Kloof 4# makes use of one onsite centrifugal compressor as well as imported compressed air from Kloof 7#. The underground compressed air link between these two shafts, directs compressed air flow through a 6-inch bypass pipe underground. Kloof 7# is also the supplier of compressed air to the nearby gold plant.

The make and installed capacities of the centrifugal compressors found at Kloof 7# are the following:

- 1 x Sulzer 4.2MW
- 1 x Sulzer 4.5MW
- 1 x Demag 4.2MW

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[9] *Personal communication – Mr. Z. Scheulen, Chief Instrumentation, Goldfields Kloof division*

- 1 x GHH 3.75MW

The installed capacity of the compressor at 4# is:

- 1 x Sulzer 4.5MW

All of these compressors make use of inlet guide vane control. The following baseline was constructed using a month's (20 June-20 July 2006) data:

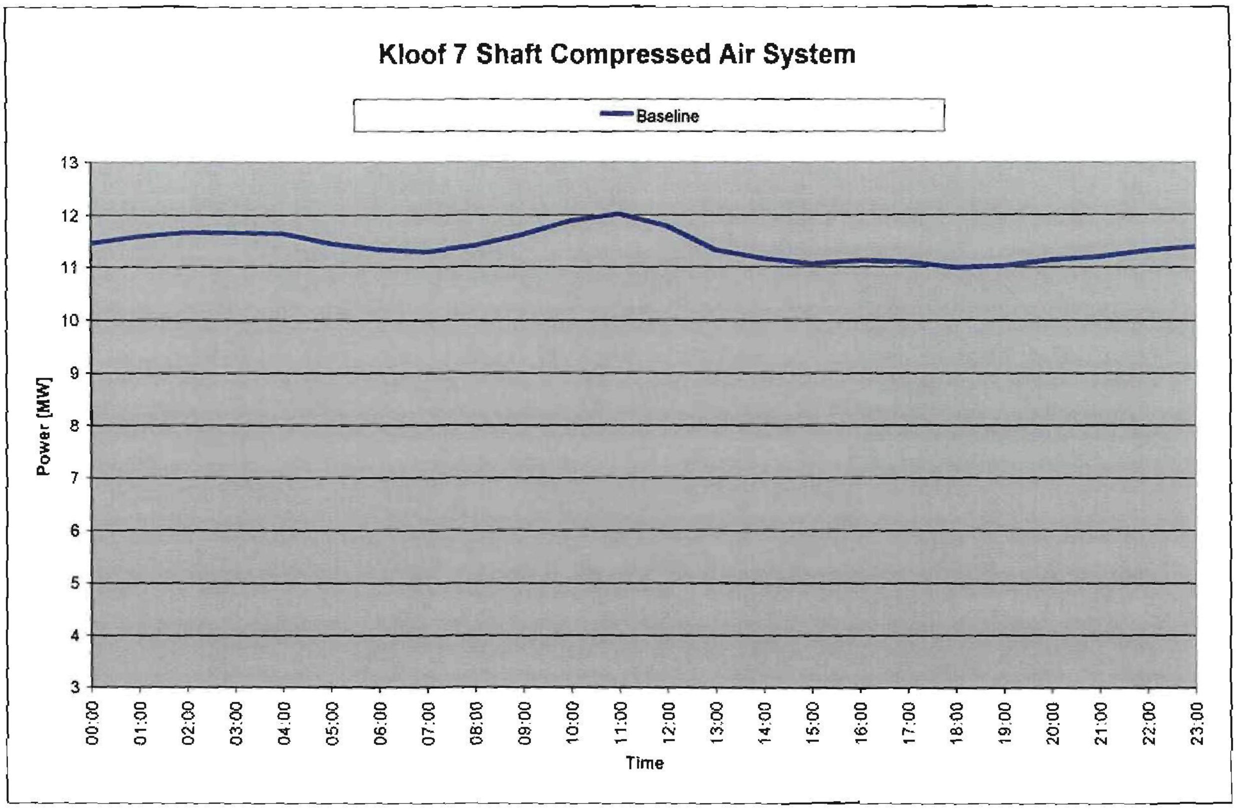

Figure 5-5 Kloof 7# baseline

The average electrical power load of the Kloof 7# compressors throughout a 24-hour profile is 11.3 MW.

5.3.2 Testing and Results

Testing was conducted from 15:40 in the afternoon until 20:00, over the period of 20-27 February 2007. The philosophy for testing was to make use of the available above ground-air control, via above ground control valves, inlet guide vane control, as well as compressor scheduling to realise electrical power savings. It was also a method of proving the effectiveness of the optimised control strategy that was discussed earlier in this thesis.

The strategy followed was to close the one above ground butterfly valve completely, throttling back on the other above ground gate valve as well as lowering the compressors' delivery pressure set points. This resulted in a higher upstream pressure, which allowed the compressors to considerably cut back on the compressed air delivery by using guide vane control.

The constraints for the tests were the specified pressure set points and were the following:

- A minimum pressure of 480 kPa for compressed air supplied to gold plant.
- A minimum pressure of 350 kPa for compressed air supplied to 23 Level.

Three different scenarios were created and the results logged as illustrated in the following figure:

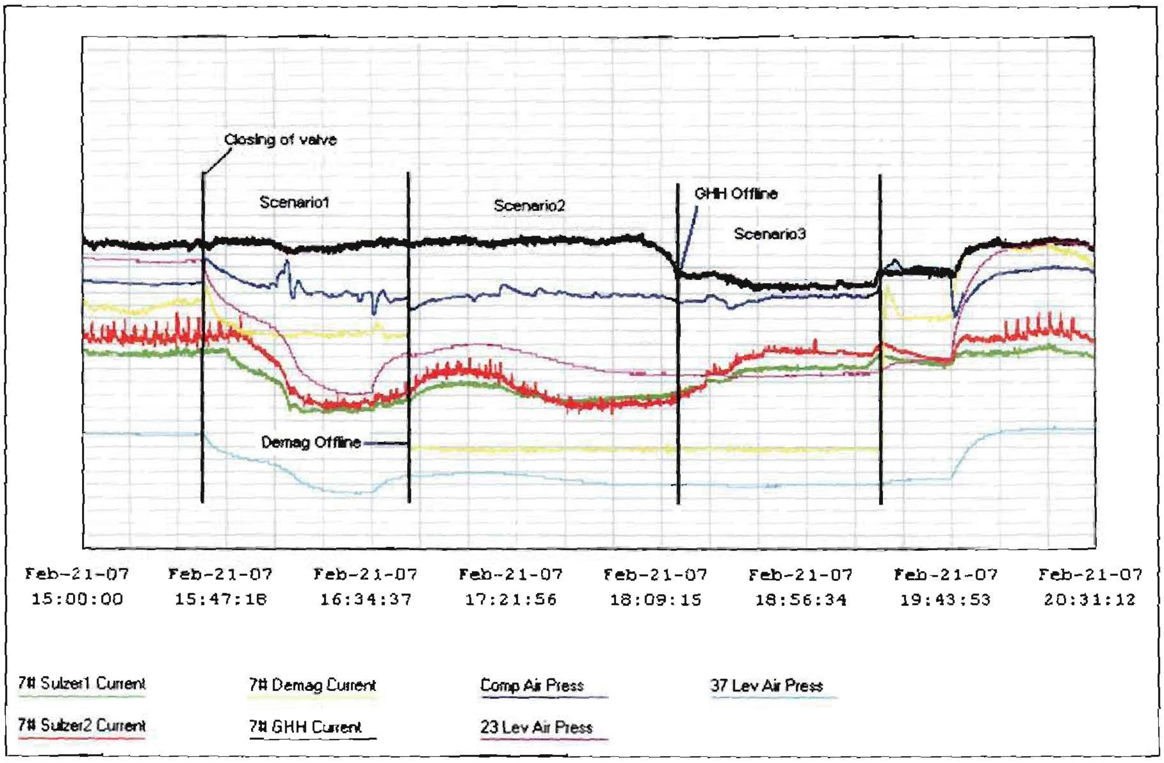

Figure 5-6 Graph illustrating compressor performance during testing [10]

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[10] *Personal communication - Mr. Andre Horn, Chief Technician, Goldfields Kloof division*

Scenario 1

All four of Kloof 7#'s compressors were operating, with delivery pressure set points set according to the constraints above. By operating the system as stated, moderate power savings were possible because of the smaller amount of compressed air that the compressors needed to deliver.

As illustrated in Figure 5-6, Scenario 1 was run from 15:40 until 16:50 at which stage the Demag compressor was taken offline. The necessary constraints were easily maintained and the average motor currents are summarised in the table seen below.

