Improving mine compressed air network efficiency through demand and supply control

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It all starts here ™

Abstract

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Eskom is in a position where they are producing sufficient electricity, although rapid expansion and an increase in demand throughout various sections in South Africa can be expected in the future. Large electricity intensive industries such as gold and platinum mines can assist by reducing their electricity demand.

Platinum mines are required to increase production output while keeping their overheads as low as possible. One of the areas that can be targeted to reduce operating expenses is mining services such as compressed air.

A compressed air network is one of the most ineffective and electricity intensive systems found on a platinum mine. This provides opportunities for implementing Eskom funded demand side management initiatives to decrease the electricity consumption on mining systems, which leads to a reduction in electricity consumption costs.

Demand side management initiatives were implemented on two case studies as means to provide electricity and cost savings. Control philosophies were developed, implemented and optimised to ensure a decrease in electricity consumption. A simulation was constructed for each case study and the effect of the control philosophy was simulated and quantified. Each simulation was verified using data from the respective mines’ databases.

In Case Study 1, automated control valves were implemented at each compressed air user and the pressure set point was decreased in the Eskom evening peak period. The flow through the compressors were reduced and/or stopped while adhering to system and operational constraints.

This resulted in electric power savings of 3.1 MW, which lead to an annual cost savings of R1.9 million. The initial calculations showed that 3.9 MW could be saved, although this was not achieved. It was determined that if repair compressed air leaks was included in this initiative, the target could be met.

In Case Study 2, a theoretical initiative was simulated. The effect on electricity consumption was investigated by replacing a single large 15 MW compressor with two less electricity intensive 4 MW compressors. The investigation showed that 76 042 MWh energy efficiency savings per day could be achieved with this initiative. This possible project would have an annual cost saving of R20 million.

In this study, it will be shown that a compressed air network can be optimised. These optimisations proved that electricity cost savings can be achieved for the platinum mining industry. In both case studies, it was seen that electricity consumption can be lowered.

Keywords: Electricity savings, demand side management, compressor network, energy services company, Eskom.

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Nomenclature

Symbol	**Unit**
C_v	flow coefficient (pressure loss)
g	gram
GWh	gigawatt-hour
kg	kilogram
kg/m^3	kilogram per cubic metre
km	kilometre
kHz	kilohertz
kJ/kg	kilojoule per kilogram
kPa	kilopascal
Kv	flow coefficient (valve position)
kW	kilowatt
kWh	kilowatt-hour
m	metre
m/s	metre per second
m/s^2	metre per second squared
MVA	megavolt-ampere
MW	megawatt
MWh	megawatt-hour
m^2	square metre
m^3	cubic metre
m^3/h	cubic metre per hour
m^3/s	cubic metre per second
oz	ounce
R	rand
yr	year
$	dollar

Abbreviations

CALDS	Compressed Air Leakage Documentation System
CPI	Consumer Price Index
DCS	Dynamic Compressor Selection
DSM	Demand Side Management
EnMS	Energy Management System
ESCO	Energy Service Company
IDM	Integrated Demand Management
JSE	Johannesburg Stock Exchange
M&V	Measurement and Verification
OCGT	Open Cycle Gas Turbine
PID	Proportional-Integral-Derivative
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
ULD	Ultrasonic Leak Detector
USA	United States of America

1 Introduction

Typical centrifugal compressor impeller [1]

"Compressed air can provide limitless amounts of clean energy using technology we have had for hundreds of years."

Bill Mollison

1.1 Electricity supply in South Africa

Eskom, the main electricity utility in South Africa, generates and provides approximately 90% of the country’s electricity demand [2]. A modest range for an electricity reserve margin is between 13−15% [3]. Eskom’s reserve margin decreased to 8% in recent year, which is much less than the international standard of 15% [4]. Eskom calculates the reserve margin as the difference between its peak generating capacity and the peak load demand [5].

Figure 1 compares the winter electricity demand with the potential capacity Eskom was able to generate for the year 2014 [6]. The blue line represents an average winter demand of electricity in South Africa, where the orange straight line represents the potential capacity Eskom was be able to generate. The red block indicates the Eskom evening peak period.

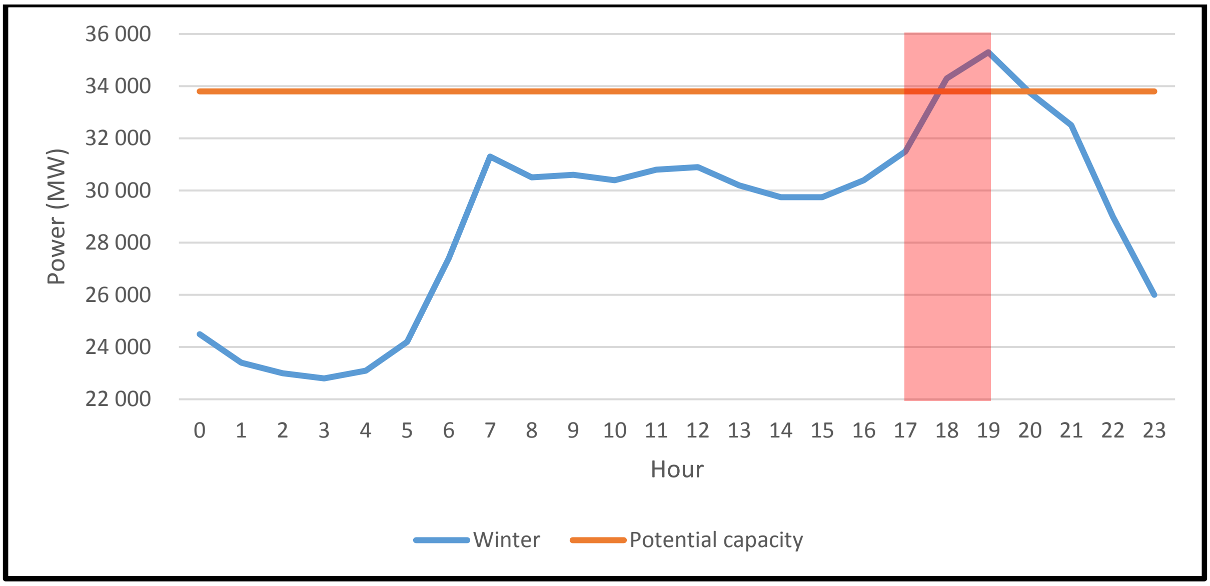


Figure 1: Winter demand profile versus potential capacity (adapted from [6])

Figure 1 shows that although the generation capacity has increased, Eskom did not have the required generating capacity in 2014 for the Eskom evening peak period. New coal fired power stations was built in recent year, thus Eskom did not lack potential generating capability in peak demand periods for the 2015/16 period. The peak electricity demand for the year 2015/16 was calculated at 33 345 MW and the maximum generation capacity Eskom can generate is 42 810 MW [5].

Figure 2 compares the peak demand with the potential capacity Eskom could generate in 2016. The red bar on the left represents the peak demand of electricity in South Africa, while the green bar on the right represents the potential capacity Eskom can generate.

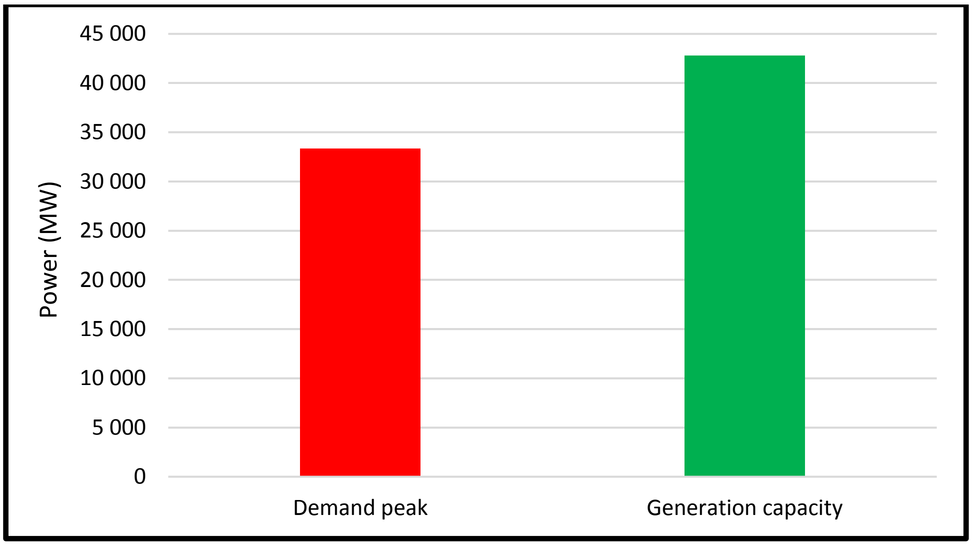


Figure 2: Demand peak versus generation capacity (adapted from [5])

When historical data is used, it can be assumed that an increase in electricity demand can be expected in the future, thus the generation capacity might once again not be sufficient for the peak demand. Eskom’s plant availability is also deteriorating [5]. Thus, reducing the peak demand period remains a focus [6].

Eskom’s solution to the lack in generation capacity was the New Build Programme, which commenced in 2005 [7]. The New Build Programme includes building new electricity generation plants to be able to generate sufficient electricity to match demand [5]. Eskom’s New Build Programme contributed significantly to the high tariff increases experienced in recent years. This New Build Programme is said to add 8 600 MW by 2020/21 [5]. The New Build Programme is unfortunately behind schedule. The first unit of the Medupi Power Station was scheduled to be commissioned at the end of 2014 [8]. The first unit was synchronised to the national grid in March 2015 [9]. The final commissioning for Medupi was extended to the year 2020 [5].

A short-term solution was needed from 2004 to generate enough electricity to satisfy the national demand, as the lead time for a new coal fired power station is between eight and ten years [10]. A short-term solution was implementing open cycle gas turbine (OCGT) power stations, which have a lead time of between two and three years [10].

The diesel cost for operating the OCGTs was R1.5 billion in July 2015 [11]. This is much higher than what was initially expected as OCGTs would only have been used in the evening peak period. When the commissioning dates of the new power stations were delayed, the

OCGTs were operated extensively [11]. OCGTs have a much higher operating cost than coal fired power stations, because the diesel used as combustion fuel is a more expensive energy source than coal [12].

Eskom is also in the process of upgrading transmission lines and substation capacity as part of the New Build Programme. Eskom has already installed 345.8 km of transmissions lines in South Africa from the beginning of 2016; the target is 6 162 km [5]. The substation capacity has also been increased with 2 435 MVA from the beginning of 2016; with a total target of 32 090 MVA [5].

Renewable energy projects are also being implemented to help with generating electricity [5]. These projects include a 300 MW wind farm [5], and Khi Solar One, which is a solar power plant located in Upington. The solar plant contributes 50 MW to the national electricity grid [13]. Once these renewable energy projects and the New Build Programme for new coal fired power stations are completed, Eskom will have a higher generation capacity. Figure 3 compares the average Eskom tariff increases with the consumer price index (CPI) from 2008 to 2016.

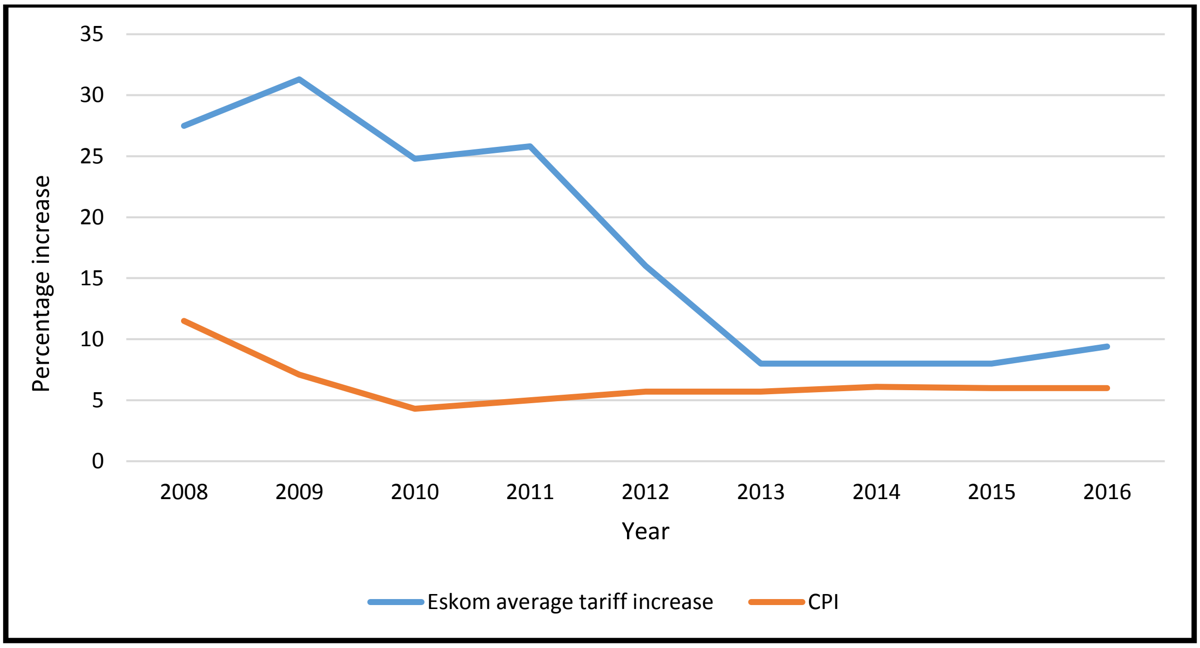


Figure 3: Average Eskom tariff and CPI increases from 2008 to 2016 (adapted from [14])

The Eskom tariff increases for 2008–2016 have always been above the CPI. Only once Eskom has been able to generate the required electricity for a few years, the Eskom tariff increases will stabilise. Tariff increases that are below inflation will benefit large electricity consuming industries in South Africa.

1.2 The platinum mining industry in South Africa

South Africa holds over 80% of the total platinum reserves in the world. South Africa produces 90% of the world's platinum with a value of approximately 130 tonnes per year [15]. The platinum industry was negatively affected by strikes that occurred in 2014, when more than 70 000 workers went on strike for a period of almost five months [16]. The combined revenue lost in South Africa was R23 billion [17].

Another aspect that also affects the profitability of platinum mining is the platinum price. The platinum price has decreased by nearly 42% from mid-January 2010 to date [18]. The decline in the platinum price can be seen in Figure 4 for the period from January 2010 until the beginning of October 2016.

Figure 4: Platinum price from 2010 to 2016 (adapted from [19])

In 2010, the maximum platinum price was $1 832/oz. In January 2016, the platinum price reached a low of $856/oz [20]. The decline in the platinum price has a direct effect on the profitability of platinum mining.

The performance of one of the largest platinum-producing companies listed on the Johannesburg Stock Exchange (JSE) has declined in recent years [21]. Figure 5 shows how this company's share price declined from January 2007 to October 2016. The maximum share price was obtained in May 2008, with a price of R146 000 per share. The lowest share price was obtained in January 2016 with a price of R17 300 per share. This represents a decrease in the share price of more than 800% within this period.

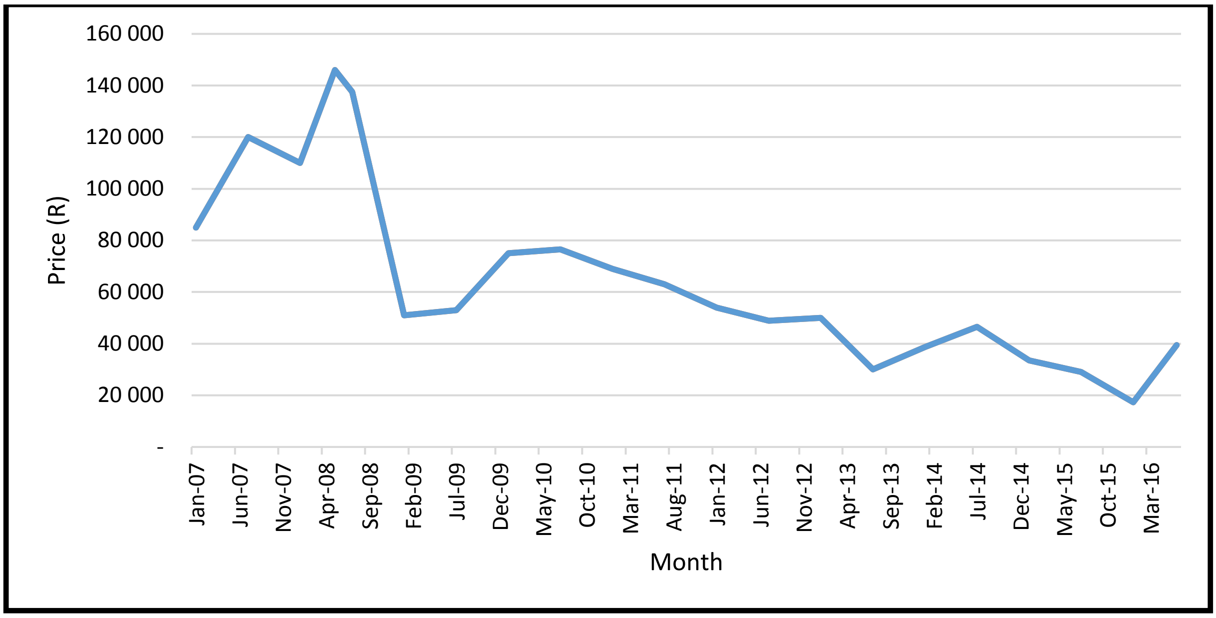


Figure 5: JSE shares declining for Company A (adapted from [21])

In 2011, the total expenditure cost for the top five platinum mining producers was calculated at R83.2 billion [22]. The platinum mining industry is also the sixth-highest consumer of electricity in South Africa [23]. Figure 6 shows how the total electricity cost is divided per section in the platinum industry; for some of these sections, the cost cannot necessarily be decreased. For example, labour – the workforce cost cannot necessarily be decreased without compromising production. A section that can be decreased without compromising production is electricity cost, with 6% of the total expenditure costs dedicated to this section. This calculates to nearly R5 billion per year. This is significant, especially when it is considered that the increase in electricity costs in the mining sector was calculated as 238% from 2007 to 2012 [22].