Compressor	Sulzer 1	Sulzer 2	Demag	GHH	Total
Motor current	290 A	290 A	214 A	300 A	1094 A

Table 5-3 Motor current readings of the compressors during testing of Scenario 1

If these values were to be implemented during the Eskom peak demand period, the optimised profile would be as illustrated in the figure below:

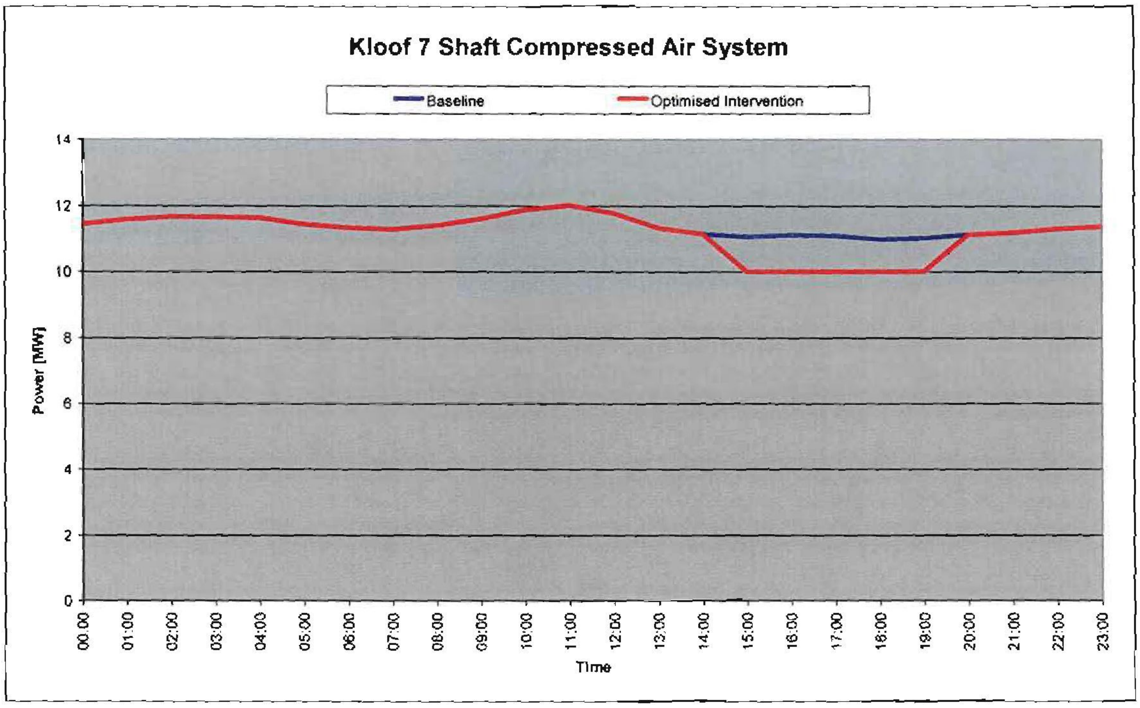


Figure 5-7 Scenario1 power savings

The total average load during Eskom's peak period (18:00 – 20:00) for this scenario is 10 MW. If Scenario 1 is run, it will result in an average saving of **1.3 MW** from the original baseline.

Estimated savings (18:00 – 20:00)	
Electrical load reduction (MW)	1.3
Energy (GJ) per annum	2,433.00
Financial (R/c) per annum (estimated)	175,572.00

Table 5-4 Savings for Scenario 1

Scenario 2

For Scenario 2, the same settings and constraints applied as in Scenario 1, except that the Demag was taken offload at 16:50. Since an offload compressor doesn't supply the system with any compressed air, it will be perceived as a switched-off compressor in this regard.

As can be seen in Figure 5-6, the other three compressors were operated from 16:50 until 18:15, when the GHH was also taken offline. The system pressure again equalised and the average motor currents are summarised in the following table:

Compressor	**Sulzer 1**	**Sulzer 2**	**Demag**	**GHH**	**Total**
Motor current	294 A	292 A	0 A	300 A	886 A

Table 5-5 Motor current readings of compressors during testing of Scenario 2

If these values were to be implemented during the Eskom peak demand period, the optimised profile would be as illustrated in the figure below:

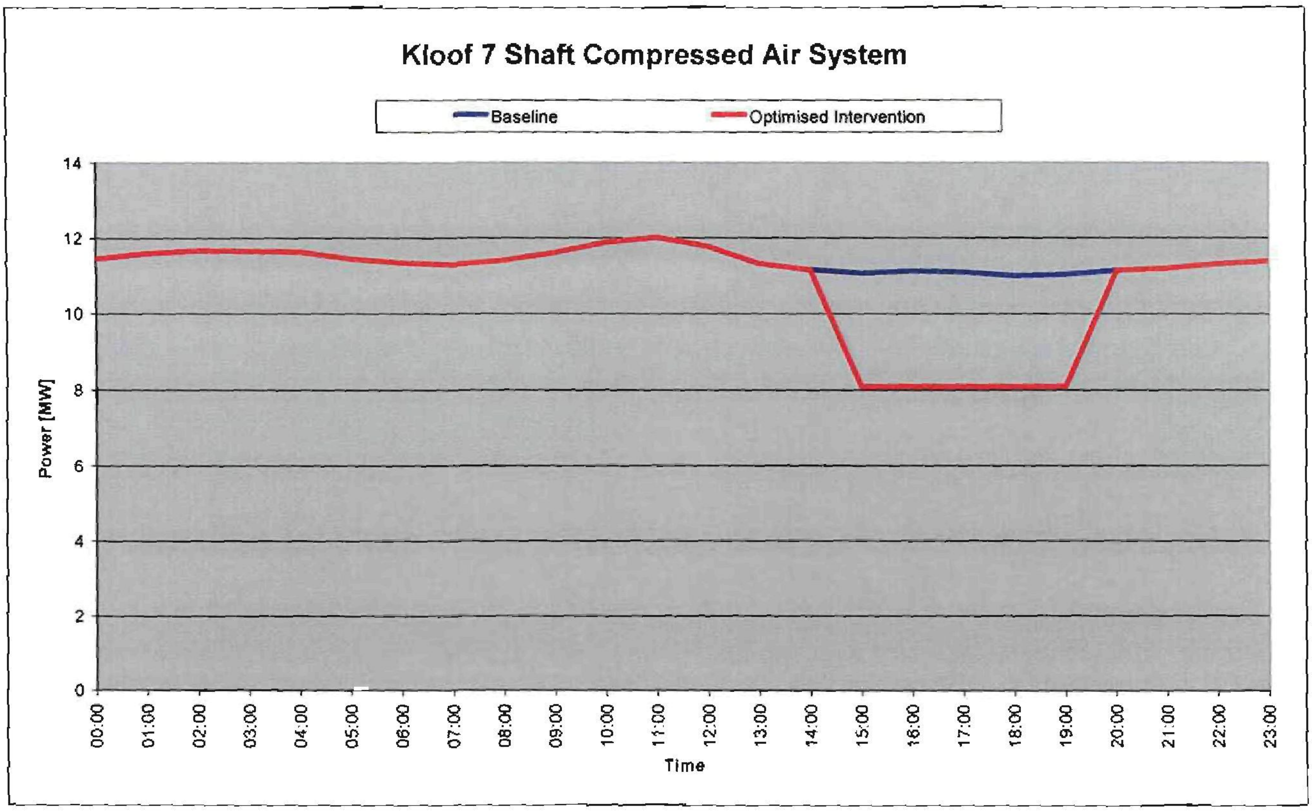


Figure 5-8 Scenario 2 power savings

The average load during Eskom's peak period for this scenario is 8.1 MW. If the proposed scenario is used, it will result in an average saving of **3.2 MW** from the original baseline.

Estimated savings (18:00 – 20:00)	
Electrical load reduction (MW)	3.2
Energy (GJ) per annum	5,990.00
Financial (R/c) per annum (estimated)	432,178.00

Table 5-6 Savings for Scenario 2

Scenario 3

For Scenario 3, only the 2 Sulzer compressors were operated. Although the GHH and the Demag were taken offload, they will be considered as being switched off, as they do not deliver compressed air to the system. The same constraints were followed and with the help of guide vane control the pressures were again easily sustained.

The following table summarises the average motor currents:

Compressor	Sulzer 1	Sulzer 2	Demag	GHH	Total
Motor current	355 A	387 A	0 A	0 A	742 A

Table 5-7 Motor current readings for testing of Scenario 3

If these values were to be implemented during the Eskom peak demand period, the optimised profile would be as illustrated in the figure below:

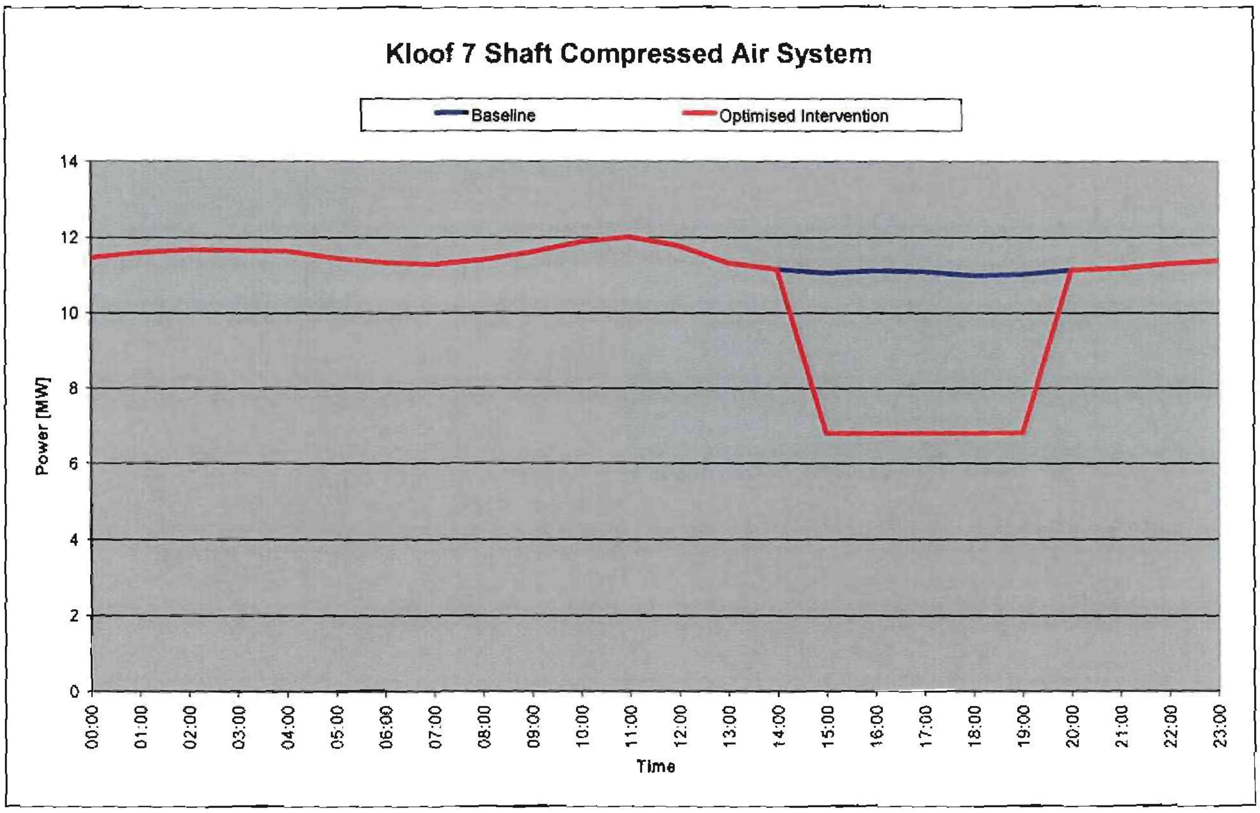


Figure 5-9 Scenario 3 power savings

The average load during Eskom's peak period for this scenario is 6.77 MW. If Scenario 3 is run it will conclude to an average saving of **4.53 MW** from the original baseline. The two Sulzer compressors were always online. The profiles of the different compressors' motor currents during the tests are illustrated in the table below:

Scenario	Sulzer 1	Sulzer 2	Demag	GHH	Total
1	290 A	290 A	214 A	300 A	1094 A
2	294 A	292 A	Offline	300 A	886 A
3	355 A	387 A	Offline	Offline	742 A

Table 5-8 Motor currents of compressors during testing of Scenario 3

5.3.3 Summary and Conclusion

By analysing the summary in Table 5-8, it can be seen that Scenario 3 provides the biggest energy saving. It was proved that **4.53 MW** of electrical energy was clipped out of the Eskom evening peak (18:00 – 20:00). Further savings will be made possible if underground isolation valves can be installed. It will cause a higher upstream pressure and further induces power savings.

Scenario 3 illustrates clearly that operating less compressors at nearly full load, delivers a larger electrical energy saving than operating more compressors at minimum load. Although the current of the two remaining compressors increases as the others are turned off, the amount of amps that are gained are less than those of the three or four compressors operating on minimum guide vane angles.

All of the above testing proved that the optimised control strategy discussed in Chapter 4 can be applied to yet another compressed air ring, the Kloof 7# / 4# complex. By utilising pressure set point control, guide vane control, above ground air control valves and operation of the most efficient machines, large power savings were realised.

Estimated Savings (18:00 – 20:00)	
Electrical load reduction (MW)	4.53
Energy (GJ) per annum	8,480.16
Financial (R/c) per annum (estimated)	611,802.00

Table 5-9 Savings achieved during testing period on Kloof 4# / 7# complex

5.4. Application 3: Rustenburg Platinum Mines

5.4.1 Overview

The Rustenburg Platinum Mining section (RPM) of the Angloplatinum group is situated near Rustenburg in the North West Province of South Africa and comprises ten business units. These business units are divided into two main areas, namely the Eastern section and the Western section. Although these subdivisions are seen as separate business units in production, the whole system will be seen as a whole and the best possible scenario will be used. This mining section consists of many intricate pipe works, which in case of the simulation should be simplified slightly.

Table 5-10 is a summary of the various business units and compressor houses. Note that West 10 is not a shaft, but a centrally based compressor house. The West 10 compressor house feeds the RPM compressed air ring with large amounts of compressed air and plays an active and important role in sustaining the system's pressure. It is also the business unit in the RPM-ring with the highest amount of compressors. RPM comprises of twelve compressors, which are all listed below:

Business Unit	Compressors	Installed Capacities (MW)
Boschfontein	RX800	4.3
	RX850	4.3
Townlands	RX850	4.3
	GHH	4.2
Paardekraal	BB	4.3
Frank	None	None

Business Unit	Compressors	Installed Capacities (MW)
Frank 2	VK40	3.7
Bleskop	None	None
Turfontein	GHH	4.3
	VK125	12.3
Brakspruit	None	None
West 10	GHH	4.3
	GHH	4.3
	GEC	3.3
	VK28	2.8
	Total	**56.4**

Table 5-10 Rustenburg Platinum business units and their compressors

The layout of the Rustenburg Platinum mine is illustrated in Figure 5-10 on the next page.

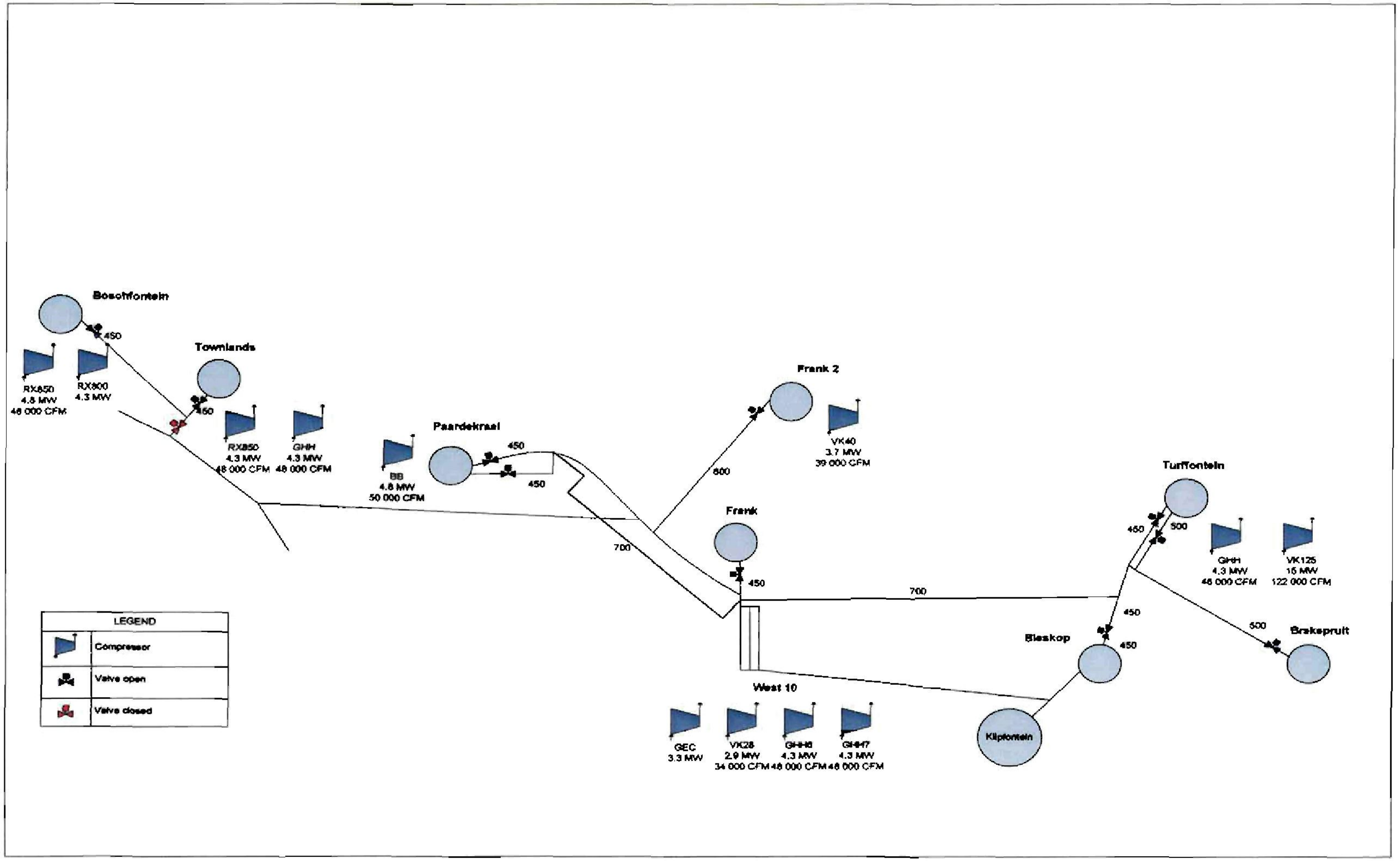


Figure 5-10 Schematic layout of the Rustenburg Platinum mine compressed air network

5.4.2 Original Situation and Control

Before the introduction of an optimised control strategy for DSM purposes at Rustenburg Platinum mines, the mine was actively operating too many compressors during the Eskom off-peak period (18:00 – 20:00). An average compressor power usage of 35 MW was measured during this critical period. The baseline was constructed for the period of 2005/01/01 – 2005/04/21.