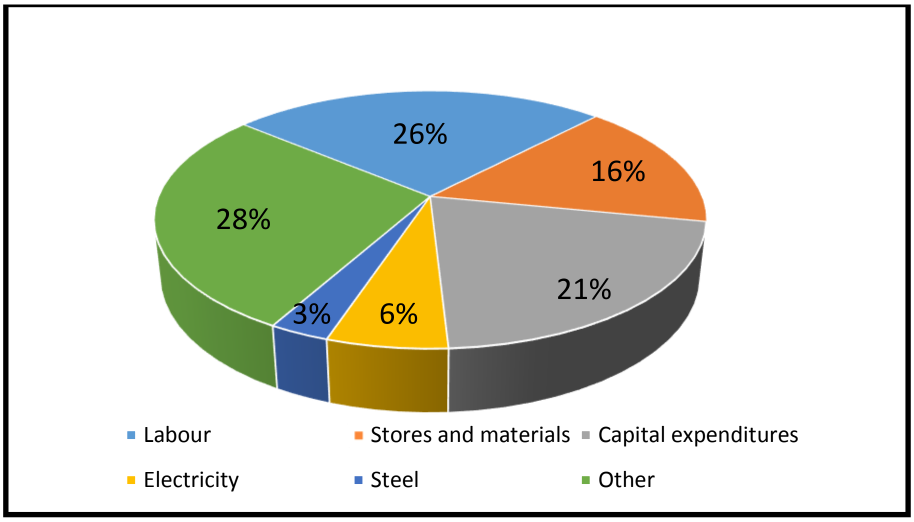


Figure 6: Platinum industry cost breakdown (adapted from [22])

Eskom focuses on reducing the peak demand as this is the period with the highest electricity consumption. An initiative which can be implemented to reduce the electricity costs in the mining industry is demand side management (DSM).

1.3 DSM

DSM is an initiative where the pattern of electricity consumption of an electricity consumer is either modified or lowered to realise electricity cost savings [24]. The three most widely used strategies include energy efficiency, load shifting or peak clipping strategies.

One of the international leaders in DSM initiatives is the United States of America (USA). USA initiated DSM in the 1970s as public concern towards the environment increased [25]. DSM contributed to increasing energy efficiency in the USA in the 1990s [25]. South Africa have the deepest mines in the world [26] and presents unique challenges. One of these challenges is the increased temperature and friction losses with increasing depth.

In 1994, the first DSM plan was released in South Africa, which included various DSM opportunities [24]. The first DSM funding was introduced in 2002 by Eskom’s Integrated Demand Management (IDM) department [24]. Eskom’s IDM programme is a short-term solution to meet the national electricity demand, especially during the morning and evening peak periods [27]. The IDM department appoints energy service companies (ESCos) to obtain energy savings in large energy-consuming industries.

ESCos are assigned by Eskom to implement DSM projects. The main focus is to decrease electricity consumption in the Eskom evening peak [28]. An ESCo will work directly with industry, using the funds from Eskom. In South Africa, DSM projects focus primarily on reducing the demand in the evening peak period [29]. When DSM projects are implemented, equipment and/or control systems are installed. This enables electricity demand reductions in the Eskom evening peak to achieve electricity cost savings.

DSM projects reduced the Eskom peak consumption by 4 000 MW up to April 2016 [30]. Most of these savings were achieved by large electricity consumers. Table 1 lists the five industries with the most DSM energy saving potential. It can be seen that the total potential savings for these industries are 8 355 GWh [31].

Table 1: Industry ranking and DSM potential savings (Adapted from [31])

	DSM potential		**Electricity use**	
	Rank	**GWh**	**Rank**	**% of total**
Gold mining	1	2 311	3	15.36
Iron and steel	2	2 289	1	22.91
Wood and wood products	3	1 458	5	8.18
Chemicals	4	1 370	4	12.54
Platinum mining	5	927	6	6.13
Total		**8 355**		**65.12**

The two largest mining industries in Table 1 include gold and platinum mining. Combined, these two mining industries consume more than 21% of the total electricity consumption in South Africa. This combined potential DSM savings are calculated at 3 238 GWh [31]. Eskom’s 2015/16 target for demand side evening peak savings was 187 MW, which was overachieved with savings of 214.9 MW [5]. Eskom’s long-term DSM target is to reduce peak demand by 5 000 MW by 2026 [32]. For this target to be achieved, it is necessary for current DSM projects to be sustainable by achieving their target savings.

A study was done where the performance of 37 DSM projects were investigated. It was found that 41% of these projects did not achieve their targets in the performance assessment phase [33]. The average underperformance of these projects was 26% less than their initial targets [33]. A solution was needed to prevent the deterioration of DSM performance.

Initially ESCos were appointed to work with clients in large energy-consuming industries to obtain electricity cost savings. The IDM department in Eskom funded these DSM projects. The

ESCo were responsible for implementing DSM projects and ensuring that these projects achieved target savings within the three-month performance assessment period [34]. After the performance assessment period, the ESCo would hand the project over to the client. The responsibility for achieving the target savings was shifted to the client for the next five years [34]. It was seen that the project savings deteriorated after handover to the client.

The solution was to increase the period where ESCos are responsible for maintaining their DSM projects. The DSM performance assessment period remained three months, although the ESCo is now responsible for obtaining the target savings of each project in the performance tracking period [34]. This performance tracking period is for three years after the initial performance assessment period [34]. Eskom will pay 30% of the total project funds after three months, with the remaining funds being paid every quarter for the next three years [34]. This extended period where the ESCo is responsible for obtaining the target savings could reduce the deterioration of DSM projects.

1.4 Compressed air usage in the mining industry

One of the large consumers of electricity on a platinum mine is compressors. Compressors are responsible for as much as 20% of the total electricity consumption on a platinum mine [23]. A study was done in 2010 where the electricity consumption was calculated for a compressed air network. The result showed that compressed air networks consume about 9% of the total electricity consumption of South Africa [35].

Various DSM strategies have been implemented on compressed air networks on mines in South Africa where large savings have been achieved. These implemented DSM strategies contributed to energy and cost savings for the mining industry. Estimations showed that compressor management can account for 25% of the total DSM savings in South Africa [36]. It was found that stopping compressors that are running unnecessarily can reduce the electricity consumption of a compressed air network by 15–25% [37].

Another problem is that compressed air leakage accounts for up to 35% of losses in a compressed air network [38]. A study was done where compressed air leaks were minimised as part of a DSM project implementation. An increase of 85% in savings was obtained as a result of minimising compressed air leakage [39].

In various studies, the compressed air ring pressure set points were adjusted. When the pressure is lowered, the compressors can be controlled to generate lower pressure. This would decrease the electricity consumption of the compressed air network.

1.5 Problem statement

The platinum mining industry is under pressure due to the decreasing platinum price and decreasing platinum company shares. Electricity is one of platinum mining industry’s expenditures that can be decreased without compromising production. This creates an opportunity where the electricity expense can be reduced to lower the total expenditure of the platinum mining industry.

Compressed air networks is a major electricity consumer in the platinum mining industry. These compressed air networks are often plagued by inefficiencies, which create opportunities for implementing DSM initiatives to reduce electricity costs. This problem will be addressed in this study and specific objectives will be stated and achieved.

1.6 Objectives of this study

This study will focus on implementing a DSM strategy on a platinum mine in South Africa to reduce its compressed air usage. This DSM strategy involves optimising the compressed air network by installing control valves at each compressed air user.

The compressed air usage reduction will ensure that compressors can be “cut back” to reduce the electricity consumption of these compressors, which will reduce electricity costs. DSM strategies in South Africa focus on the Eskom evening peak period, as this is the period Eskom focuses on to reduce the electricity consumption demand.

In order to address the problem successfully, objectives are defined for this study, which will be addressed in the chapters that follow. In the final chapter of this study, it will be discussed how each objective was achieved. The objectives of this study include:

- Identifying opportunities where airflow and/or pressure can be reduced.
- Controlling the compressors to generate the lower required flow and/or pressure; this will reduce the electricity consumption of compressors.
- Simulating solutions for reducing electricity costs. The simulations will be verified by using data obtained from the mine’s database.

- Implementing the solution for reducing the compressed air consumption in the Eskom evening peak period.
- Verifying the results.
- Validating the electricity cost savings.

1.7 Overview

Chapter 2

Chapter 2 will give background information needed to understand the methodology and control philosophy of this study. This information will include subjects such as compressed air systems with optimal choices for the platinum mining industry. The information will include optimal compressor choices and the type of network used to link compressors and users. The implications of air leakage and leak detection methods will also be included. Previous research on compressed air networks will be reviewed to verify whether this study has been done in the past.

Chapter 3

Chapter 3 will include the methodology and control philosophy of the strategies to be implemented to ensure that electricity cost savings are achieved. The implementations will be discussed. Simulations will be built, which can be compared with actual results to verify the methodology. When these simulation models are verified, the simulations can be adjusted to simulate the effect of the control philosophy.

Chapter 4

In Chapter 4, the actual results from the project will be compared with the simulated results. In Case Study 1, the results will be validated using data from the mine’s database. Case Study 2 is a theoretical project, where the simulated flow and simulated pressure will be compared with actual data to calculate if this is a viable project to implement.

Chapter 5

Chapter 5 will serve as the conclusion to the document. Furthermore, the performance of the initiative will be discussed. The final section of this dissertation will include recommendations for future initiatives which can conclude that more electricity cost savings can be achieved.

2 Background on compressed air networks

Centrifugal compressor casing [40]

"How we approach mining today versus 50 years ago is altogether different."

Bill Scales

2.1 Introduction

In this chapter, information is provided on the operation and components of a compressed air network, combined with previous research done on this topic. Both the demand and supply side of the compressed air network will be discussed.

Usually compressed air networks consist of more than one compressor on surface, which supplies compressed air to all the compressed air users by means of a compressed air ring. A compressed air ring is the link between the compressed air users and compressors. These compressed air users are located either on surface or underground.

2.2 Compressed air on a platinum mine

2.2.1 Compressed air users

Compressed air is used for various purposes on a platinum mine. The equipment using compressed air can be divided in two sections, namely, high- and low-pressure users. High-pressure equipment, such as pneumatic drills, need a pressure of between 500 kPa and 700 kPa [41]. Low-pressure systems, such as refuge bays, require a pressure of between 50 kPa and 200 kPa [41]. Four compressed air consumers that are important to DSM projects on compressed air networks are pneumatic drills, loading boxes, agitation and refuge bays [42].

Pneumatic drills

Pneumatic drills used in the mining industry require high pressure. These pneumatic drills are mainly used in the drilling shift to drill holes for the explosives used in the blasting period [43].

Loading boxes

Loading boxes are used to hold and carry ore to desired locations. These loading boxes require high pressure to operate [43].

Agitation

Agitation is used to prevent raw materials from settling in a dam by using compressed air. It is implemented in water dams by installing open-ended tubes at the bottom of these dams [43]. The density of the compressed air exiting the tubes is lower than the density of the raw materials in the backfill dams. This provides agitation as the raw materials are not able to settle.

Refuge bays

Refuge bays provide a safe area on each level of a vertical shaft [43]. These bays provide safe areas for mining personnel to use in case of emergencies and are required according to the Mine Health and Safety Act [44]. These refuge bays should receive compressed air throughout the day [45]. The minimum pressure required by refuge bays determines the minimum required pressure needed in the Eskom evening peak period, as these bays are the users with the highest pressure requirements during this period.

2.2.2 Comparison of energy carriers

Safety and ease of use are reasons compressed air is used as an energy carrier in the mining industry, although it is less effective than other energy carriers used for drilling, such as electricity, and hydrodynamic and oil electro-hydraulic power [46]. Table 2 indicates how ineffective compressed air is when compared with other energy carriers specifically used for drilling in a mine.

Table 2: Efficiencies of various energy mediums (adapted from [46])

Drilling: % energy delivered to face	Efficiency of compressor or pump	Reticulation pressure or voltage drop	Energy left after leakage	Efficiency of drill	Overall efficiency
Compressed air	58	75	18	24	2%
Oil electro-hydraulic	80	80	100	36	23%
Hydropower pumped	85	80	95	31	20%
Hydropower gravity	96	89	90	31	24%
Electric drill	100	90	100	35	32%

Table 2 shows that compressed air has the lowest overall efficiency. Mines prefer compressed air because of its ease of use and the safety aspects thereof. Compressed air equipment has simple designs, thus making it easy for mining personnel to use. When there is a compressed air leak, it is not considered as dangerous as other energy mediums.

2.2.3 Compressed air requirements

Figure 7 shows the daily mining schedule of a typical platinum mine combined with the typical average pressure requirements for each period. It can be used to identify periods where the pressure set points can be lowered. When the pressure set points are lowered, compressors can be controlled to generate only the required pressure, leading to lower power consumption.

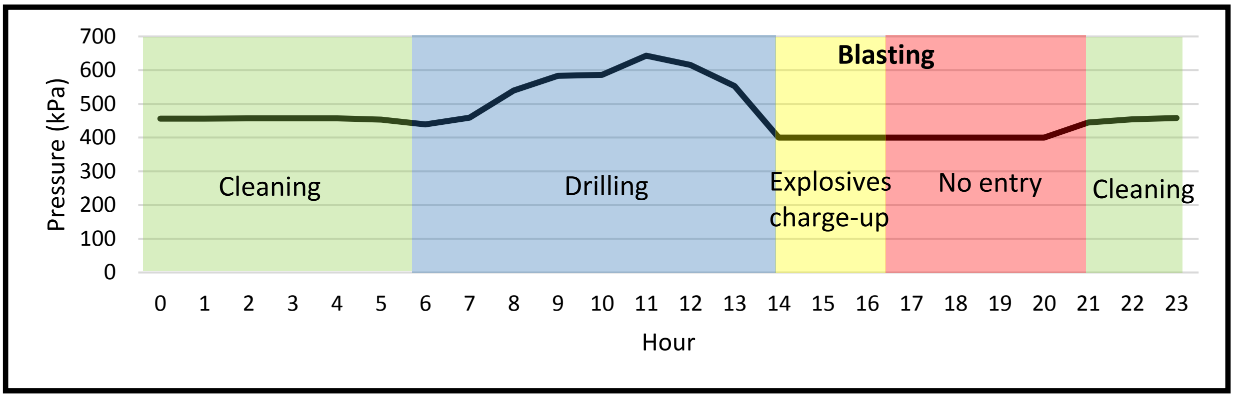


Figure 7: Average pressure requirements for a daily mining activities (adapted from [45])

In the cleaning shift, the pressure required is 450 kPa. The drilling shift's pressure requirement peaks at 650 kPa. The pressure requirement for the explosives charge-up shift is 500 kPa and the "no entry" shift requires 400 kPa.

A mining schedule can be used to identify periods where the pressure set points can be adjusted. Compressed air usage reaches a peak in the drilling shift, which is between 06:00 and 14:00 each weekday. The minimum compressed air usage is between 14:00 and 21:00; this includes the explosives charge-up and "no entry" periods.

The "no entry" period follows the blasting period, which is typically at 16:30 each weekday. This period coincides with the Eskom evening peak period when electricity is expensive and electricity consumption should be minimised. During the "no entry" period, minimum pressure is needed, which is determined by the minimum compressed air requirements of the refuge bays. The reason for this is that the refuge bays are usually the compressed air users with the highest pressure requirements during the Eskom evening peak period. This presents an opportunity to implement a DSM intervention to obtain electricity cost savings on the compressors.

In the Eskom evening peak period, the demand for compressed air reduces, there is thus a risk of oversupplying the compressed air network. This is an indication that the compressed air network would benefit from installing control valves, which can be used to lower the pressure of compressed air for each user.

2.2.4 Optimising a compressed air network on the demand side

Figure 8 compares the average compressed air flow profile of a mine with the Eskom Megaflex tariffs for 2016/17. This shows that it would be beneficial for the mine to minimise the compressed air flow during the Eskom evening peak period, especially in the high-demand season when higher tariffs apply. The mine will benefit from lower flow in the Eskom evening peak period, as the electricity tariffs are more expensive in these times. When the flow generated by compressors is decreased, the electricity consumption of compressors decreases, thus resulting in a decrease in electricity costs.