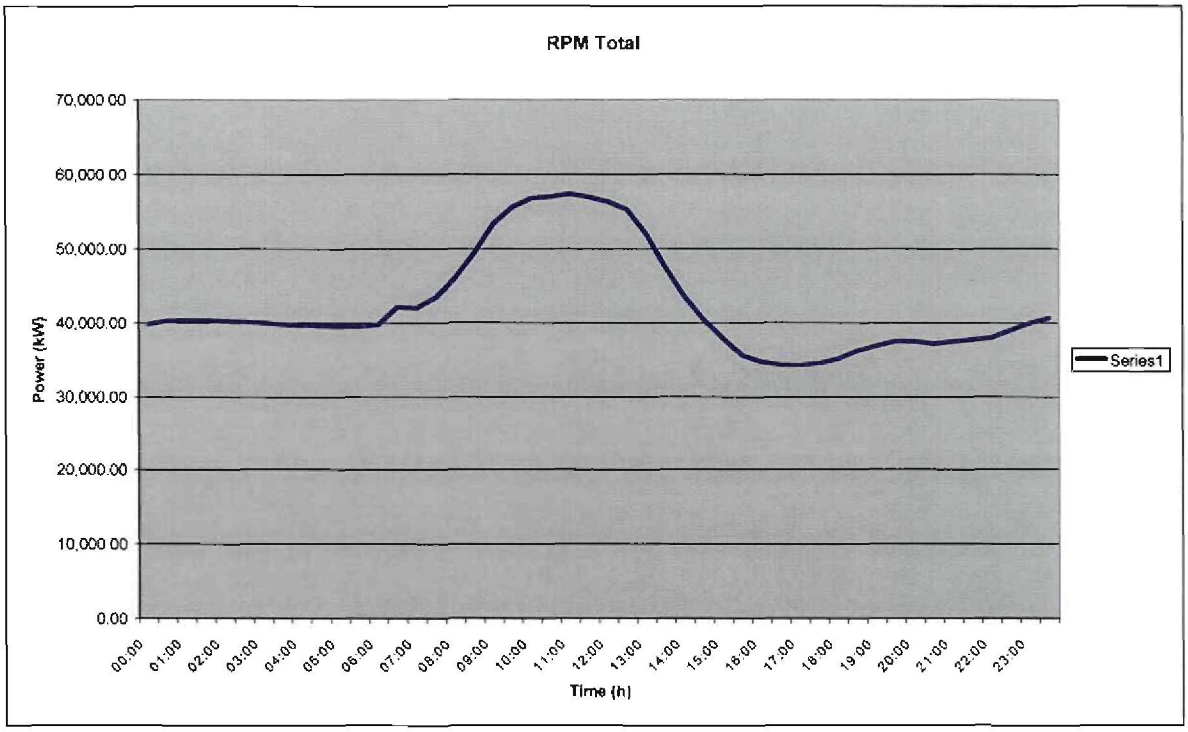


Figure 5-11 The average monthly 24-hour electrical power load profile of RPM

After careful investigation, it was found that this system is using too much compressed air during the Eskom evening peak period (18:00 – 20:00). A huge power saving opportunity was identified, as minimising this amount of wasted compressed air would be highly beneficial for the mine's electricity bill.

Further investigations lead to the identification of an opportunity to implement the control strategy that was discussed earlier.

The scope will consist of the following hardware:

Control Room
Description
Central PLC Equipment
Supervisory Software
Remote Communication Hardware
PLC and SCADA Engineering
Klipfontein Tower
Installation and Commisioning
Individual Compressor Control Systems
Description
Townlands - GHH
Frank 2 - VK40
Paardekraal - RIK
West 10 Master PLC
Compressor Power Metering
Description
Power Monitoring Hardware
Shaft Air Control - Surface valves
Description
Frank 1
Boschfontein
Townlands - GHH
Frank 2
Bleskop
Brakspruit
Paardekraal

Table 5-11 Summary of hardware upgrades for the RPM compressed air system

5.4.3 Testing Results and Optimised Control Strategy

At RPM, the compressed air demand is at a maximum at the following three business units:

- Turffontein
- Paardekraal
- Frank 2

After initial investigations, it was clear that large energy savings would be possible through implementing an effective control strategy, incorporating a minimum required pressure profile. Preliminary investigations led to believe that an energy saving of up 13 MW could be possible during the Eskom evening peak period (18:00 – 20:00).

To achieve this, only the following compressors at the following shafts must be in operation:

- Turffontein - VK125
- Boschfontein - RX850
- Townlands - RX850

Boschfontein and Townlands are isolated from the rest of the system via a centrally situated isolation valve and only the two RX850s are operating on these shafts. The only other compressor that must be operating during this period, to achieve the 13 MW saving, should be the VK125 on the other isolated part. Verification tests were then initiated after decent planning.

An illustration of the setup, delivering a 13 MW electrical power saving out of the Eskom evening peak period (18:00 – 20:00) can be seen in the following diagram:

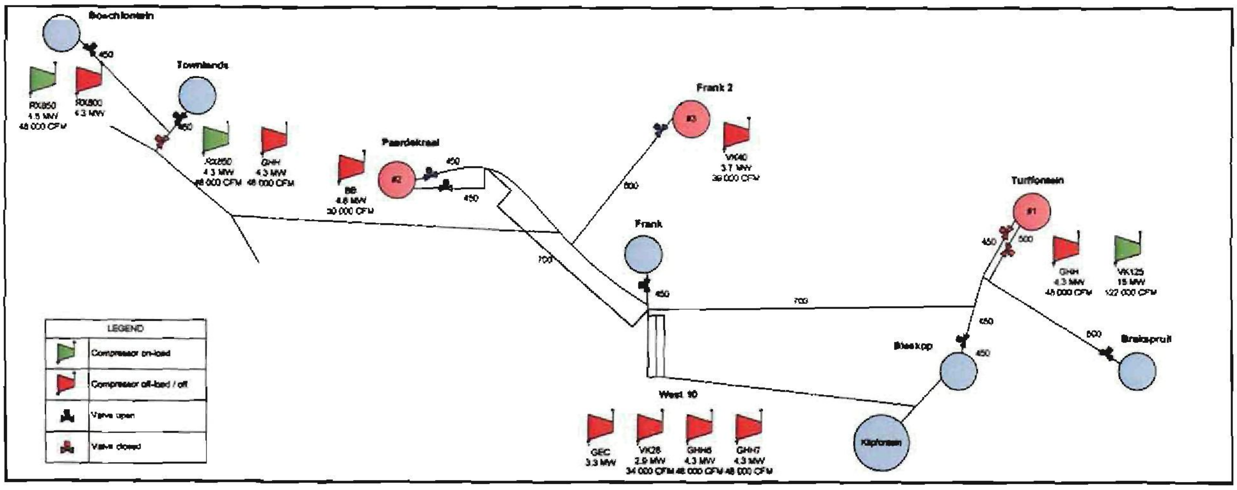


Figure 5-12 Illustration of the proposed setup to achieve a 13 MW electrical saving

The constraint on the tests was that the pressure on the respective shafts should not drop below 390 – 400 kPa. There is also a minimum pressure constraint at West 10 of 380 kPa, as they require at least the specified pressure for their instrumentation. If the pressure on West 10 drops below 380 kPa, it will be difficult to start another compressor. Therefore, the pressure will be kept above 380 kPa at West 10.

If the proposed scenario is successful, the baseline will be as in the following graph, illustrating the 13 MW saving:

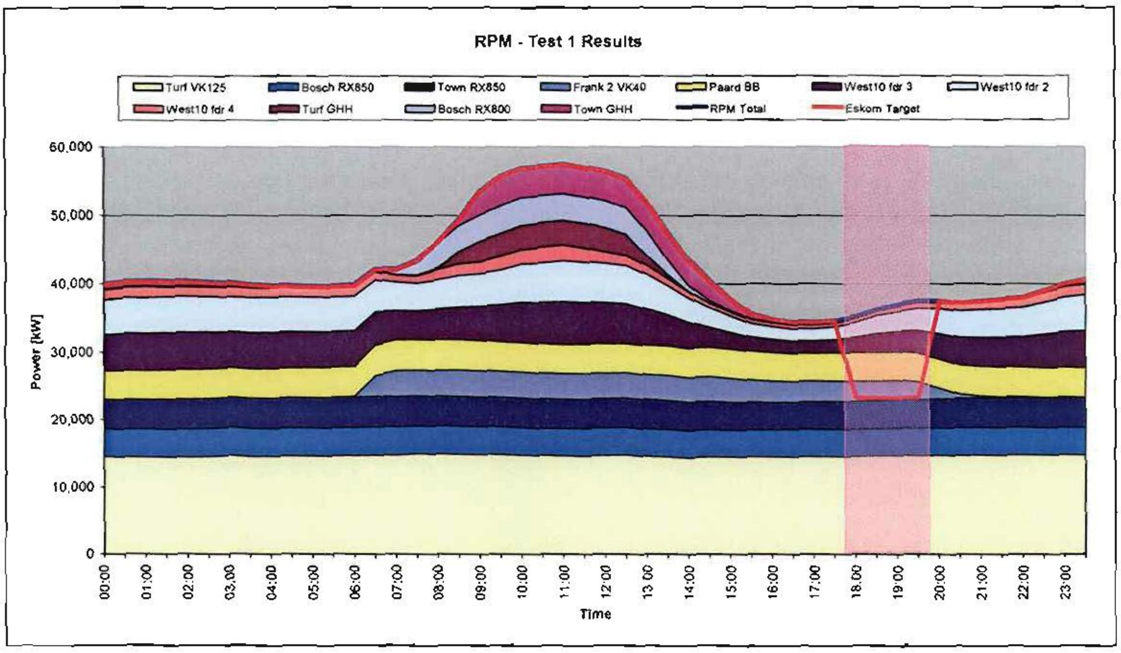


Figure 5-13 Baseline of RPM, showing a possible 13 MW electrical energy saving

Testing Scenario: Operating the Minimum Amount Compressors, without Above Ground Valve Control or Inlet Guide Vane Control