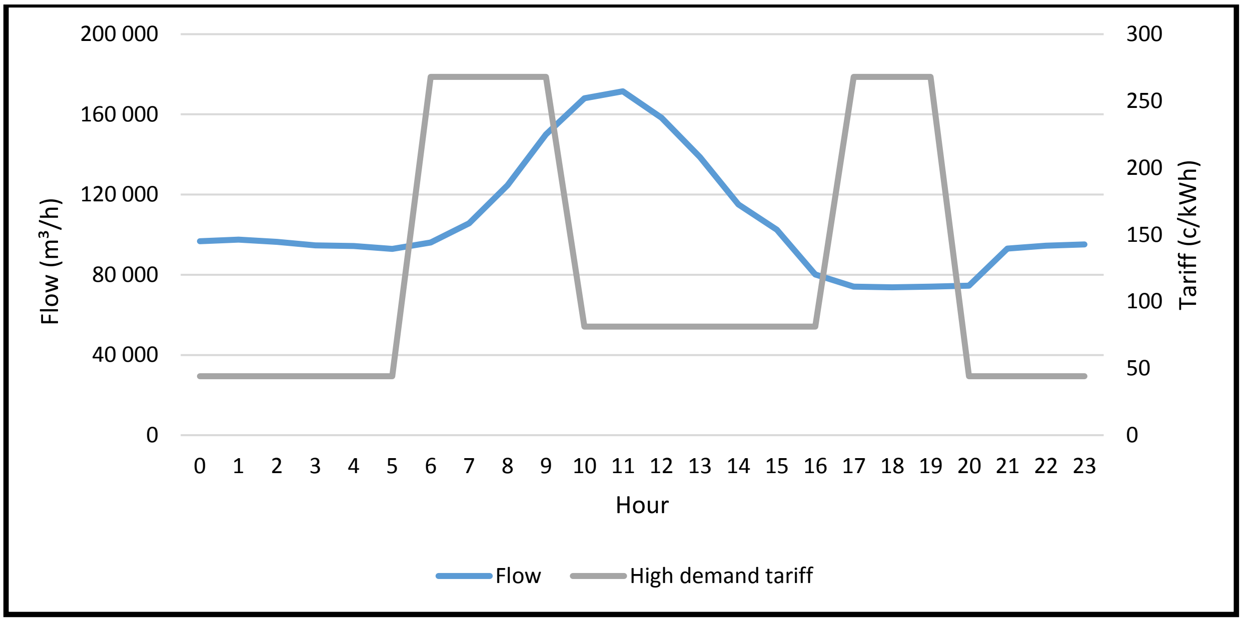


Figure 8: Flow compared with Eskom tariffs

A cost-effective method for reducing compressed air consumption is installing control valves. Control valves are fitted with actuators that can be controlled using a supervisory control and data acquisition (SCADA) system via a programmable logic controller (PLC) [42]. The valves are installed on the main compressed air pipeline at each compressed air user on surface. The valves are controlled by the SCADA using downstream pressure requirements as reference. To determine the required pressure and flow needed by the compressed air users, compressed air flow calculations are done to ensure that all the requirements are met.

2.2.5 Compressed air flow calculations

Flow calculations are used to determine the optimal velocity, flow and pressure in a compressed air network. The two important characteristics are flow and pressure; these are used to determine the control philosophy of the compressed air network.

Each compressed air user must receive the required compressed air pressure and flow to obtain the required production. Bernoulli’s theorem is used to determine the amount of compressed air needed by the demand side of the compressed air network. When the velocity of compressed air increases, pressure increases. Equation 1 can be used to calculate this statement [47].

$$\frac{1}{2}\rho v^2 + \rho g H + p = \text{constant}$$

Equation 1: Bernoulli’s theorem

The components of Equation 1 are:

- ρ: Fluid density (kg/m^3)
- v: Fluid velocity (m/s)
- g: Gravitational acceleration (m/s^2)
- H: Height above a reference point (m)
- p: Pressure at the measurement point (kPa)

Equation 1 can be used to calculate the change in velocity when the pressure difference is known. The constant value in Equation 1 is unique to each system. The velocity of the compressed air in the piping will be used as a guideline to calculate the optimal flow and pressure. If the air velocity is too high, drains that capture moisture and water within the compressed air network will not function. If the velocity is too low, users will not receive the required flow. The general mining guideline for velocity is usually between 10 m/s and 15 m/s.

Equation 1 is used to determine the values shown in Table 3, with the pipe diameter set at 450 mm. Table 3 shows how a change in velocity affects the pressure in a compressed air network.

Table 3: Difference in pressure due to difference in velocity

Velocity (m/s)	**Pressure (kPa)**
7.5	274.56
10	297.59
12.5	327.21
15	363.41
17.5	406.19

Figure 9 shows the near linear relationship between velocity and pressure.

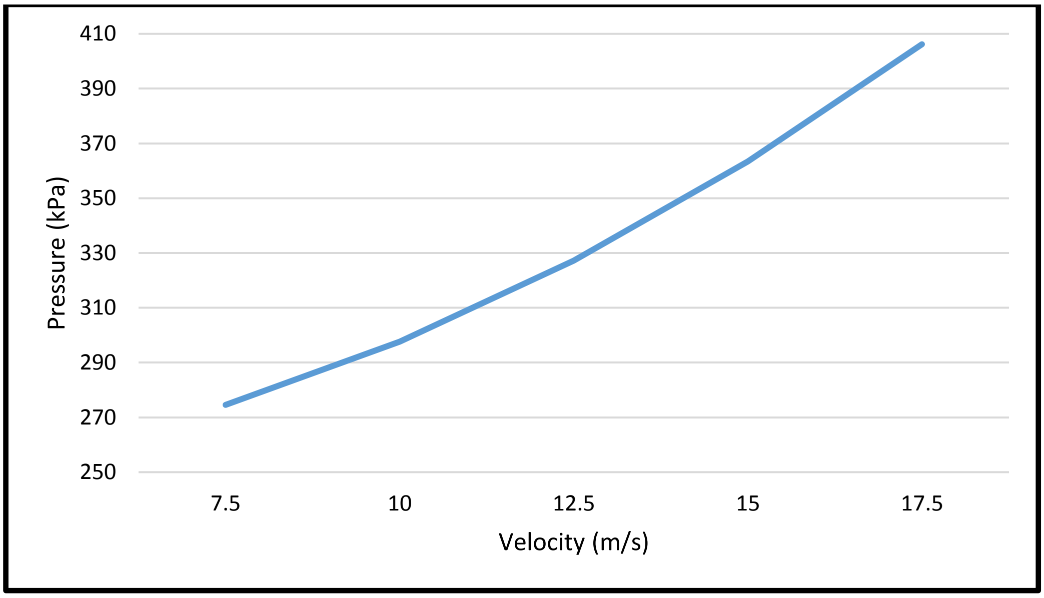


Figure 9: Linear relationship between pressure and velocity of compressed air

The velocity and pipe diameter are used to calculate the volume of compressed air. Equation 2 is used for this purpose [48]. This can also be used to calculate the pressure required by the network.

$$Q = v \times A$$

Equation 2: Flow formula

The components of Equation 2 are:

- Q: Volumetric flow (m^3/s)
- v: Velocity of the fluid, which is air in this case air (m/s)
- A: Area (m^2)

Equation 2 indicates that the compressed air velocity is dependent on the diameter of the pipe. If the diameter decreases, the fluid velocity increases to ensure a constant volume [49]. In Figure 10, Equation 2 is used to plot compressed air flows against various pipe diameters for different velocities. The velocity is increased from 7.5 m/s to 17.5 m/s in intervals of 2.5 m/s. The diameter is increased from 0.56 m to 0.98 m. Each line represents a different velocity profile. Figure 10 shows that the flow can be increased by increasing the diameter of the pipe, while the pressure is kept constant.

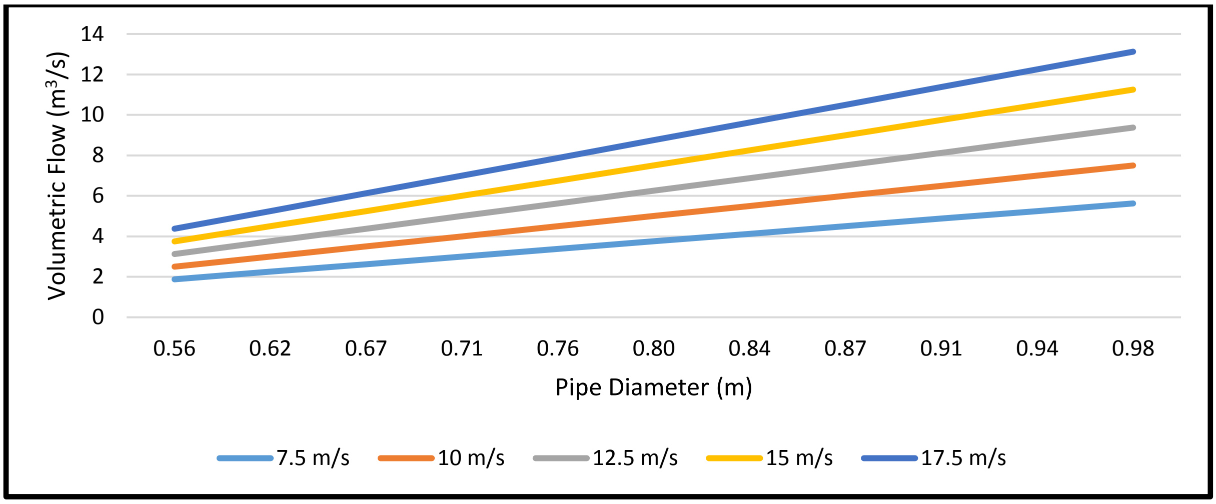


Figure 10: Difference in flow due to change in pipe area

Figure 10 shows that pipe diameter affects the flow of compressed air. This must be considered when a pipeline is replaced to ensure that compressed air users receive the required amount of compressed air flow. When flow is calculated, it must be considered that each compressed air user also requires a minimum set point pressure.

Equation 3 is used to calculate the minimum set point pressure, depending on the volume flow and height of the compressed air, where the height is used to indicate a pressure difference between the pressure before the impeller and the delivery pressure [48].

$$P = \rho Q H$$

Equation 3: Pressure formula

The components of Equation 3 are:

- P: Pressure (kPa)
- ρ: Density (kg/m^3)
- Q: Volumetric flow (m^3/s)
- H: Height (m)

Equation 1, Equation 2 and Equation 3 are used to calculate the required flow and pressure to ensure that the compressed air requirements are met.

2.3 Components of a compressed air network

2.3.1 Compressed air network

A platinum mine uses a compressed air network to transport compressed air between the supply- and the demand side of the air network. There are two types of network configuration that are commonly used, namely [27], [45]:

- Stand-alone system; and
- Ring feed system.

The stand-alone system is a simple and low-cost configuration compared with a ring feed system. This type of network consists of a single compressor connected directly to the compressed air users. The compressor is usually located close to users to minimise the amount of piping required and pressure drop losses due to friction. Figure 11 shows a simplified layout of a stand-alone compressed air network [45].

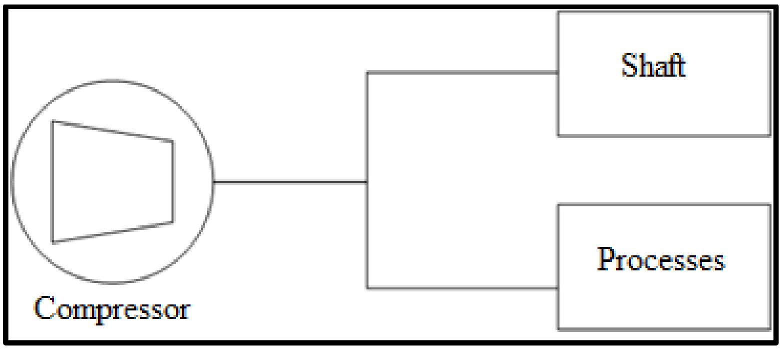


Figure 11: Simplified layout of a stand-alone compressed air network

The advantages of a stand-alone network are ease of maintenance and a low installation cost. The disadvantage is that compressed air users do not receive compressed air when a compressor malfunctions [27], [45]. A stand-alone compressed air network does not have redundancy in case of a problem arising.

A ring feed system is more complex than a stand-alone system. This is due to more interlinking parts that can affect the entire compressed air network. A basic layout of a ring feed system can be seen in Figure 12. Note that that the system has multiple compressor houses located at different positions. This configuration is costly due to the piping required to link all components.

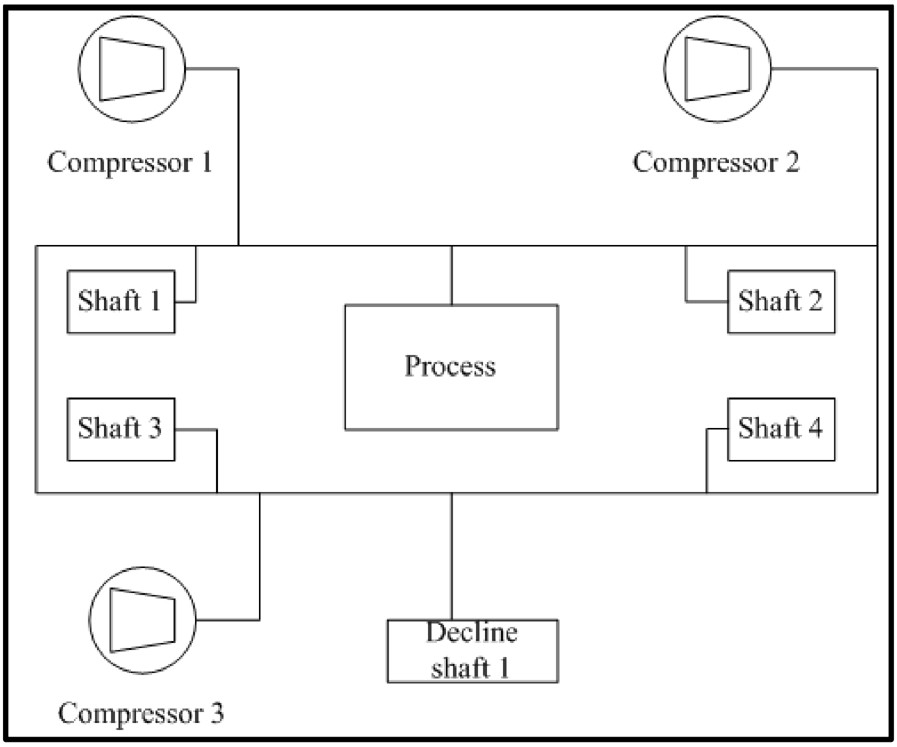


Figure 12: Typical layout of a ring feed compressed air network

The advantages of a ring-feed network are as follows [27], [45]:

- It is unnecessary for each shaft to have its own compressor house.
- No specific consumer will suffer from a lack of compressed air when a compressor has to undergo maintenance.
- If a compressed air consumer uses less air, there will be more compressed air available for the rest of the compressed air consumers.

The disadvantages of a ring-feed network are as follows [27], [45]:

- The extra piping required will result in increased friction losses.
- Leaks will be a larger problem considering the increase in piping.
- When large air leaks occur or compressed air is wasted, it reduces the pressure of the entire system.
- Additional piping will have higher installation and maintenance costs.

A ring feed network is often preferred over a stand-alone network, because of the redundancy of compressors. Safety is also important; for example, if a compressor trips during the Eskom evening peak period, the remaining compressors will still provide the required compressed air pressure to the refuge bays.

2.3.2 Supply side of compressed air networks

The supply side of a compressed air ring refers to the compressors. Centrifugal and axial compressors will be discussed in this section. The most suitable compressor type for the mining industry will also be pointed out.

Centrifugal compressor

Centrifugal compressors were developed to provide high-pressure compressed air in large volumes. A centrifugal compressor is efficient (±85%) and does not need to deliver a constant amount of flow to be effective [48].

A centrifugal compressor consists of the following elements as illustrated in Figure 13:

- *Casing:* This component forces compressed air to compress by decreasing the flow area.
- *Suction port:* This is the point where air enters the compressor.
- *Impeller:* This element forces the air to enter the eye of the compressor and compresses the air via the casing.
- *Diffuser:* This is the exit of the compressor and is used to direct the air in order to achieve higher efficiencies [48].

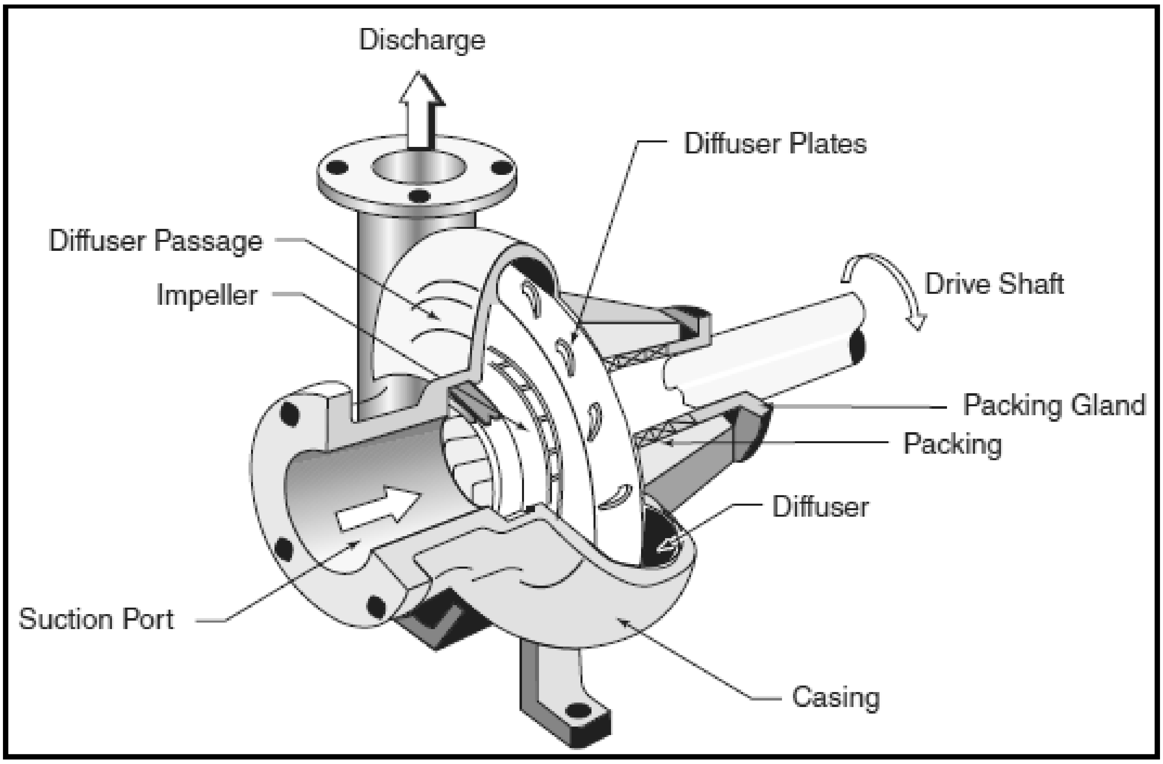


Figure 13: Elements of a centrifugal compressor [50]

It is important to understand the effect that pressure differences between two impeller blades can have on the efficiency of a compressor and the amount of mass flow it can generate [48]. This concept is important as it will be used later in this section to understand surging. Equation 4 is used to calculate the pressure ratio between two impeller blades [48].

$$\frac{P_{02}}{P_{01}} = f\left(\left(\frac{T_{02}}{T_{01}}\right), \left(m\frac{T_{01}^{\frac{1}{2}}}{P_{01}}\right), \left(\frac{N}{T_{01}^{\frac{1}{2}}}\right)\right)$$

Equation 4: Theoretical characteristics of a centrifugal compressor

The components of Equation 4 are explained below:

- $\frac{P_{02}}{P_{01}}$: Pressure difference between two impeller blades
- $\frac{T_{02}}{T_{01}}$: Temperature difference between two impeller blades
- $m\frac{T_{01}^{\frac{1}{2}}}{P_{01}}$: Mass flow parameter
- $\frac{N}{T_{01}^{\frac{1}{2}}}$: Speed parameter

Equation 4 is used to plot pressure and temperature differences against the mass flow rate parameter for alternating values of speed parameters. The plot can be used to illustrate possible issues such as surging of a centrifugal compressor [48].