Testing was commenced during the period 2007\02\20 to 2007\02\27. It was decided to operate the VK125 at Turffontein and the VK40 compressor at Frank 2 on the Eastern flank. If the pressure did not drop below 400 kPa during the testing period, the VK40 could also be switched off for additional savings. The Centac RX850 compressor at Boschfontein and the Centac RX850 at Townlands should also be operated on the Western flank of the ring.

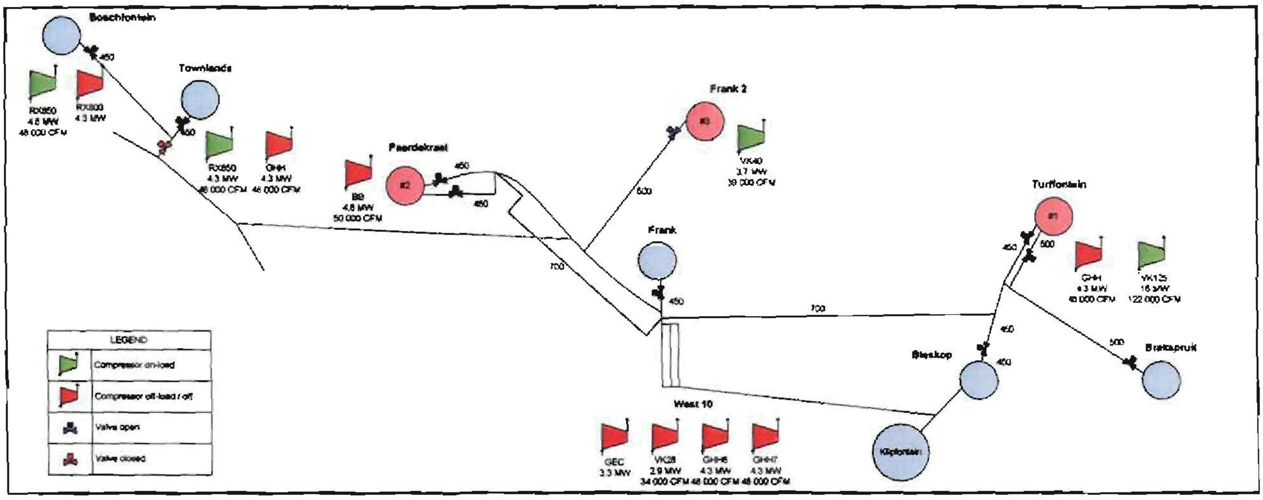


Figure 5-14 Testing scenario 1

The above figure illustrates the compressors that are operating during Eskom's evening peak time, as well as the three shafts that consume the most air, apart from the two Western flank shafts, Boschfontein and Townlands.

The average pressure profile during the tests is illustrated below:

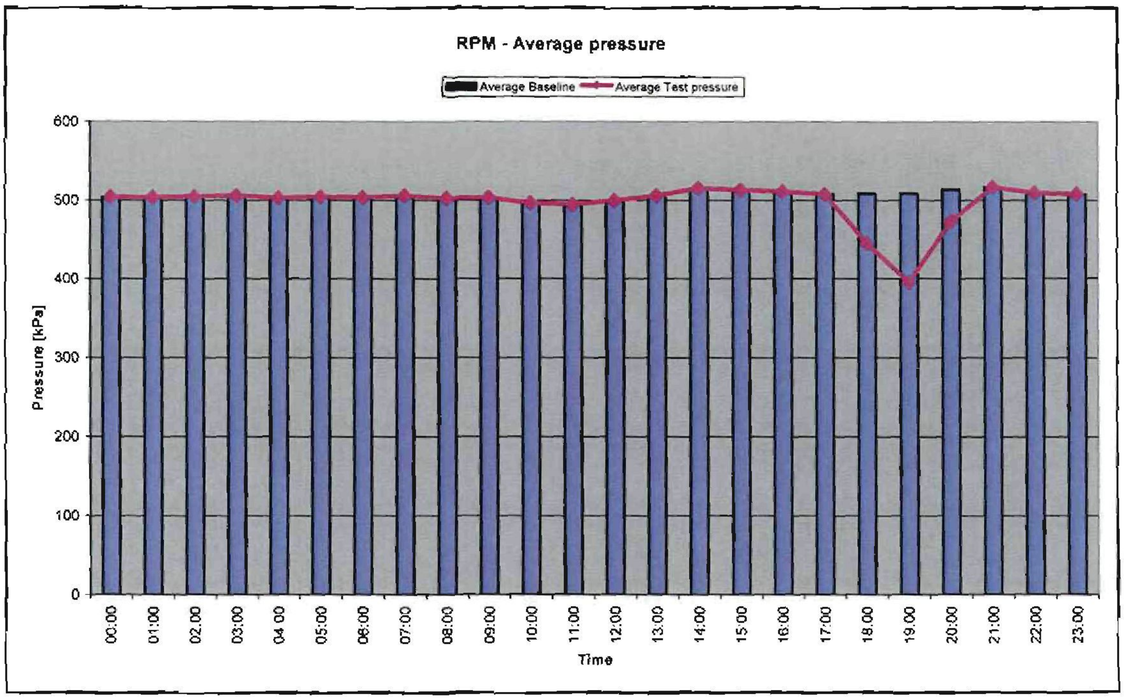


Figure 5-15 Average pressure profile for Scenario 1

As can be seen the average ring pressure did not drop below 400 kPa during testing. It was immediately evident that the pressure will drop below 400 kPa on the shafts if the VK40 was also switched off. The lowest pressure recorded for the duration of the tests was 350 kPa at Bleskop. Although no official low pressure complaints were received, 350 kPa is a minimum pressure as the refuge bays must be pressurised at 320 kPa.

Pneumatic valves are installed on all of Turffontein #'s underground dams. The valves control the water flowing into the dam, as well as out of the dam to the stopes. The specific pneumatic valves used on this shaft do not function properly if the pressure drops below 380 kPa. Thus the minimum compressed air pressure for safe operation on the whole RPM compressed air ring is at least 390 kPa.

By operating the compressed air system to sustain a minimum pressure of 390 – 400 kPa, the following compressors must be operating on load:

- VK125 – Turffontein
- VK40 – Frank2
- RX850 – Boschfontein
- RX850 – Townlands

The result for Scenario 1 is illustrated in Figure 5-16 on the next page:

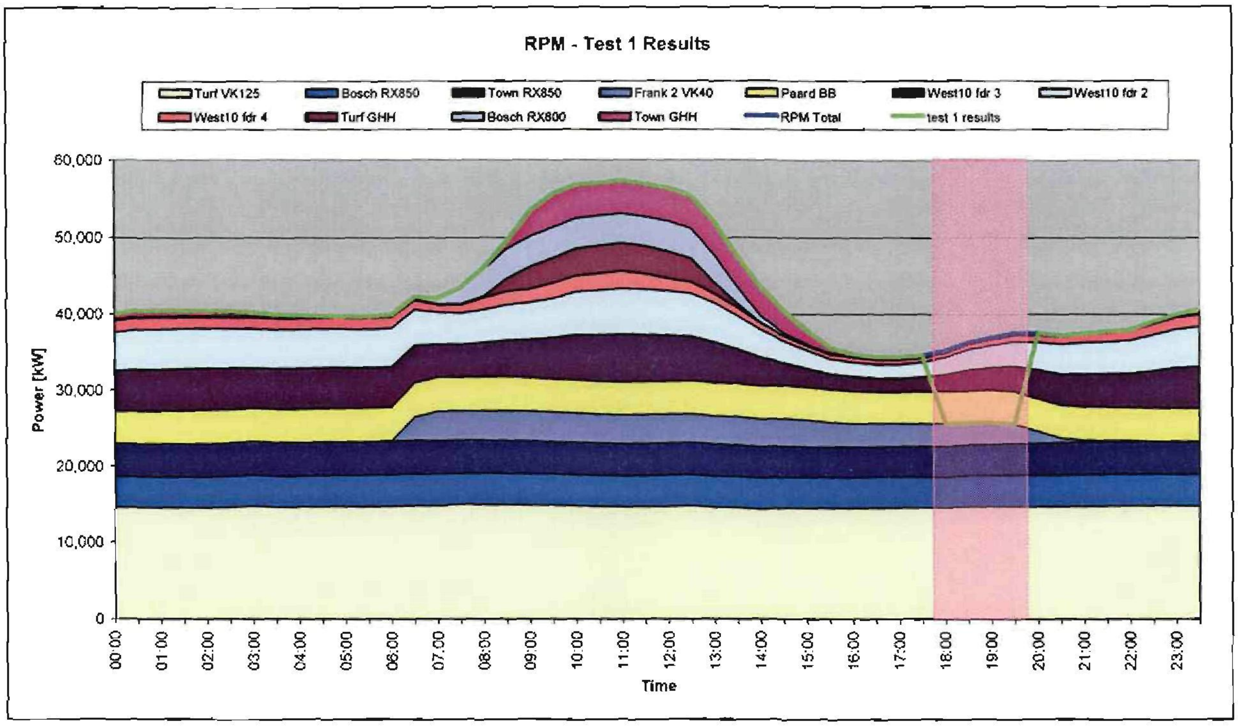


Figure 5-16 Energy load results of Scenario 1

5.4.4 Summary and Conclusion

As can be observed, that an average of **10.8 MW** of electrical energy was safely removed from the Eskom evening peak (18:00 – 20:00) during the tests, whilst remaining true to the pressure constraints. Operating the ring at a too low pressure would cause problems with various components and instruments. It can also be concluded that an average of a seven-day profile gives an accurate example of a typical mining week.

It is important to notice that compressor scheduling was the only segment of the optimised control strategy that was effectively used. Inlet guide vane control would definitely add benefit, but only if the minimum required compressed air pressure in the mine could be dropped even further, but not enough to switch off a compressor.

Above ground air control valves will not add benefit at this stage, as the underground air usage (wastage) at most shafts is too high. Underground control valves are a definite answer, as they would ensure that air wastage is minimised. None of these are currently automated, but an automatic underground control system would cause additional savings. Another saving that will be realised by implementing an automatic control system will be the cost of labour that will be saved. There are currently 30 attendants working at the compressor houses. In future the mine will only require half of them. At a cost to company of R12,000 per month, an annual saving of: 15 people x R12,000 x 12 months = R2,160,000.00 will be realised. Thus a total saving of

Estimated Savings (18:00 – 20:00)	
Electrical load reduction (MW)	10.8
Energy (GJ) per annum	20,217.60
Financial (R/c) per annum (estimated)	1,458,601.00
Including labour savings	3,618,601.00

Table 5-12 Savings for the RPM ring

5.5. Application 4: Vaalriver Operations

5.5.1 System Details and Overview

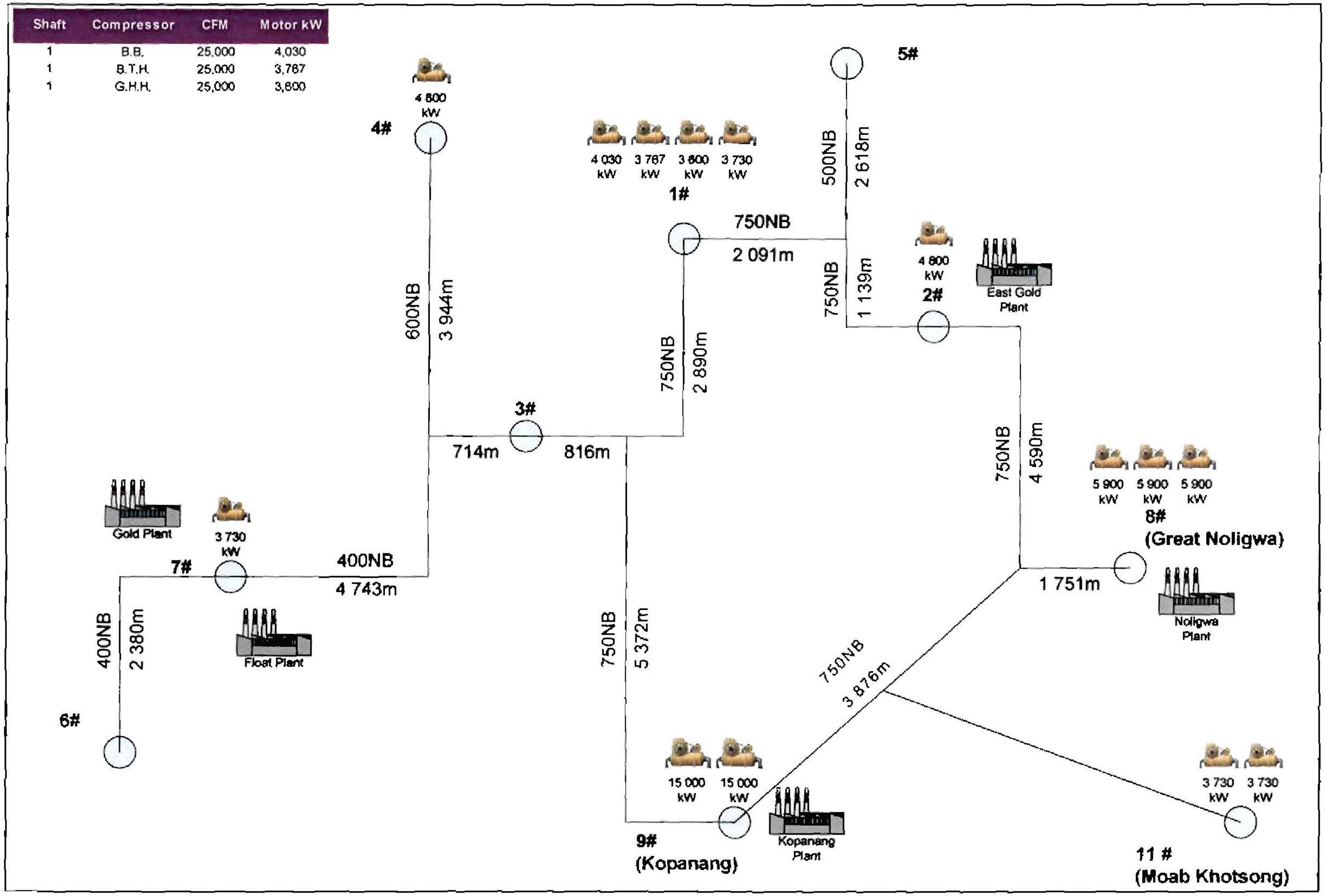
The Vaalriver ring of the Anglogold Ashanti is situated near a town called Orkney in the Nort West province of South Africa although the ring stretches over the Vaalriver into the Free State Province. The ring consists of the following shafts:

- 1#
- 2#
- 3#
- 4#
- 5#
- 6#
- 7#
- Moab Khotsong
- Koponang
- Great Noligwa

These shafts are connected via various lengths and diameters of compressed air lines and consist of the following compressors:

Shaft	Compressor	CFM	Motor MW
1	B.B.	25,000	4.0
1	B.T.H.	25,000	3,7
1	G.H.H.	25,000	3,6
1	B.G.E.	20,000	3,7
2	Sulzer	30,000	4,8
4	Sulzer	30,000	4,8
7	Demag	18,000	3,7
Moab Khotsong	Demag	20,000	3,7
Moab Khotsong	Demag	20,000	3,7
Great Noligwa	Sulzer	40,000	5,9
Great Noligwa	Sulzer	40,000	5,9
Great Noligwa	Sulzer	40,000	5,9
Kopanang	Sulzer	100,000	15,0
Kopanang	Sulzer	100,000	15,0
Moab Khotsong (Tau Lekoa)	Demag	100,000	10,3
		Total	**93.94**

Table 5-13 Summary of all the compressors on the Vaalriver ring



Shaft	Compressor	CFM	Motor kW
1	B.B.	25,000	4,030
1	B.T.H.	25,000	3,767
1	G.H.H.	25,000	3,600

Figure 5-17 System layout of the Vaalriver operations compressed air ring

5.5.2 Proposed Control and Implemented Control

Although no official test results have been acquired for the Vaalriver ring, it came to known that the CIC engineer of the Vaalriver operations was busy implementing a similar control strategy. Utilising a system of inlet guide vane control, compressor scheduling and also the future implementation of above ground- and underground-air control valves, Vaalriver operations are saving reasonable amounts of electrical energy.

By dropping the overall system pressure during the Eskom evening peak period (18:00 – 20:00) in the Vaalriver ring from 660 kPa to 550 kPa an electrical power saving of 10 MW can be achieved. This is done by only operating the 2 most effective machines at Kopanang, as well as utilising inlet guide vane control to further optimise the compressed air delivery to the shafts. Underground control valves at Kopanang also cause an immense pressure build-up on the upstream side of the valves and initiates extra electrical power savings.

Figure 5-18 illustrates the old 2005-baseline, with the proposed peak-clipping baseline plotted over the old baseline. The red line illustrates the real-time effect of the proposed pressure set point control. As can be seen, not only is the predicted electrical energy saving of 10 MW achieved during the Eskom evening peak period (18:00 – 20:00), but by dropping the required pressure throughout the day, energy efficiency savings over a 24-hour period can be achieved.