Tests can be done where the pressure difference is plotted against the mass flow parameter, where the speed is kept constant. The tests can be done at different speed intervals. Figure 14 plots an example of a fixed speed scenario [48]. The pressure ratio is P_{03}/P_{01} and the non-dimensional mass flow is $mT^{½}/P_{01}$.

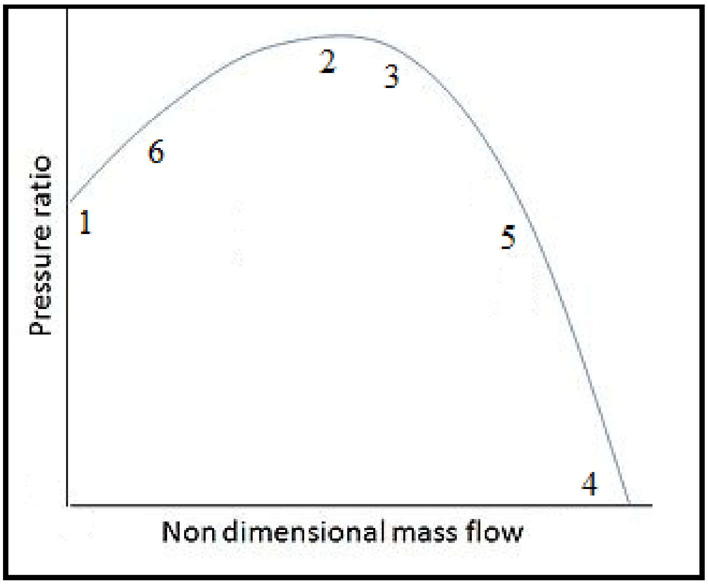


Figure 14: Characteristics of a centrifugal compressor [48]

The y-axis on Figure 14 is the pressure ratio between the inlet and outlet pressure of each impeller, where P_{03} is the delivery pressure after the air is compressed. The x-axis on Figure 14 is the mass flow parameter of the compressor, which indicates the amount of mass flow generated by the compressor, P_{03}/P_{01}.

This plot is specific to a centrifugal compressor. There is a control valve situated at the diffuser of the compressor. When the valve is fully closed, Point 1 will be achieved in Figure 14, meaning that the flow rate is zero and a certain pressure ratio will be achieved [48]. This condition is usually achieved when a compressor starts up.

When the valve is opened gradually, Point 2 will eventually be reached, which is the maximum pressure ratio. When the mass flow is increased, Point 3 will be reached where the maximum efficiency will be, although the pressure ratio has decreased slightly. Point 3 is the designed operating point on most centrifugal compressors [48]. Point 3 is the optimal operating point as this is the point where the mass flow to pressure ratio is the highest.

If there is a temporary blockage or build-up of pressure in the outlet of the compressor, the mass flow will decrease slightly and the delivery pressure (P_{03}) will increase. This forces the working point to move to Point 6, which is an unstable scenario [48]. This scenario is unstable because the flow can easily decrease and eventually become zero.

When the delivery pressure decreases, the mass flow rate will also decrease. This will continue until Point 1 is reached, where there is no mass flow and a certain pressure ratio exists. At this stage, the pressure is high because of the build-up of pressure.

If the pressure at the inlet of the compressor (P_{01}) decreases significantly when the temporary blockage is overcome, the mass flow and pressure in the compressor will slowly increase until the designed mass flow is reached. The compressor will overshoot the operating point a few times before it stabilises. This phenomenon is called surging. Surging is an unstable and severe condition, which could lead to major failures in a compressor [48].

Surging tends to originate in the diffuser where the friction is high enough to decrease the mass flow of the air. Surging can be reduced when the impeller is designed with an odd number of impeller vanes, which is multiplied by the number of diffuser vanes. This is due to the pressure fluctuation, which can be evened out [48].

The guide vanes at the inlet of a compressor are used to control the mass flow generated by the compressor. The guide vanes are mounted on the first stage of a compressor. These guide vanes will shift from a parallel position to a perpendicular position, which will result in a lower mass flow and also reduce the power consumption of a compressor [38]. The general term for this action is to cut back a compressor, which can be seen in Figure 15. This is done when lower compressed air requirements are needed, for example, in the “no entry” period.

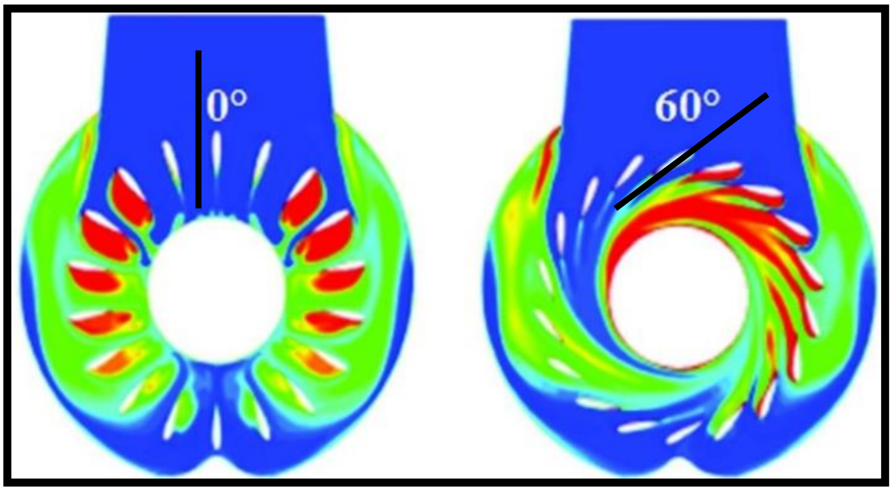


Figure 15: Guide vane position [51]

The guide vane position is controlled by a control system. This control system uses real-time information to calculate if a specific compressor can be cut back, which can mean that the angles of the guide vanes can be adjusted to an optimal position [38].

The guide vane angle has a direct influence on the power consumption of a compressor [52]. When the guide vanes are closed to 0° as on Figure 15, the power consumption will be lower. When the guide vanes are opened, the power consumption will be higher. The information needed to calculate the control parameters includes all the users' actual mass flow and pressure requirements. The mass flow can be cut back until the minimum flow point is reached, which is called the surge line. Surging must be avoided when mass flow is cut back, as previously discussed [53].

Axial compressor

An axial compressor can have a high efficiency (±90%) if operated at its optimal efficiency point. This means that a constant mass flow should be generated to achieve these high efficiencies. If any alterations are made, for example, if a compressor is cut back, the efficiency of the compressor decreases drastically [48]. An axial compressor consists of the elements as illustrated in Figure 16.

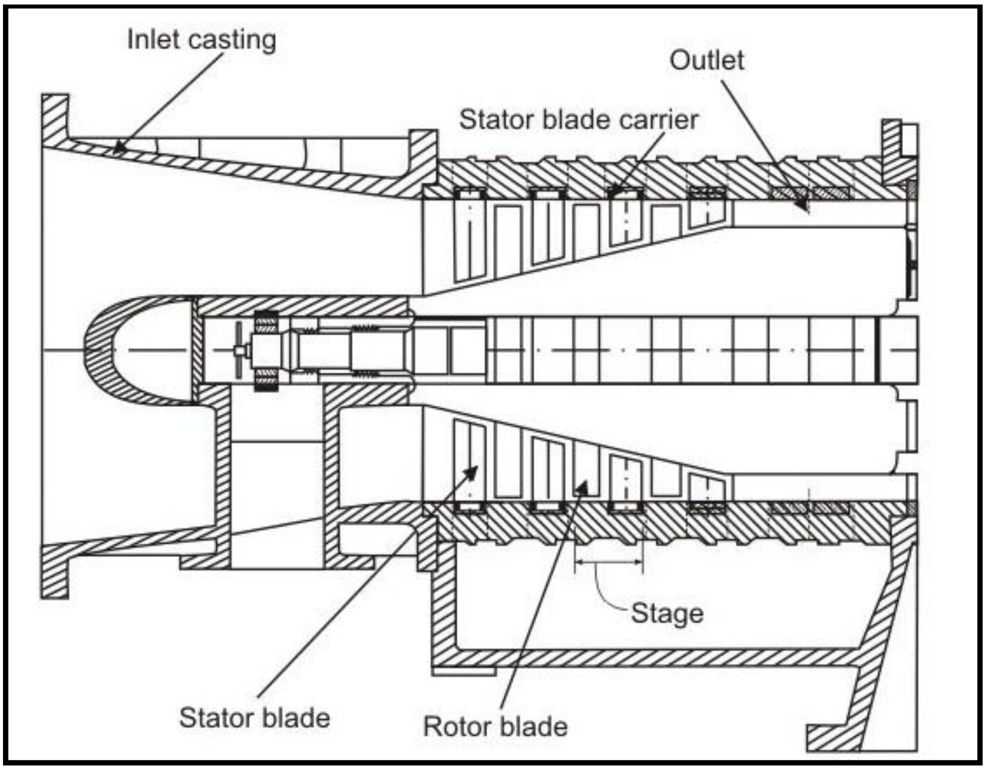


Figure 16: Axial compressor [54]

An axial compressor is designed for constant mass flow generation [48]. There are clear differences between an axial compressor and a centrifugal compressor, which include that an axial compressor has no guide vanes. When considering a compressor type for the mining industry, an optimal compressor must be used to minimise inefficiencies in the system.

Optimal compressor type for the mining industry

Reliability and ease of maintenance are important factors when choosing a type of compressor to use in severe mining conditions. An axial compressor can provide higher efficiencies and higher flow than a centrifugal compressor. The problem with an axial compressor is that the efficiency has a limited operating range. A centrifugal compressor is efficient over a larger operating range than an axial compressor. Thus, a centrifugal compressor is the optimal compressor type for the mining industry because it does not need to deliver a constant airflow to be efficient. A centrifugal compressor is better-suited for delivering different airflows during certain periods of the day, which is a requirement in the mining industry. It is also more durable and easier to maintain than an axial compressor [48].

2.4 Compressed air leakage

2.4.1 Compressed air leakage effects

A common problem on a compressed air network on mines is compressed air leakage. One of the most effective ways of improving compressed air network efficiencies is to detect and repair leaks [39]. Compressed air leakage needs to be managed properly to ensure compressed air network efficiency and sustainability [41]. DSM projects may miss their targets due to compressed air leaks being mismanaged throughout the network [56].

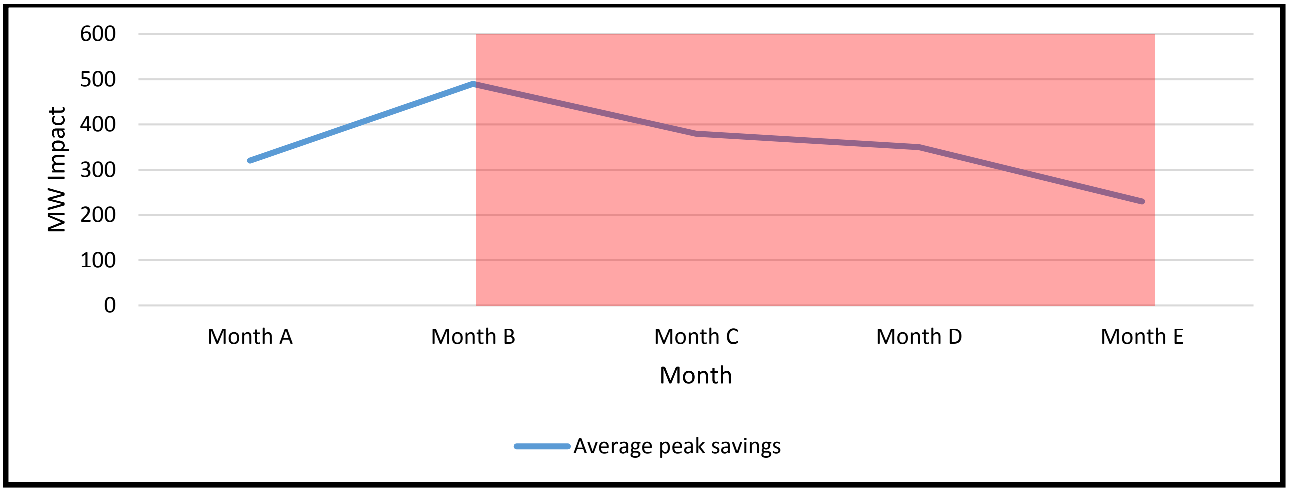


Figure 17: DSM performance decay [57]

Figure 17 illustrates the average monthly impact of an evening peak clipping project where savings decreased after Month B. A large contribution to the performance decreasing was that no compressed air leaks were repaired. Compressed air leakage increased when the pressure in the pipes increased. The red area in Figure 17 represents the time when no compressed air leaks were repaired.

Small leaks seem to have little effect on a compressed air network, although the loss in electricity savings may be larger than expected, as illustrated in Figure 17 [57]. Table 4 shows the financial impact of compressed air leaks of different sizes. This provides sufficient motivation for repairing compressed air leaks regularly.

Table 4: Compressed air leaks (adapted from [38])

Hole diameter (mm)	**Area of leak (m^2)**	**Mass flow (kg/s)**	**Mechanical energy (kJ/kg)**	**Power wasted (kW)**	**Energy savings (kWh/yr)**	**Cost savings (R/yr)**
3	0.000007069	0.01	271.43	1.71	15 245	13 816
6	0.000028274	0.03	271.43	6.82	60 978	55 265
10	0.000078540	0.07	271.43	18.95	169 384	153 513
25	0.000490874	0.44	271.43	118.43	1 058 650	959 454
50	0.001963495	1.75	271.43	473.73	4 234 599	3 837 817
100	0.007853982	6.98	271.43	1 894.93	16 938 398	15 351 270
150	0.176714590	15.71	271.43	4 263.60	38 111 395	34 540 357
200	0.31419270	27.93	271.43	7 579.74	67 753 591	61 405 080

The magnitude of compressed air losses increases when the compressed air pressure increases [58], [59]. When the number of compressed air leaks reaches a significant point, it is viable for the mine to invest in a method to detect and repair compressed air leaks. Leaks in a compressed air network can cause pressure drops in the system. Additional capacity is then required to compensate for these losses resulting from the air leakage [60]. When the compressed air losses decrease, the required compressor capacity decreases.

2.4.2 Leak detection methods

From the previous section it is thus clear that compressed air leaks should be detected and fixed to use compressed air optimally. Various leak detection methods are described in the subsections that follow.

Walk and report leaks

When compressed air flows through a leak orifice, a sound, named white noise, is generated. The frequencies made by the leaks differ depending on the size of the leak [61]. The first leak detection method includes walking along the pipe network and listening for white noise. Larger holes in the network will result in a louder and lower tone noise. Smaller leaks (<6 mm) can be difficult to notice using this method. This method thus only applies to large leaks [62].

Ultrasonic leak detectors

Ultrasonic leak detectors (ULDs) are used to detect frequencies that cannot be detected by the human ear. Figure 18 shows a ULD being used to detect a leak. A method where high inaudible frequencies are converted to audible frequencies ranging between 38 kHz and 42 kHz is specifically used for detecting compressed air leaks. Detecting leaks with ULDs is effective as this method has a specific frequency range for detecting compressed air leaks. This method can be time-consuming, especially when investigating the entire compressed air network [63], [64].

Figure 18: ULD [65]

Automated detection of acoustic waves

Compressed air leaks can be detected using computer-based systems [66]. Compressed air leaks and their positions can be detected by the acoustic waves emitted by each leak. Sensors can be placed throughout the compressed air network and connected to the SCADA. When there is a leak in a pipe network, acoustic waves are emitted in all directions. The time difference between different sensors detecting the same wave can be used to locate the position of the leak [66].

Pigging

Pigging is a method where a device that can detect compressed air leaks is placed inside the piping of the compressed air network. The device will be set to move downstream and perform certain functions, which depend on the different types of equipment fitted on the device. These functions include detecting and recording compressed air leaks, cleaning internal piping, and detecting and recording geometrical information regarding the inside of the pipe. A pigging device is shown in Figure 19 [67].