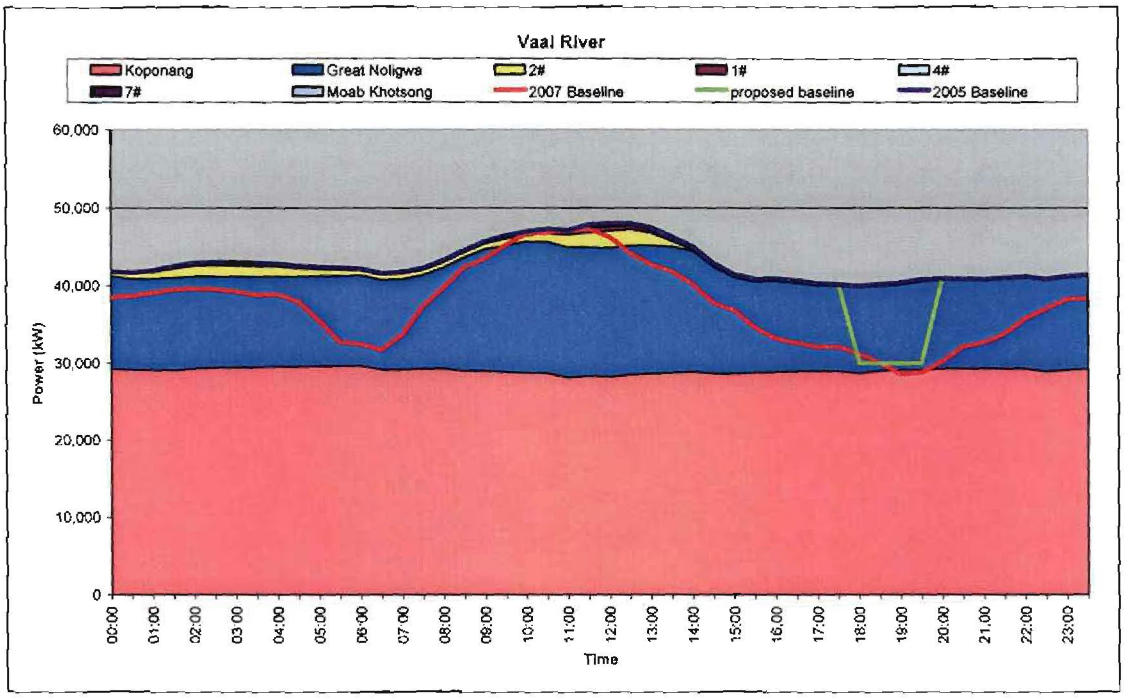


Figure 5-18 The Vaalriver operations baselines

5.5.3 Summary and Conclusion

The effects of the proposed optimised control strategy on the Vaalriver operations' average electrical power usage baseline, proves yet again that the optimised control strategy that was discussed earlier in this thesis, is purposeful. It also proves the value of such a system, as **10 MW** of electrical energy is being saved between 18:00 and 20:00 every evening.

Estimated Savings (18:00 – 20:00)	
Electrical load reduction (MW)	10
Energy (GJ) per annum	18,720.00
Financial (R/c) per annum (estimated)	1,350.557.00

Table 5-14 Savings on the Vaalriver ring

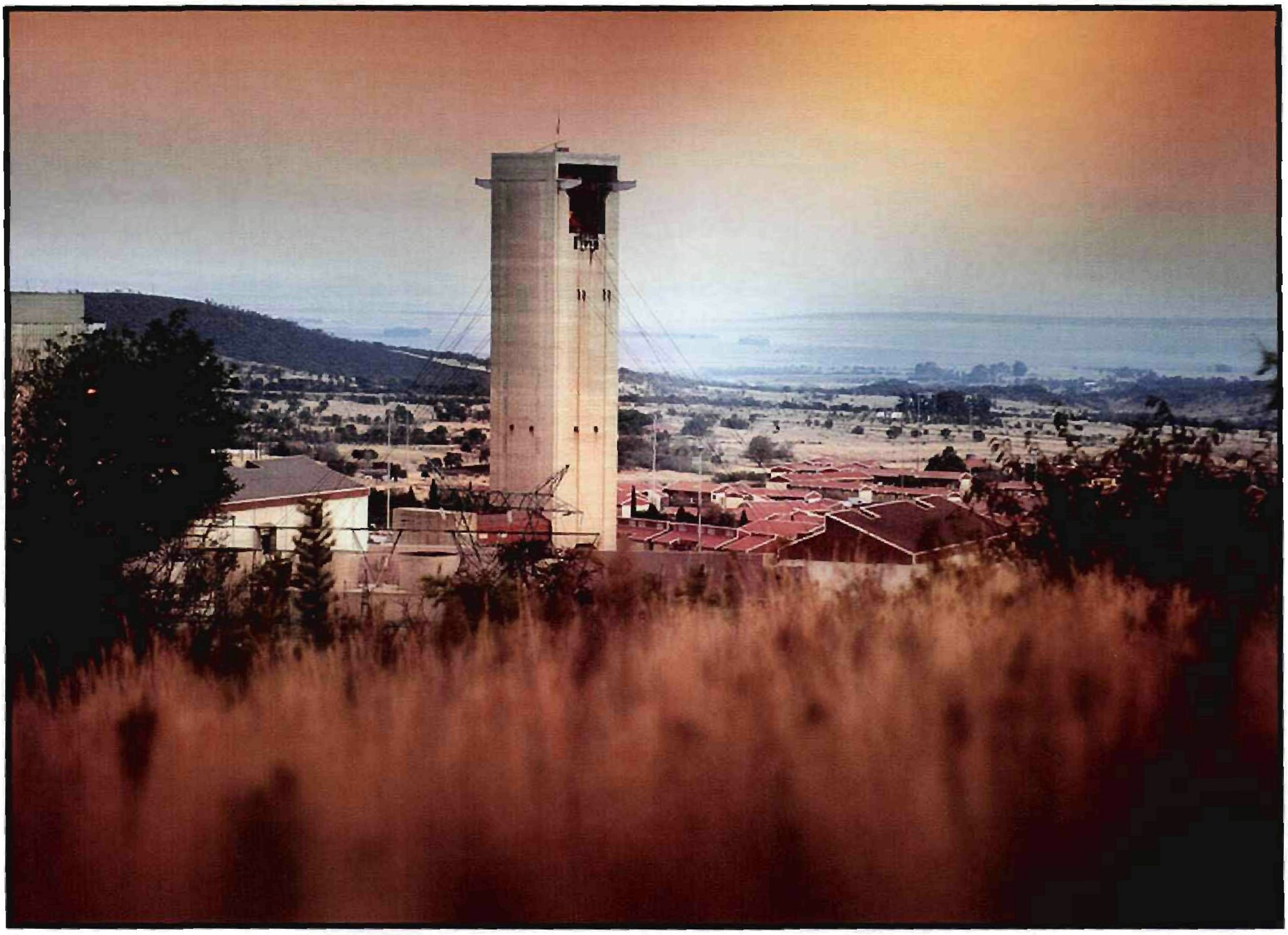
5.6. Summary of Results

Mine	Electrical Power Saving (MW)	Energy Saving (GJ)	Financial Saving (R/c)
Tau Tona / Savuka	4.77	8,929.44	644,307.00
Kloof 1# / 3#	9.2	17,222.40	1,242,512.00
Kloof 4# / 7#	4.53	8,480.16	611,802.00
Rustenburg Platinum mines	10.8	20,217.60	1,458,601.00
Vaalriver Operations	10	18,720.00	1,350,557.00
Totals	**39.3**	**73,569.60**	**5,307,779.00**

Table 5-15 Summary of the verification and case studies

An average electrical power load of **7.86 MW** was eliminated from the Eskom evening peak period (18:00 – 20:00) during the abovementioned studies. A minimum electrical power load of **4.53 MW** was eliminated and a maximum electrical power load of **10.8 MW.** According to the current Eskom tariffs, it is possible to achieve an average R/c saving of **R 1,061,555.00** per annum for the case studies. An average energy saving of **14,713.92 GJ** was also achieved during testing.

CHAPTER 6: Conclusion



This chapter is a summary of the impact of the study, as well as recommendations for future studies on related subjects.

6. Chapter 6: Conclusion

6.1. Conclusion

The development of an above ground compressed air simulation model assists in accurately planning tests on compressed air rings and also in the development of a central control system. With such a simulation, above ground pressure can be predicted with a R^2 accuracy of 0.997 and many technical difficulties can easily be identified. It was also actively used in the development of the REMS CM© automatic compressed air controller, which will be implemented on the above case studies and also various other compressed air projects.

The optimised control strategy that was formulated and discussed in this thesis holds various advantages for many parties. Firstly, the client, whether it is a mining ring or industrial setup, will save large amounts of electric energy This is achieved by reducing electrical power usage during the more expensive Eskom evening peak period, and thus realising huge financial savings in the process. Saving money will enable the mine to further upgrade instrumentation and other critical equipment to further enhance the control and possibly realising additional savings.

It was proved through the above case studies, that large financial savings are possible for most compressed air rings currently being used in South Africa. Annual financial savings between R600,000 and R1,500,000 can be achieved on the tested compressed air rings. Eskom's megaflex tariffs are possibly rising by up to 18% in 2008 and a further 17% in 2009 [49]. When taken into account, financial implications could be large. Within two years any industry implementing the optimised control strategy on its compressed air ring could be saving up to between R810,000 and R2,030,000 per annum.