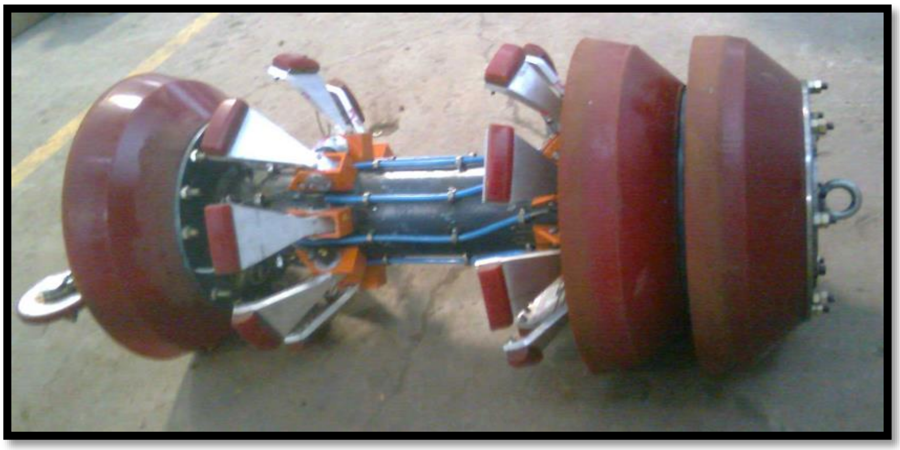


Figure 19: Pigging device [68]

A disadvantage with this method is the downtime on the network, because the device needs to be disassembled and reassembled at every pipe end. The use of a pigging device for leak detection is a time-consuming method that may affect production output [69], [70], [71].

Soap water

A simple method is using soap water, which is illustrated in Figure 20, to detect the location of small leaks on the compressed air network. When soap water is sprayed on a leak, bubbles will form due to compressed air exiting the pipe. It is a very low-cost method with no downtime and production losses [72].

Figure 20 shows leaks detected with soap water. Unfortunately, this method is impractical on large compressed air networks, because it is not feasible to spray the piping of an entire network with soap water [62].

Figure 20: Leak detection using soap water [73]

Dye additives

Air leaks can easily be identified by adding a dye to the network. The leaks can be detected where the dye exits the network. The dye is visible under ultraviolet light as seen in Figure 21 [62]. Figure 21 shows how this method indicates the location of a leak. The problem with this method is that compressed air leaks should be detected in the dark, when mining personnel need to be paid overtime.

Figure 21: Leak detection using ultraviolet light [74]

Theoretical method

The last method entails loading and unloading compressors to determine the amount of time it takes to pressurise and depressurise the network. The time it takes to pressurise the network after it is unpressurised can be used to calculate the system leakage. Although this method allows the system leakage and percentage leakage to be determined with ease, the location of the leaks cannot be determined [62].

The system leaks can be calculated with the following equation:

$$\text{System leakage (kW)} = \left(\frac{load\ time}{load\ time + unload\ time}\right) \times \text{(capacity of compressors)}$$

Equation 5: System leakage

The next step would be to calculate the percentage leakage with the following equation:

$$\text{Leakage (\%)} = \left(\frac{System\ leaks}{capacity\ of\ compressors}\right) \times 100$$

Equation 6: Percentage leakage

Conclusion

The optimal method for detecting compressed air leaks is a computer-based method, such as automated detection of acoustic waves. This is an expensive method, but if used on a regular basis, the financial advantages outweigh the high initial costs.

Studies have shown that the operating costs of a compressor is five times more than the installation costs over its lifetime [42]. This means that it would be beneficial for a mine to repair compressed air leaks regularly. Unnecessary running time of compressors can be decreased, which can lead to lower compressor consumption and lower electricity costs. When running times of compressors are decreased, maintenance and the amount of downtime also decrease [43]. Compressed air leak repairs should be included in DSM projects to decrease the unnecessary operation of compressors to save costs.

2.5 Saving opportunities on compressed air networks

2.5.1 DSM techniques

When considering the demand- and supply side of a compressed air network on a mine, the demand side consists of compressed air users; the supply side consists of compressors. The remainder of this section will focus on the demand- and supply side of a compressed air network.

The supply side will focus on the compressors to supply sufficient compressed air as required by the demand side at the lowest possible electricity consumption. The compressed air network will also be inspected from both a demand- and supply side to ensure the users receive the correct amount of compressed air pressure and flow [42].

Therefore, compressed air supply is a relevant focus area for the implementation of DSM projects. DSM projects include energy efficiency, peak clipping and load shifting strategies. Each of these strategies can be implemented to obtain electrical or energy cost savings.

Energy efficiency

A network is more energy efficient if service delivery increases for the same energy input, or if there is a constant service delivery for less energy input [75]. Figure 22 shows the effect of an energy efficiency initiative with the red blocks indicating the Eskom evening peak period during the low-demand season.

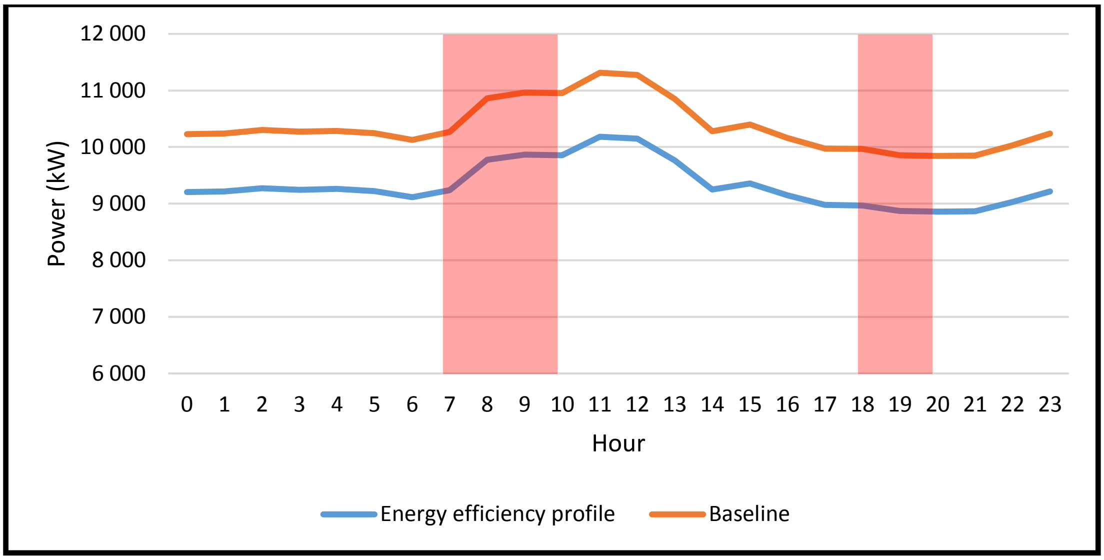


Figure 22: Energy efficiency profile

Figure 22 shows that the total electricity consumption has been lowered throughout the day. Generally, an example of this type of technique includes stopping an unnecessary compressor.

Peak clipping

When equipment is stopped or turned off in the evening peak period, it reduces the power usage within that period [76]. A peak clipping initiative can be implemented in the morning and/or in the evening peak periods. Figure 23 shows the peak clipping results of the reduced power consumption between 18:00 and 20:00, where the red block is used to indicate the Eskom evening peak period.

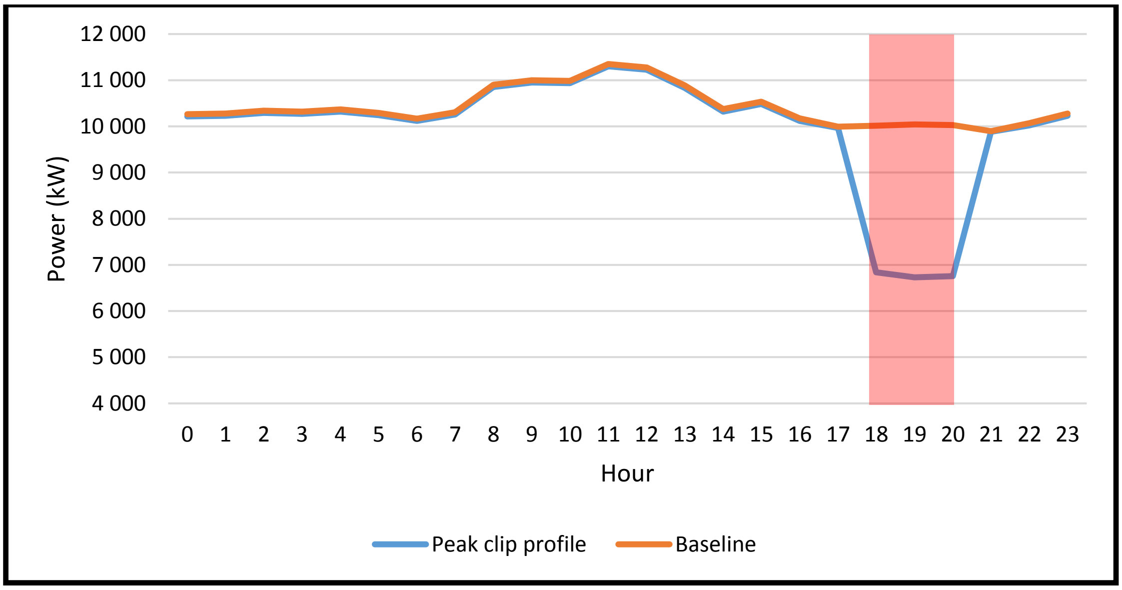


Figure 23: Peak clipping profile

In Figure 23, the profiles only differ between 18:00 and 20:00. This is the period where electricity consumption is reduced. An example of this technique is where a compressor is cut back within this period, and the compressor consumption decreases.

Load shifting

When a load shifting project is implemented, the power consumption in peak periods is lowered and shifted to periods when lower tariffs apply [77]. The purpose of a load shifting project is not to save electricity, but rather to achieve electricity cost savings. Figure 24 shows the effect of load shifting, where the red blocks are used to indicate the morning and evening peaks.

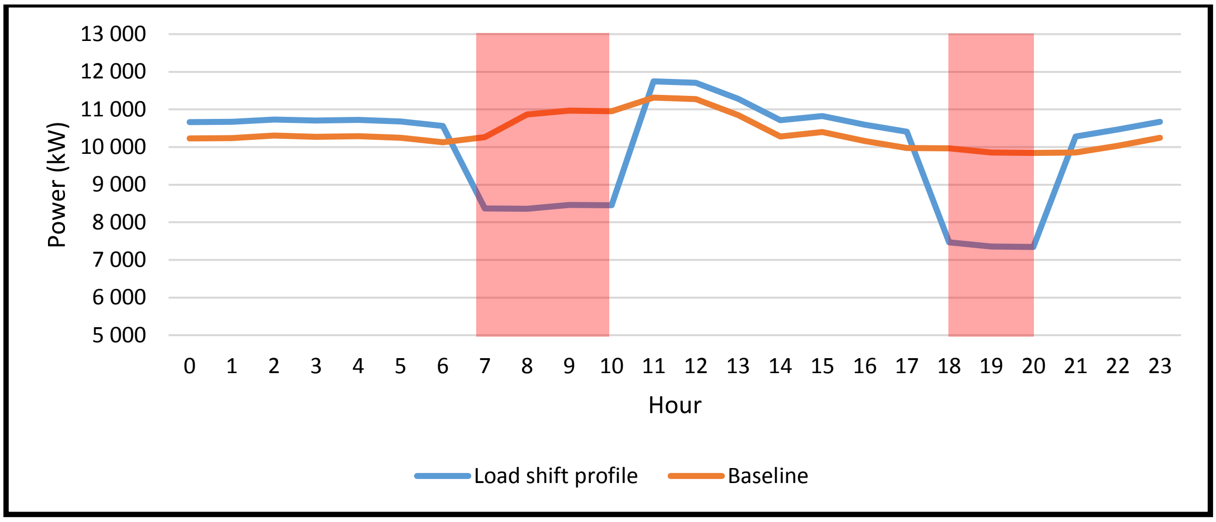


Figure 24: Load shifting profile

The power profile in Figure 24 decreased from 07:00 to 10:00 and again from 18:00 to 20:00. The rest of the profile increased, although the total energy consumption remained the same. An example of this technique would be where pumps are operated in Eskom off-peak periods, and stopped in Eskom peak periods.

2.5.2 Previous research

In this section, previous research specific to compressed air networks will be discussed. This will include an author's specific study and what was done. This will be followed by a short discussion on how this study differs from existing literature.

Minimising the effect of leaks in a compressed air network

Van Tonder [39] investigated the effect of leaks in a compressed air network. It was found that the amount of electricity wasted is often much more than what was anticipated. It was found that if leak repairs were managed efficiently, it could increase a project's savings by 85%. Van Tonder introduced the Compressed Air Leakage Documentation System (CALDS) as an efficient solution for managing compressed air leaks.

Repairing compressed air leaks can be time-consuming and may result in downtime on a compressed air network, which can lead to production loss. In this study, the implementation of a CALDS will not be discussed, but rather used in combination with other solutions to optimise the amount of electricity savings achieved.

Implementing control strategies

Kriel [78] found that control strategies on deep level mines were often outdated, which caused insufficiencies. These strategies included controlling underground level valves with a proportional-integral-derivative (PID) controller. This was an opportunity for implementing new strategies that could improve electricity cost savings. For example, a valve was installed and controlled on each mining level on the underground compressed air network.

This study will focus on implementing control valves and optimising the compressed air network as per the mine's schedule. These control valves will be implemented on the main line of the compressed air network before it enters the site of each compressed air user. This will ensure that the total compressed air flow towards each user will be controlled.

Reconfiguring compressed air networks

Bredenkamp [43] found opportunities where a mine's compressed air network could be optimised by reconfiguring the network to achieve electricity savings. This compressed air network was reconfigured by interconnecting two shafts and relocating a compressor. Simulations were built to ensure that this project would be viable before it was implemented.

Relocating a compressor is not always a viable solution, especially when considering the high cost and effort that is required. For this reason, it would be more viable to focus separately on each compressed air user to ensure that each user uses less air, which can make it possible to cut back compressors.

Rescheduling compressors

De Coning [79] built simulations to investigate the opportunity to optimise the control strategy of a compressed air network by rescheduling the compressors. Compressors would be stopped in the Eskom evening peak periods, specifically in the periods where low compressed air flows are needed. They would be started when the next cleaning shift commenced. This ensured electricity and cost savings in the Eskom evening peak period.

This is a viable solution, although some mine personnel do not allow compressors to be stopped and started frequently. They claim it reduces the lifetime of compressors, which forces them to do maintenance more regularly. A solution to this problem is to load and unload compressors instead of starting and stopping them.

Implementing energy efficiency solutions such as variable speed drives

Schroeder [80] investigated possible energy efficiency solutions on compressed air networks at gold and platinum mines. His investigations included implementing variable speed drives on compressor motors, which decrease the negative pressure difference in the system for compressed air distribution. The temperature on the discharge side of the compressor was also controlled, compressed air leaks repaired and the compressor selection controlled.

Using variable speed drives can significantly reduce the power consumption of compressor motors. Purchasing and installing a variable speed drive is, however, very expensive [81]. A less expensive solution would be to reduce the demand of the compressed air network to achieve electricity cost savings on the compressors.

Selecting the most effective compressor combination

Venter [82] developed a dynamic compressor selector that monitors the compressed air network continuously. This selector chooses the most effective compressor combination to satisfy the demand. This project reduced the total power consumption of the compressed air network and the cycling of compressors.

This study will focus on cutting back or stopping compressors to achieve electricity savings, although the dynamic compressor selector could also add great value to the compressed air networks considered in this study. This selector could be implemented after the demand side control of the users has been implemented.

Choosing the most efficient compressors

Lodewyckx and Kleingeld [45] investigated different strategies for controlling a compressed air network on a gold mine. These strategies targeted both the demand and the supply side. The most efficient compressors were chosen in the testing phase, where there were 10 compressors to choose from. It was also found that it was possible to cut back some of the compressors.

The problem with this is that not all mines in South Africa have more than 10 compressors to choose from. Not all compressors considered in this study could cut back as effectively as those on the mine used in the case studies by Lodewyckx and Kleingeld. The compressors that cannot cut back, will thus be run as baseload compressors or will be stopped.

Strategies of this study

This study will include installing control valves on the main compressed air pipeline. Two valves will be installed at each compressed air user on surface, where one will be used to seal the main compressed air pipeline in the Eskom evening peak period. The second valve will be installed with a bypass pipe with a smaller diameter than the main pipeline. The smaller valve will be used to control the pressure set point to each compressed air user in the Eskom evening peak period. The compressor selection will be chosen manually in the Eskom evening peak period, where different configurations will be tested to obtain maximum electricity savings.

2.6 Conclusion

Chapter 2 provided the necessary knowledge needed to understand how a compressed air network operates. This is beneficial, as possible savings can be achieved and possible problems identified. To understand a compressed air network, the demand and supply side of this network is required.

The demand side of the compressed air network was discussed with all the compressed air users. The compressed air user requirements were discussed. How to calculate the flow and pressure were also included. Two types of compressors were discussed, compared and the optimal type was chosen for the mining industry. The optimal compressor type is the axial compressor, because of high efficiencies over a large operating range. Compressed air users were also discussed and were low pressure requirement periods were identified to cut back on compressors. A ring feed compressed air ring was seen as the optimal choice, because off compressor redundancy

Leaks form an important aspect of maintaining a compressed air network, thus detection methods were discussed and optimal method was chosen to minimise financial losses. This knowledge can be used to identify DSM projects to decrease the electricity consumption of a compressed air network.

DSM techniques were discussed with the differences of each method. Finally, previous research regarding compressed air was reviewed with a discussion to the reason how this study is different.

In the next chapter, the methodology of the project will be discussed. This will include a breakdown of the simulation software used to simulate the project. Actual results will be used to verify if the simulation is a viable representation of the compressed air network.

3 Air network model

Centrifugal compressor installed on a platinum mine

“Engineering is the art of directing the great source of power in nature for the use and convenience of man.”

Thomas Tredgold

3.1 Introduction

Chapter 2 provided the necessary background information on the components of a compressed air network. An improved control philosophy was implemented where specific components were used to enable the control. Two case studies are presented in this chapter, where significant electricity cost savings can be achieved by improving each case study’s control philosophy. Each case study will be discussed individually to optimise the control and achieve larger electricity cost savings. A baseline simulation will be built for each case study, which will be verified using real-world data obtained from the mines where the case studies are located.