Secondly, the electrical power provider, Eskom, will also realise savings, having to generate less peak power for the mining and industrial sector. The process as a whole will assist Eskom DSM in its quest to overcome South Africa's electrical energy shortage. In having extra reserves available, power outages throughout the country can be minimised or eliminated. It also takes strain off the Eskom generators/power stations and minimises maintenance and the risk of possible critical failures on power generating equipment.

Thirdly, although not major, environmental advantages are also achieved. The impact on the country's coal reserves will also be positive. Wasting less electrical energy will cause the power plants to consume less coal and water, and thus extending the life of coal reserves. The current rate of coal used to produce 1 MWh of electricity is **0.512 ton/MWh**. Taken into account that an average electricity load reduction of **7.86 MW** per project was sustained on the **5** case studies over a two a 2 hour period, an annual coal saving of **10,633.32 ton** can be achieved. The rate of water used to generate 1 MWh of electricity is **1346.84 litres/MWh**. Again taking into account that an average electricity load reduction of **7.86 MW** per project was achieved for the **5** case studies over a 2 hour period, annual water savings of **711,132.58 litres** can be achieved.

In a world where environmental issues, such as global warming, etc., are ever increasing, minimising the amount of carbon emissions will also realise positive effects on the environment and motivate others to follow. An international intervention called Clean Development Mechanism (CDM) [50] has been instigated to motivate carbon consuming instances to reduce carbon emissions and effectively minimise the world's carbon depletion rate. Implementing the proposed control strategy on compressed air rings throughout the country and even the world, will reduce the need for energy considerably and will reduce carbon emissions emitted by coal power stations by decent amounts. The amount of CO_2 being emitted by a coal power station to produce **1 MWh** of electricity is **0.0009 ton**. If taking into account the abovementioned **5** case studies, a total of **3.71 ton CO_2** will be achieved per annum.

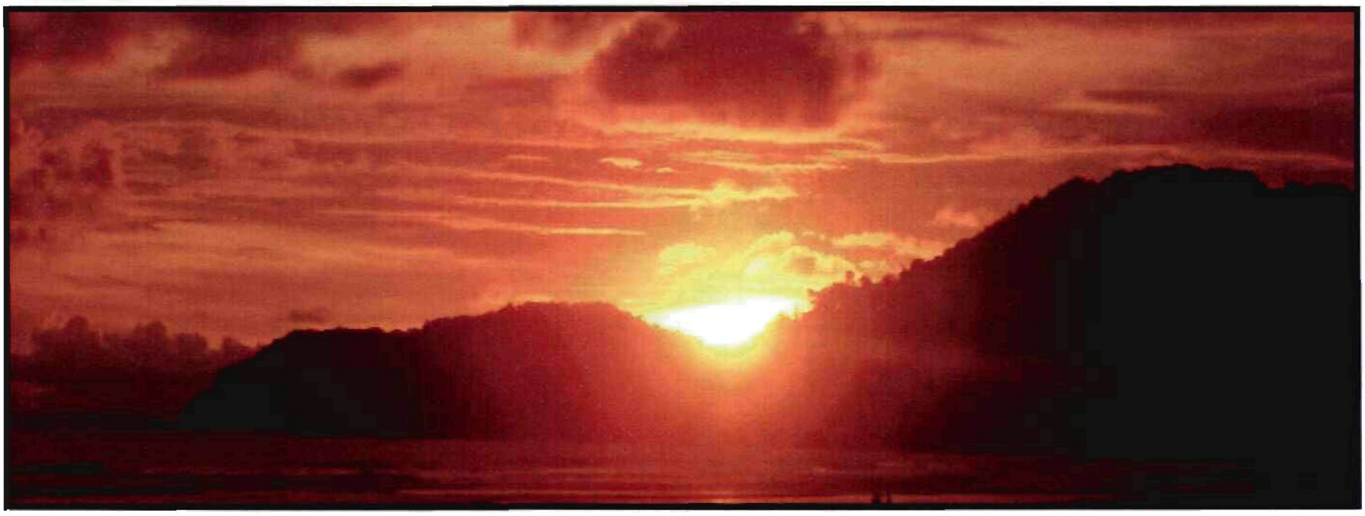
After all evaluations, it can be concluded that the proposed control strategy not only holds financial advantages to the users of compressed air rings, but are also of importance, although only in a lesser way, prolonging the country of South Africa's natural coal and water reserves. A fair amount of emissions can also be saved. Such a system will also very effectively assist in contravening the ever increasing countrywide electrical power demand.

6.2. Recommendations for Further Study

It is proposed that further studies be done on the precise and effective underground control of compressed air in the mining environment. Demand side control is one of the most efficient ways of identifying compressed air leakages and also eliminating leakages through isolation. Underground compressed air control will allow upstream pressure build-ups and thus realise further power and financial savings.

It is also recommended that further studies be done on energy efficiency. In this study the focus was put on the Eskom evening peak period (18:00 – 20:00). The reasons for this are the current nature of the DSM contracts, as well as the safety of off-peak periods on the mines during 18:00 and 20:00. Energy efficiency focuses on saving electrical power over as much as a 24-hour period. This provides new challenges, but will create fair opportunities for power and financial savings.

CHAPTER 7: References



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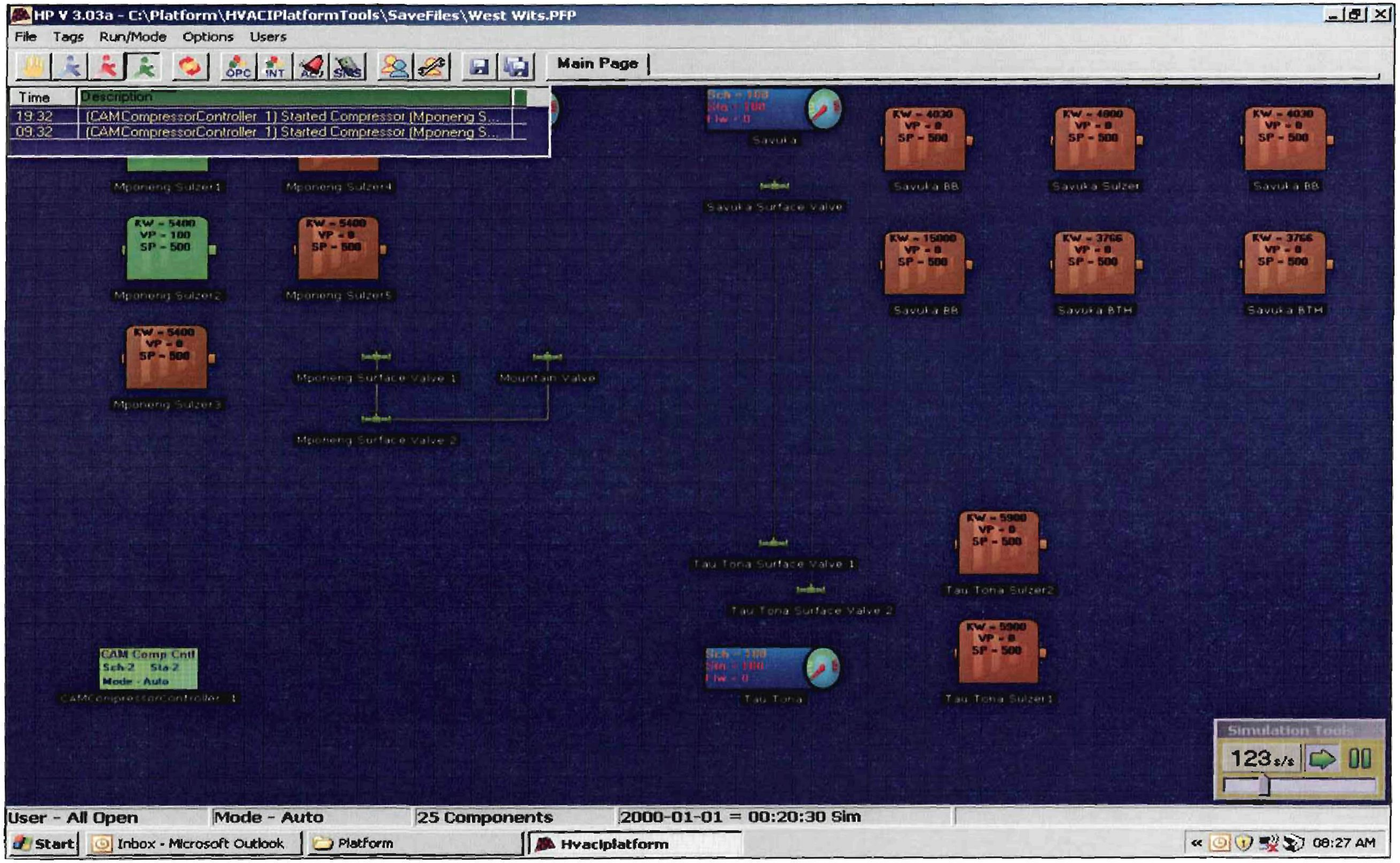
APPENDIX A



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Time	Description
19:32	(CAMCompressorController_1) Started Compressor (Mponeng S...
09:32	(CAMCompressorController_1) Started Compressor (Mponeng S...

User - All Open | Mode - Auto | 25 Components | 2000-01-01 = 00:20:30 Sim

Figure 7-1 Screenshot of the REMS CM automatic compressor controller