3.2 Case Study 1: Simulation to reduce evening demand by implementing valves

3.2.1 Background

The current compressed air network control philosophy at the case study mine entails that the output pressure set points of the compressors are set at a minimum value of 500 kPa. An improved control philosophy for the compressor output set point pressure will be developed by evaluating the demand and supply side of the compressed air network. While doing so, the mine’s schedule should be considered so that the production of the mine is not influenced. The mining schedule can be investigated to identify opportunities where output pressure set points can be lowered. When the output pressure set points are lowered, the compressors will cut back and their electricity consumption will decrease.

An energy management system (EnMS) is used to control the network, which in this case is the compressed air network of Mine A. This is named as the compressor management system on the EnMS. An EnMS is linked with the mine’s SCADA to retrieve the correct data. The EnMS will calculate the required set points and return them to the SCADA. This could ensure that the network control is optimised by the EnMS.

3.2.2 Improvement strategy

Supply side of the compressed air network

An improved control philosophy for the compressor output pressure set points will be developed for a typical mining schedule. This implies that the compressor output pressure set points will be lowered during certain hours of the day when less pressure is required for specific mining activities. By using the investigation, improved pressure set points can be calculated on an hourly basis. In the Eskom evening peak period, the refuge bays will determine the minimum required set point pressure.

A typical mining schedule can be seen in Figure 25. In the "no entry" and explosives charge-up periods, the compressed air requirements are lower than in the drilling period. The "no entry" and explosives charge-up period overlap with the Eskom evening peak period, where the compressors output pressure set points can be lowered. This means that only the necessary pressure and flow will be supplied to the network.

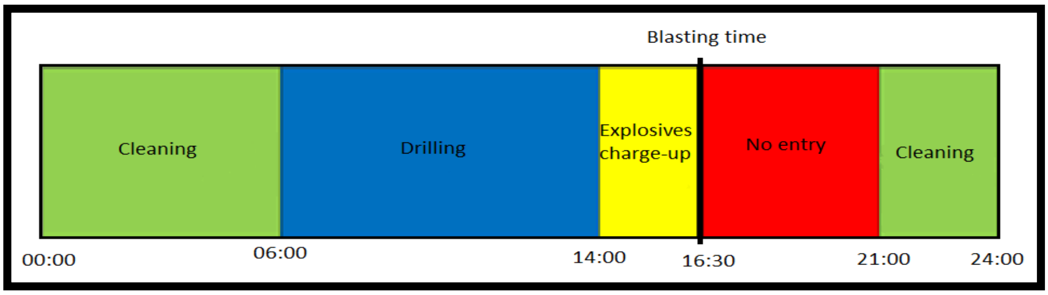


Figure 25: Typical mining schedule

These electricity savings are achieved by lowering the set point pressure of the compressors in the Eskom evening peak period. It will create the opportunity for certain compressors to cut back. The compressed air ring should be monitored at various critical points in the compressed air network to ensure that the minimum pressure is kept at the set point pressure of 350 kPa. The pressure can only be lowered to 350 kPa at surface. This is to compensate for pressure losses due to friction in the pipes to ensure the correct pressure is received at each refuge bay. The red area in Figure 26 indicates the minimum set point pressure of 350 kPa.

Monitoring the compressed air ring will ensure that each compressed air user will receive the required amount of compressed air. When the explosive charge-up period commences, the pressure of the network can be lowered to supply compressed air only to the refuge bays of each shaft.

Figure 26 compares the pressure set points before project implementation with the optimised pressure set points. The optimised pressure set points can be seen where the pressure decreases between 14:00 and 20:00.

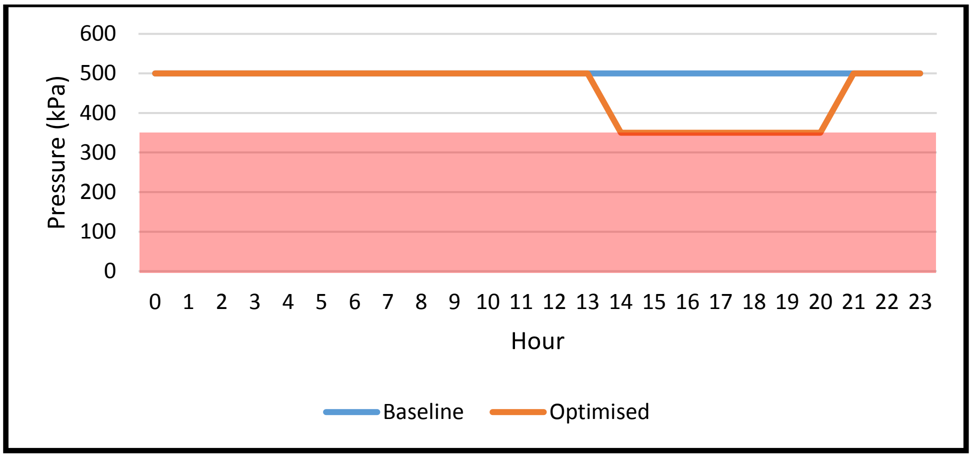


Figure 26: Pressure profiles before and after optimisation

Demand side of the compressed air network

Mine A has six shafts that require compressed air; two of which are decline shafts. The decline shafts are closed although they still consume compressed air because the piping towards these shafts has compressed air leaks resulting in significant compressed air losses.

Figure 27 plots the average flow before project implementation with the Megaflex high-demand tariff of 2016/17. Colour was added to clearly illustrate the time-of-use periods. High-demand tariff costs are plotted with the flow to illustrate where the flow should be reduced to achieve cost savings.

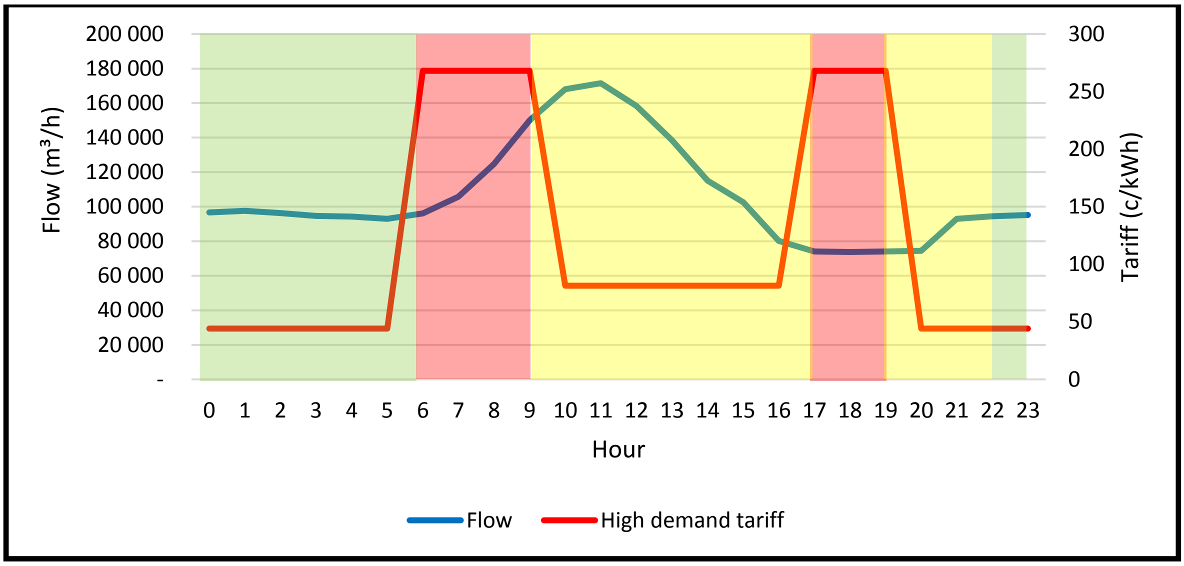


Figure 27: Flow comparison with Eskom tariffs

The flow rate requirement of each consumer is an important concept that needs to be considered when developing an improved control philosophy. The shafts will need more flow for drilling purposes than the smelter, although the shafts require lower pressure than the smelter. The compressed air ring must be able to supply ample compressed air to all consumers.

Each compressed air consumer has a minimum required flow rate. The flow rate generated can be controlled by cutting back the compressors. When the compressors are cut back, they will produce a lower flow resulting in a lower pressure. Figure 25 shows that the blasting time is 16:30 and that the cleaning shift commences at 21:00.

On Mine A, it was determined that the operating pressure in the system is between 500 kPa and 600 kPa. This is a safe operating pressure range. Higher pressures could lead to compressed air pipes bursting.

3.2.3 Simulation

Simulation objective

The main reason for the simulation would be to determine if a project is viable in terms of implementation cost when compared with the potential electricity cost savings. Another reason could be to identify future projects, where further investigations may lead to electricity cost savings. A simulation will be developed to simulate actual control of a network to establish a baseline simulation before it is adjusted to simulate the effect of DSM projects. When the results obtained by the baseline simulation corresponds to the system being simulated, it indicates that the simulation is a realistic representation of the actual system. A clear understanding of this simulation is needed before the simulation is built.

How the simulation works

The simulation of Mine A is based on the actual site layout as seen in the Appendix A. The simulation can be divided into the supply side, the demand side and the compressed air ring. The compressed air ring is the link between the demand- and supply side of the compressed air network.

Supply side

Figure 28 shows the compressor component used in the simulation. Each compressor should be set up individually; this includes the maximum power rating, maximum output pressure, maximum flow and compressor load fraction. The compressor load fraction can be used to simulate the control of each compressor on an hourly basis and can be compared with when a compressor is cutting back.

The compressor component can simulate blow-off conditions; this happens when the compressed air ring pressure is higher than the set point pressure. The compressor's blow-off valve will open to ensure that the compressed air ring pressure will decrease until the ring pressure set points are reached. When the blow-off valve opens, compressed air will escape and the flow supplied to the compressed air network will reduce. This must be avoided to minimise compressed air losses.

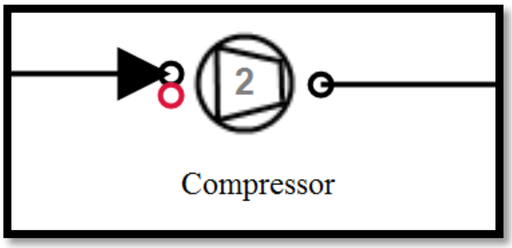
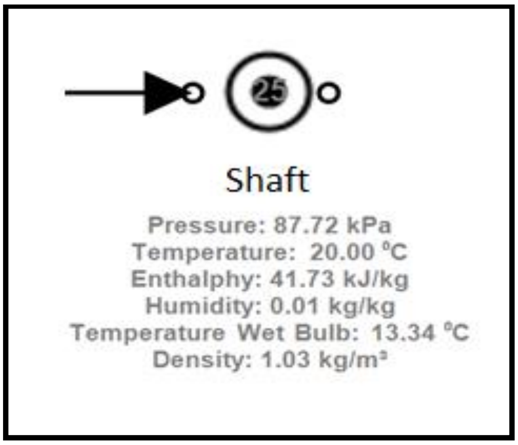


Figure 28: Compressor component used in the simulation

Demand side

Every compressed air pressure boundary must be set to the ambient pressure of the mine. The air pressure boundaries are used as a starting point of the compressed air network to set ambient conditions and to represent compressed air users. In the simulation software, an air boundary is used as a boundary component where ambient conditions are set. Figure 29 shows an air boundary where it is used as a shaft.



Pressure: 87.72 kPa
Temperature: 20.00 °C
Enthalphy: 41.73 kJ/kg
Humidity: 0.01 kg/kg
Temperature Wet Bulb: 13.34 °C
Density: 1.03 kg/m³

Figure 29: Compressed air boundary used as a shaft in the simulation

Air network

Figure 30 shows a compressed air pipe component in the simulation. These components are used to link the supply side and the demand side of the compressed air network. The values that can be altered on the pipes are the pressure drop over the pipe, maximum flow, valve fractions and friction loss properties. The valve fractions can be used to simulate a butterfly valve. The friction loss properties include the Cv value, Kv value, dynamic loss coefficient etc. (see Table 5).

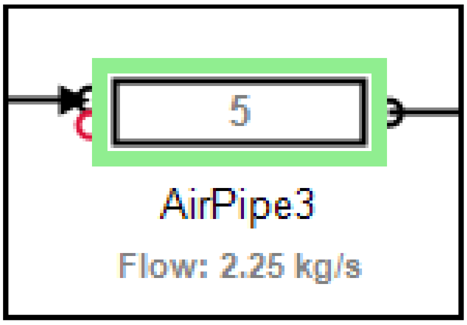


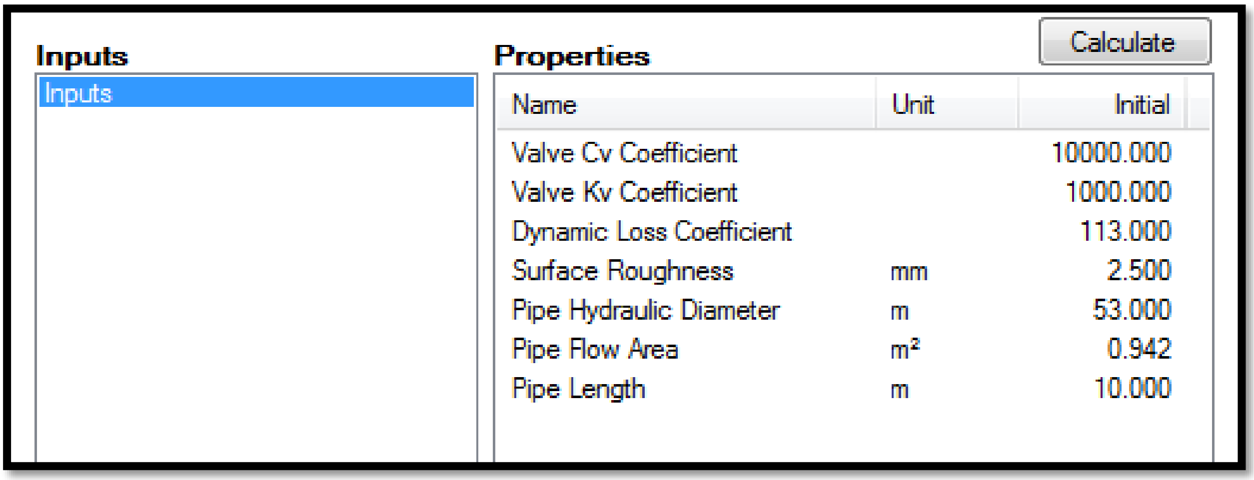
Figure 30: Compressed air pipe component in the simulation

Table 5 explains the fiction loss properties. These properties are used to add friction to all pipes within the simulation. Friction losses have a large influence on a compressed air network. Calculating these losses will ensure that the simulation is a more realistic representation of the actual compressed air network.

Table 5: Friction loss properties

Friction loss property	Description
Cv value	Indicates the pressure losses due to a valve and/or orifice.
Kv value	Indicates the pressure losses due to the valve positioning.
Dynamic loss coefficient	Used to indicate the pressure losses due the dynamic changes of the previous properties.
Surface roughness inside a pipe	Used to indicate the friction losses due to the inside roughness of the pipe.
Pipe hydraulic diameter (Ph)	Used to calculate pressure losses in ducts of pipes.

Figure 31 shows the typical values of these properties. The properties are important for the calculation as they will increase the losses in the simulation to more realistically represent the actual compressed air network.



Name	Unit	Initial
Valve Cv Coefficient		10000.000
Valve Kv Coefficient		1000.000
Dynamic Loss Coefficient		113.000
Surface Roughness	mm	2.500
Pipe Hydraulic Diameter	m	53.000
Pipe Flow Area	m²	0.942
Pipe Length	m	10.000

Figure 31: Pipe properties calculation using the simulation software

These properties will be incorporated when a simulation is built. Each pipe in the simulation will have unique property values, which will depend on the diameter, length, pipe roughness and the type of pipe.

Simulation set-up steps

Figure 32 uses a process flow diagram to illustrate the steps that will be used to create the simulations in this study. After each step, it must be decided if this step has been successful before continuing to the next step. If not successful, the step should be reiterated until completed successfully.

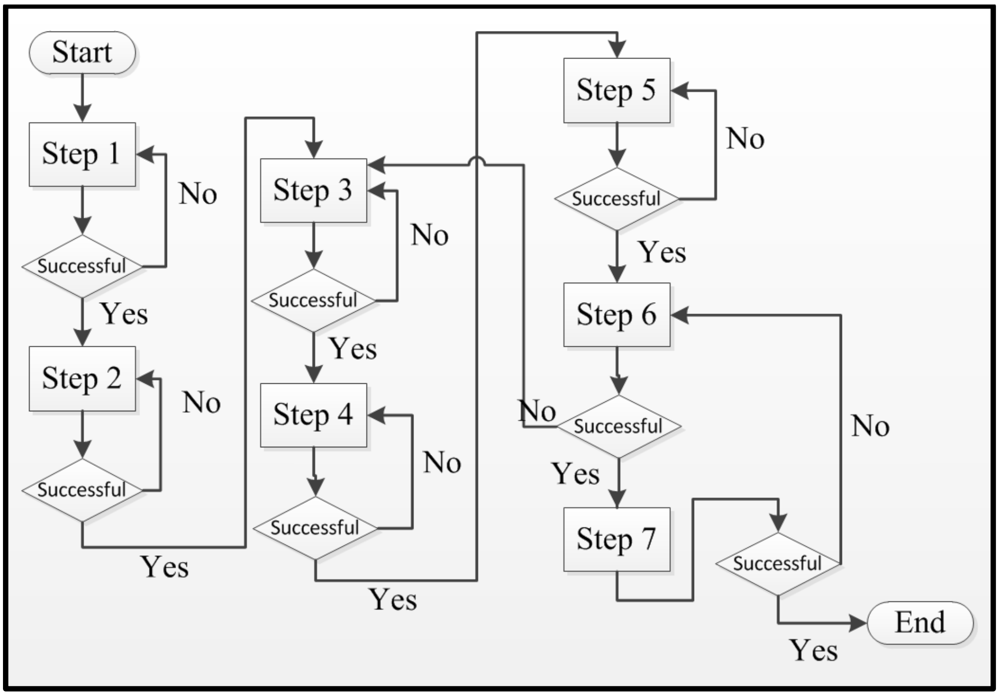


Figure 32: Simulation process flow diagram

Step 1: Build initial simulation

The sequence of the components is important as each of them can only connect to a specific type of component. There should be pipes on both sides of a compressor, as can be seen in Figure 33. This ensures that no flow is lost due to the blow-off valve of the compressor.

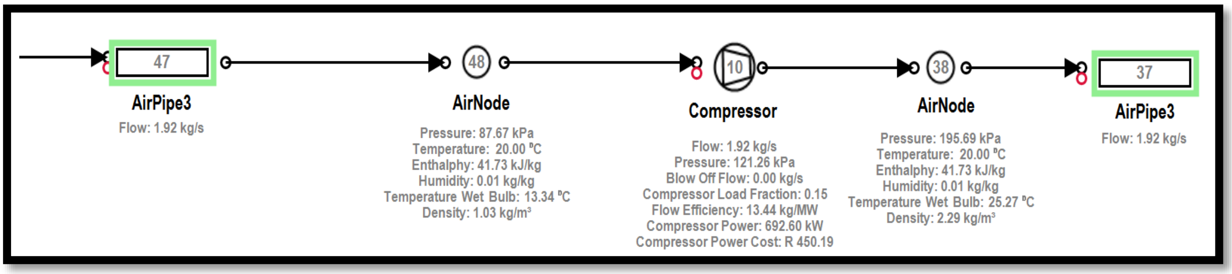


Figure 33: Step 1 of building the simulation

Step 2: Build additional simulation

Figure 34 shows a section that should simulate without errors. Simulating sections simplify fault-finding. If there are errors, in most cases they would be in the last section added. The next section should only be added if there are no errors. This can be repeated until the entire platform is completed. The term “platform” is used to indicate the entire compressed air network in the simulation, as it can be seen in the Appendix A and Appendix B.

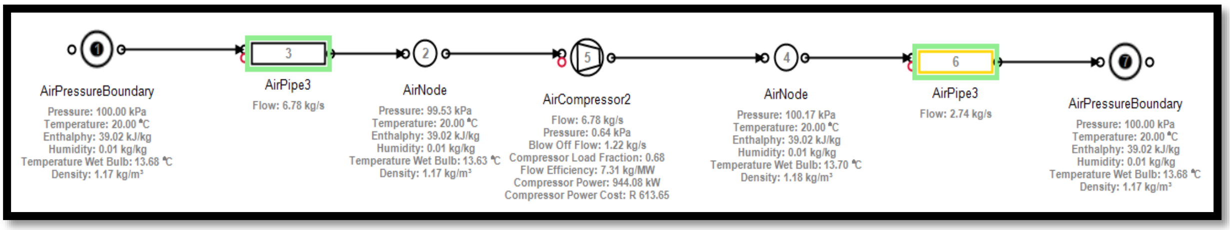


Figure 34: Single compressed air network line

Step 3: Calibrate flow

The delivery flow must be adjusted individually for each compressor. The flow of each compressor together with the compressor load fraction should be altered. The flow value changes hourly throughout the day. The load fraction and the valve positioning can alter flow and pressure values; this can be used to simulate when a valve is open, closed or any percentage open when a valve is controlled.

The simulation software divides the total compressed air flow between all the compressed air users. When a specific compressed air user is adjusted to receive the correct amount of compressed air flow, the flow to other compressed air users will be affected. This is the reason for the time-consuming iterative step – to ensure that each compressed air user receives the correct amount of compressed air.

Step 4: Calibrate power

The power consumption of each compressor component must be altered in the simulation to ensure that each compressor consumes the correct amount of power. Each compressor can be controlled using a PID controller. This controller can be used to control the flow, which will affect the amount of electric power consumed by each compressor. This controller can be adjusted on an hourly basis and can be used to increase the accuracy of the simulations. This is done to calibrate each compressor in the simulation. Figure 35 represents a simulated power profile of a compressor.

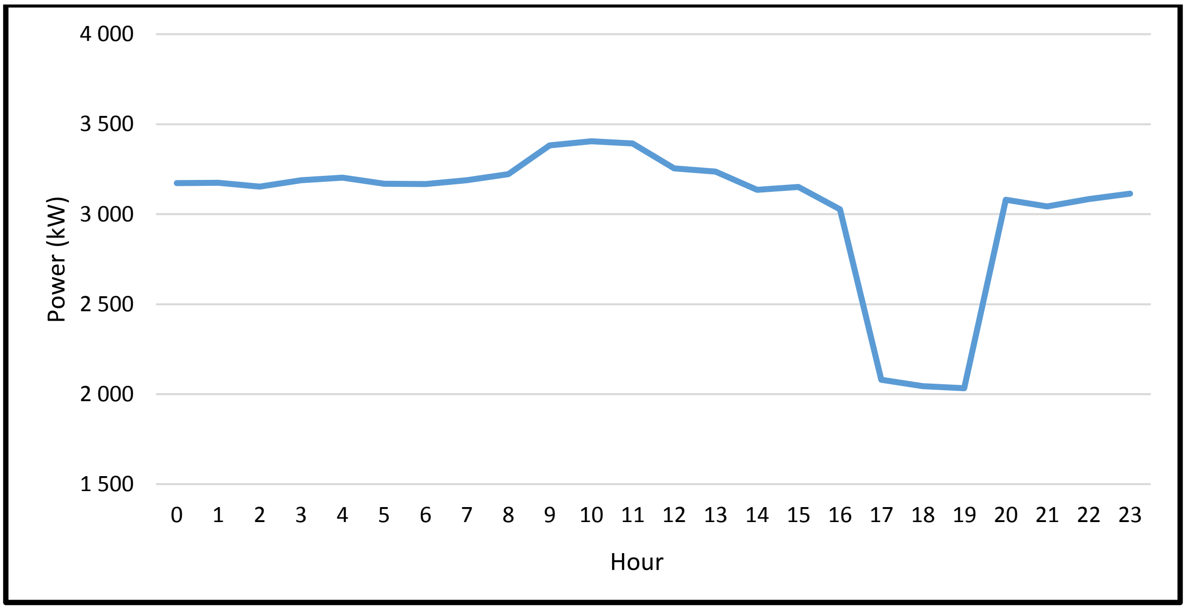


Figure 35: Simulated compressor profile

Total power consumption of the simulated system is an important factor in the simulation. Any alterations made in the simulation should be done only to improve it. For example, if the load fraction of a compressor is lowered, the actual compressor should be able to cut back as much as the compressor load fraction indicates. Secondly, alterations can be used to calculate the potential savings that could be generated if this project is implemented. Only if the solution is viable, can financial viability be calculated.

Step 5: Calibrate pressure

The delivery pressures of all compressors must be calibrated to represent the correct values for each hour. The parameter used is the maximum pressure of the compressor; an average value is used with the compressor load fraction. The compressor load fraction value for the power and pressure would be similar.

Step 6: Iterate steps

Iteration of the previous steps should be done from Step 3 until all the values are a realistic representation of the compressed air network. The number of iterations depends on the complexity of the network that is being simulated because each change being made to the simulation affects the entire system. For example, if the flow towards a specific user is increased, the rest of the compressed air users will receive a decreased amount of compressed air.

Step 7: Determine accuracy

Finally, all values calculated in the simulation should be compared with real-world data. The accuracy of the simulation should be determined; a method would be to divide the simulated values with the actual values. If this value is between 0.95 and 1.05, the simulation is accurate within 5%. Equation 7 was used to calculate the percentage error between the actual and simulated data.

$$\text{PE} = 1 - \frac{SD}{AD} \times 100$$

Equation 7: Percentage error

The components of Equation 7 are:

- PE: Percentage error
- AD: Actual data
- SD: Simulated data

The results of the calculation showed that the baseline simulation was a good representation of the compressed air network of Mine A. Figure 36 shows the actual power baseline for a three-month period before the project has been implemented. The baseline profile will be compared with the power profile after implementation to calculate electricity cost savings.

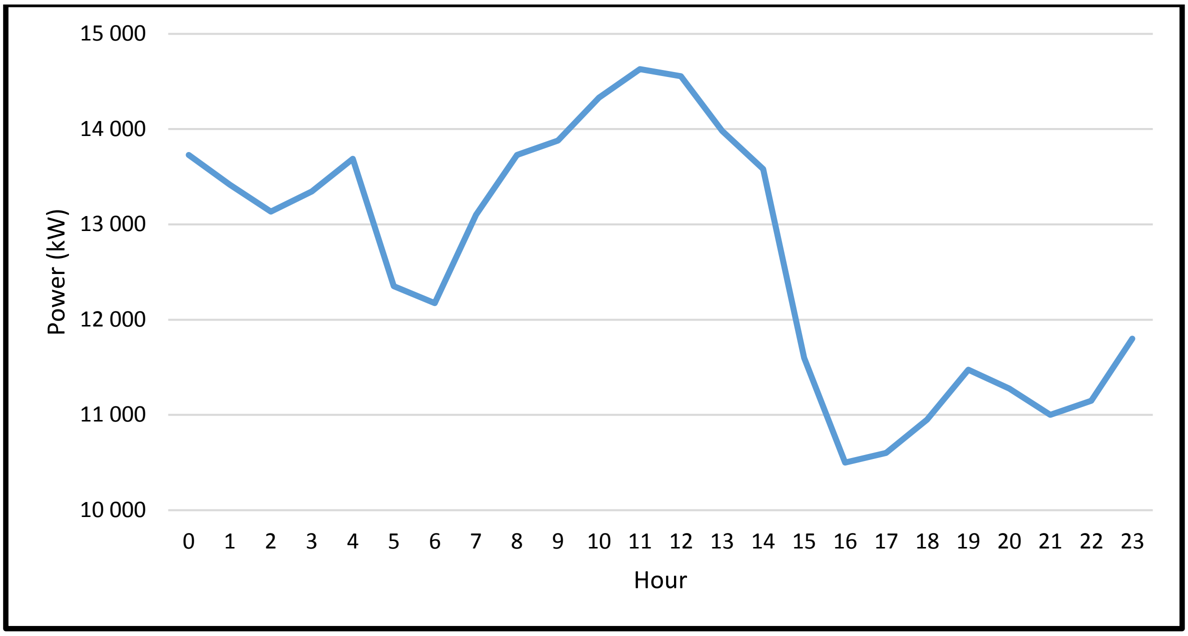


Figure 36: Mine A baseline

The representation of the simulation can be seen in Appendix A. The results of the simulation will be presented and discussed in Chapter 4 as it has significant value for each project and the savings that can be achieved.

3.2.4 Implementation

Control valves are used to restrict the compressed air flow within the Eskom evening peak period. When less flow is required by the compressed air users, the compressors can be cut back to achieve electrical and cost savings.

In Mine A, the compressed air flow needs to be reduced during the Eskom evening peak period. This was done by using a bypass control valve installation that can be seen in Figure 37. Actuators were installed on both valves to control the valve positions.

Figure 37: Bypass valve installation

These bypass control valves were installed on all six shafts. Figure 38 shows the compressed air network layout of Mine A, where a green component is shown by a yellow circle on the right side of the figure. This is an example of the location of one on the valve configurations implemented on this compressed air network.

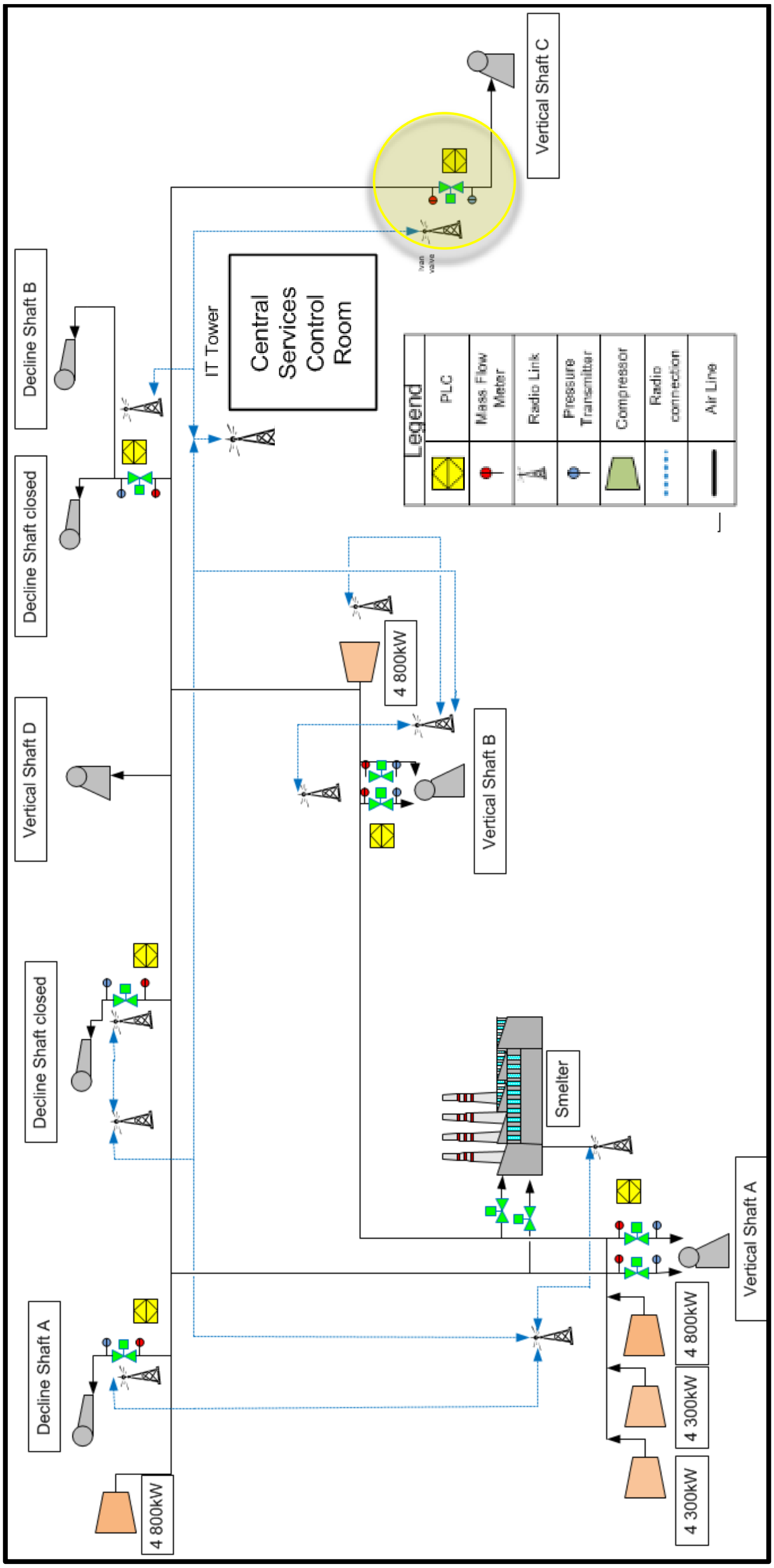


Figure 38: Mine A compressed air network layout

Figure 39 shows a diagram of the implementation where the pipe diameters, flow transmitter, pressure transmitter and both actuators can be seen. The schematic representation also includes the positions of the components and each valve's Cv (flow coefficient) value. These valves are installed on the main compressed air pipeline towards each compressed air user as it can be seen in Figure 38.

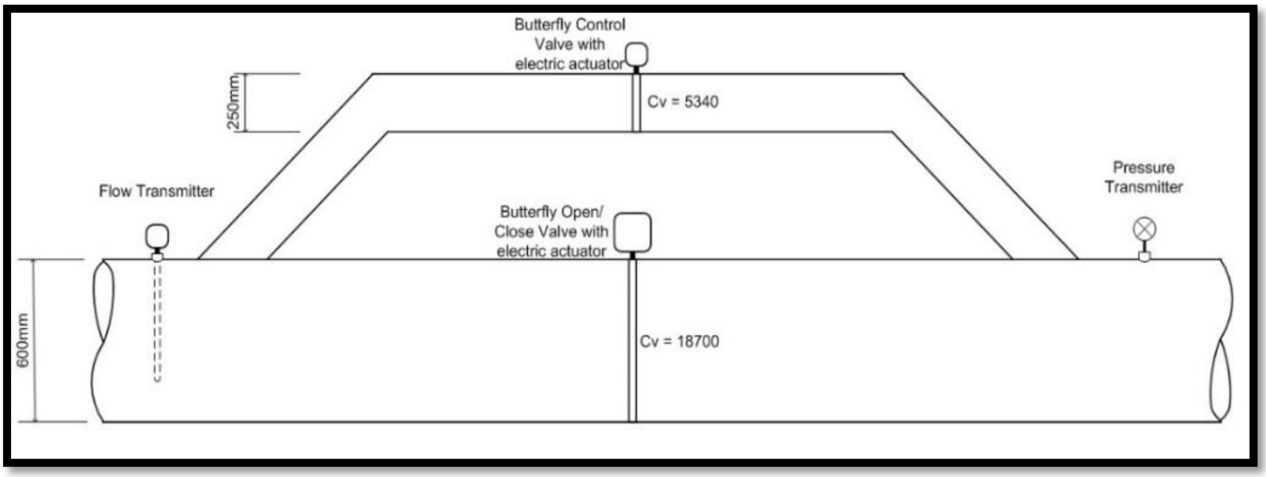


Figure 39: Diagram of a bypass pipe and valve combination

The main pipeline's butterfly valve will be closed and the bypass pipeline's butterfly valve will be opened in the Eskom evening peak period. This bypass pipeline's butterfly valve will be controlled to ensure that the compressed air consumer will receive the correct amount of compressed air.

3.2.5 Verification of Mine A's model

Figure 40 plots the average actual power data and the average baseline simulation power data on the same graph for a 24-hour profile. The blue line represents the actual power and the orange line represents the simulated power.

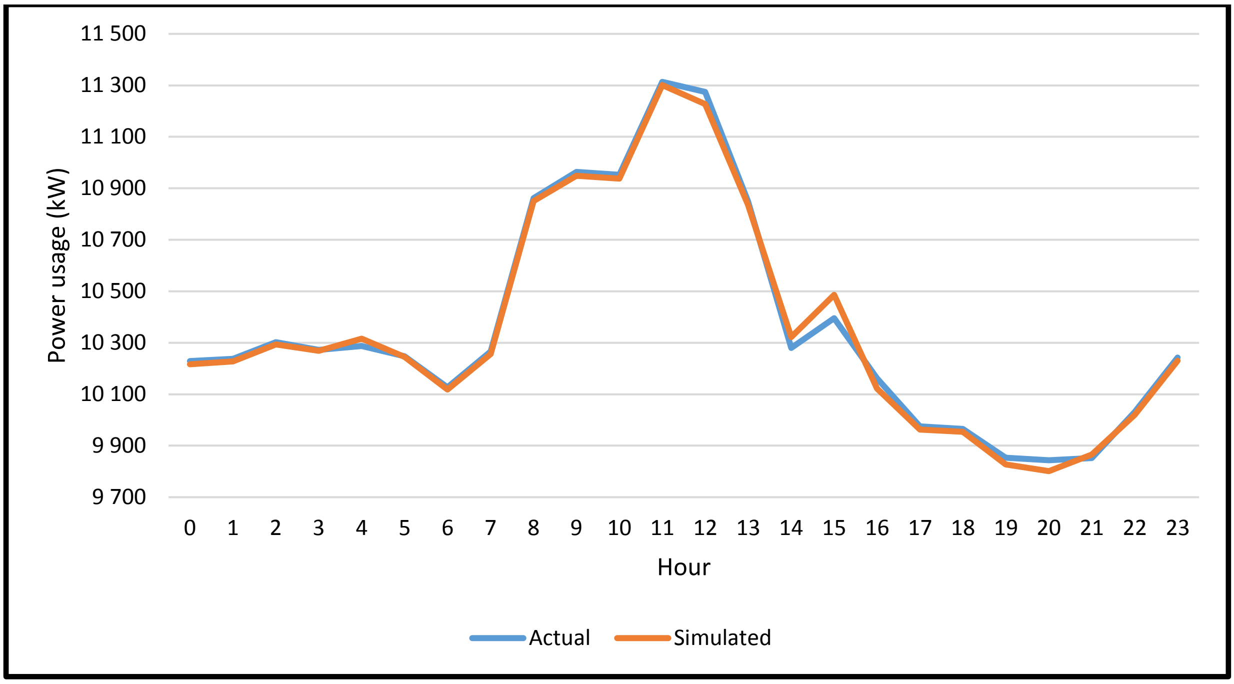


Figure 40: Mine A power data versus simulated power data

In Figure 40, the simulated power data is close to the actual power data. The total compressor consumption in the Eskom evening peak period is lower than the compressor power consumption during the drilling shift. This project aims to decrease the power consumption in the Eskom evening peak period even further.

Table 6: Actual power versus baseline simulated power of Mine A

Hours	Actual (kW)	Simulated (kW)	Percentage error
0	10 229	10 217	0.12%
1	10 237	10 228	0.09%
2	10 302	10 293	0.08%
3	10 273	10 269	0.04%
4	10 287	10 316	0.28%
5	10 247	10 245	0.02%
6	10 127	10 118	0.09%
7	10 266	10 257	0.09%
8	10 862	10 851	0.10%
9	10 964	10 948	0.14%
10	10 952	10 938	0.13%
11	11 314	11 301	0.11%
12	11 274	11 227	0.42%
13	10 849	10 836	0.12%

Hours	Actual (kW)	Simulated (kW)	Percentage error
14	10 280	10 322	0.41%
15	10 396	10 487	0.87%
16	10 162	10 122	0.39%
17	9 975	9 963	0.12%
18	9 965	9 954	0.12%
19	9 854	9 828	0.26%
20	9 844	9 801	0.43%
21	9 852	9 866	0.14%
22	10 031	10 020	0.11%
23	10 242	10 230	0.12%

The second column in Table 6 shows the actual power data obtained from Mine A’s database. The values are calculated by summing all compressors on the network for each hour. The data used was logged for three consecutive months and an hourly average was calculated. The third column is the simulated power from the baseline simulation. The fourth column shows the percentage errors. The maximum percentage error is lower than 1%.

3.3 Case Study 2: Energy efficiency by exchanging compressors

3.3.1 Background

The control philosophy of this compressed air network and savings opportunities will be investigated and simulated to improve the compressed air network. The focus will be on the supply side of the compressed air ring. This improved control philosophy will not be implemented on Mine B, although it will be simulated. This is seen as a theoretical case study as purchasing two new compressors is expensive, although more information will be given.

3.3.2 Improvement strategy

Mine B’s control improvement philosophy includes replacing the large 15 MW compressor with two 4 MW compressors as baseload compressors. The baseload compressors are the specific compressors that are used throughout the day. The 15 MW compressor will be used for emergencies and/or when the smaller compressors are unavailable.

The two 4 MW compressors should be added and set as baseload compressors in place of the 15 MW compressor on the SCADA of Mine B. This will cause the parameters to be modified on the SCADA for the two new compressors. These parameters will include:

- Flow
- Compressor output pressure and blow-off pressures
- Schedule
- Surge line parameters
- Necessary alarms or notifications

Flow

Monitoring the flow will be important as the compressors should not generate an excess amount of compressed air as this would be a waste of energy. Flow is a parameter that needs to be monitored continuously for safety reasons – ensuring that the refuge bays receive enough compressed air as per safety regulations.

The SCADA should be able to monitor if the instantaneous flow of a user changes. If the demand decreases, the compressors could be cut back to generate lower flow. If the demand increases, the compressors could be controlled to deliver maximum flow. Flow data retrieved from Mine B could be used to improve the set point values. Another important parameter is the output pressure of the compressors.

Compressor output pressure and blow-off pressures

Pressure is also an important factor to monitor. The compressed air network has a maximum pressure it can withstand; beyond that point it is unsafe to operate. When the compressed air network’s pressure is too high, there is a risk of a pipe bursting. Using blow-off valves in compressors is a method to prevent this. When the blow-off valve opens, compressed air is released into the atmosphere. The pressure within the pipeline subsequently decreases, thus preventing a compressed air pipe from bursting. When determining the optimal time per day to decrease the compressors’ output pressure, the mining schedule should be kept in mind.

Schedule

The optimal times to cut back a compressor would be the period after the drilling shift until after the “no entry” period. Between these periods, minimum flow and pressures are required within the mine; usually only the refuge bays require compressed air. The exact times of when each shift starts and stops are usually indicated on the schedule of each mine. Within these times, the compressors should be cut back to minimise the electricity consumption of the compressors, thus surging needs to be monitored as well.

Surge line parameters

After establishing that the set points are altered for optimal use, the focus should be on compressors to cut back and avoid surging. The minimum pressure and flow set points will be included when each new compressor is installed on the compressed air network. This control should be able to prevent the compressor from surging. If a compressor’s operating point is close to the surge line, the operator should be notified by using alarms.

Alarms

Every set point should be linked to an alarm and a notification system. When a problem arises, for example, a compressor is close to its surge line, a notification should appear on the SCADA, where the problem is indicated with possible corrections. The alarms or notifications can avoid major failures if there is an immediate response. When all the necessary corrections have been made to the compressed air network and the EnMS has been implemented, the EnMS can take over control. This would include controlling the stopping and starting of compressors.

When all the necessary parameters have been adjusted and the SCADA shows the two new compressors, a simulation will be built. This simulation should firstly be set up as a baseline simulation.

3.3.3 Simulation

Figure 41 shows the baseline of Mine B, which is set up using actual data from three consecutive months. An hourly average for each compressor was calculated and summed. This baseline will be used to calculate if the target savings were achieved.

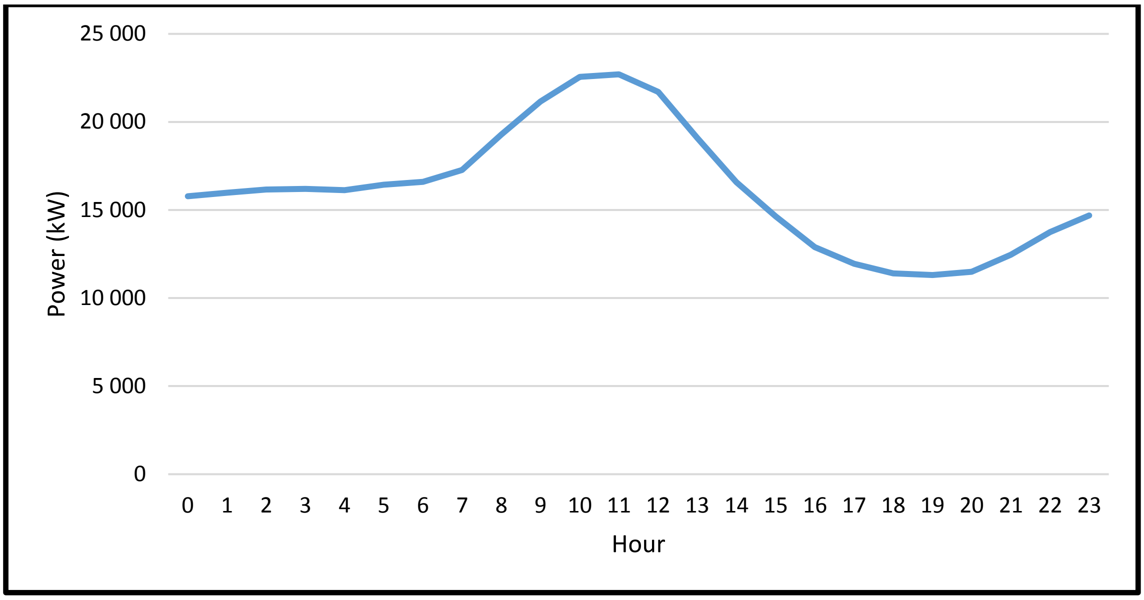


Figure 41: Mine B baseline

Calculations were made to compare the simulated values with representative values from the network before the simulation was adjusted to simulate the theoretical project. The calculations include the average values for pressure, flow and power for the compressed air network.

After all the necessary calculations are done, a simulation should be created. Similar to Mine A, the exact steps would be needed to complete this simulation. Firstly, a simulation needs to be built based on the baseline. When an acceptable accuracy is achieved between the actual baseline and simulated values, the simulation can be adjusted to simulate the effect of the proposed project implementation.

3.3.4 Possible future implementations

Possible future implementations should be done with great care, especially when a new compressor is introduced to the compressed air network. The large 15 MW compressor will still form part of the network, as it will be used in case of emergencies. Before future implementations are considered, the baseline simulation of Mine B's compressed air network should be verified.

3.3.5 Verification of Mine B model

Mine B's improved control philosophy will not be implemented; thus the simulation data will only be verified. This verification will include verifying the baseline simulation data against the actual data. A simulation was built based on the compressed air network of Mine B.

In Figure 42, the actual power is plotted with the baseline simulation power data. The blue line represents the actual data and the orange line represents the simulated data. The simulation can be considered as accurate. The data with percentage errors can be seen in Table 7. The percentage errors in Table 7 are calculated using Equation 7, as was the case for Case Study 1.

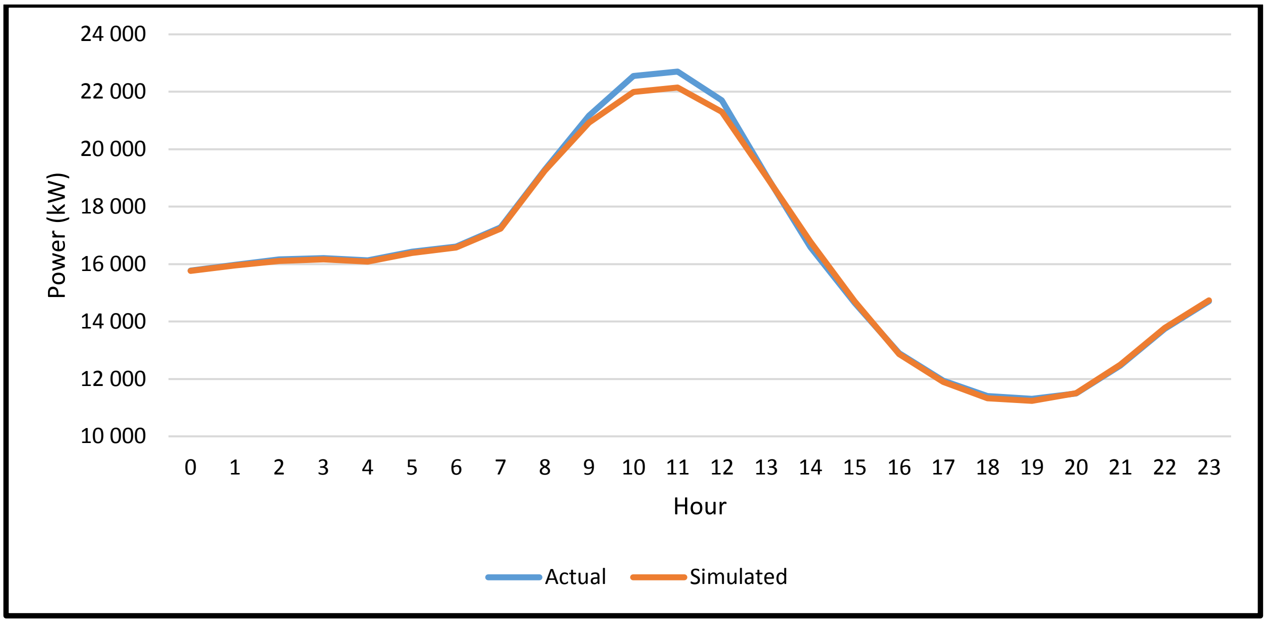


Figure 42: Mine B actual versus simulated power

The next step would be to calculate the accuracy of the simulated power data by comparing it with actual power data, which could have been used as a baseline for this project. These calculations can be done by using the same calculations used in Mine A, Equation 7. The third column in Table 7 shows the difference between the simulated results and actual results.

Table 7: Actual power versus simulated power of Mine B

Hours	Actual (kW)	Simulated (kW)	Difference (kW)	Percentage Error
0	15 774	15 765	−9	0.06%
1	15 979	15 954	−25	0.16%
2	16 158	16 106	−52	0.32%
3	16 206	16 159	−47	0.29%
4	16 130	16 083	−47	0.29%
5	16 433	16 390	−42	0.26%
6	16 606	16 571	−35	0.21%
7	17 280	17 230	−50	0.29%
8	19 282	19 247	−36	0.19%
9	21 163	20 926	−238	1.12%

Hours	Actual (kW)	Simulated (kW)	Difference (kW)	Percentage Error
10	22 555	21 995	−559	2.48%
11	22 703	22 148	−555	2.45%
12	21 702	21 299	−404	1.86%
13	19 089	19 049	−40	0.21%
14	16 589	16 773	184	1.11%
15	14 645	14 708	63	0.43%
16	12 893	12 870	−24	0.18%
17	11 941	11 892	−49	0.41%
18	11 409	11 330	−80	0.70%
19	11 308	11 236	−72	0.64%
20	11 488	11 502	14	0.12%
21	12 459	12 501	42	0.34%
22	13 741	13 779	38	0.28%
23	14 699	14 731	32	0.22%

3.4 Conclusion

Control philosophies were improved by using the mining schedule and a decreased compressor rating combination in the Eskom evening peak period. Simulations were built and verified with actual data.

3.4.1 Mine A

Chapter 3 introduced the concept of optimising a compressed air network on a mine and the viability thereof. A simulation was built before the project was implemented and necessary adjustments were made to ensure the simulation represented the optimised control philosophy. The mining schedule of Mine A was used to identify opportunities to optimise the control philosophy. Implementing control valves for each high compressed air user was used to optimise the compressed air ring. The control philosophy was implemented on the compressed air network of Mine A. The project results will be discussed in the Chapter 4, although the verification of Case Study 1’s model was discussed in Section 3.2.5.

3.4.2 Mine B

The same procedure was followed as for Mine A, although the simulations were more time-consuming due to the complexity of the compressed air network, which can be seen in Appendix B.

The control philosophy was implemented on Mine B’s simulation. This was done by replacing the single 15 MW compressor with two 4 MW compressors. Actual data was used to verify the initial simulated values. Afterwards, the simulation was altered to simulate the theoretical project. The verification of Mine B’s model was discussed.

Chapter 4 will discuss the results of this study. The results for Case Study 1 will include the actual project results, which will be validated. The results for Case Study 2 will include the simulated project results, simulated pressure and simulated flow.

4 Results

Miner using a compressed air drill underground [83]

"Engineering is the art or science of making practical."

Samuel Florman

4.1 Overview

Chapter 3 provided information regarding the control philosophy of each case study. The building of a simulation was also discussed and how to implement the proposed project after completing the baseline simulation. Each case study’s baseline simulation was verified using actual data obtained from the database of each mine.

In Chapter 4, the simulation of Case Study 1, after it has been adjusted to simulate the proposed project, will be validated with the actual data of the project. In Case Study 2, the simulation was adjusted to simulate the effect on the compressed air network if the large 15 MW compressor would be replaced with two 4 MW compressors. Case Study 2 cannot be validated, as this is a future project. The application to the industry will be discussed next, where the effect that Case Study 1’s control philosophy can have on the industry.

4.2 Comparison of simulated and actual results

When discussing results, it is necessary to point out the difference between verification and validation. Verification is a process that checks if data points are transferred accurately [84]. Validation is where these data points are evaluated and checked to be accurate [84].

4.2.1 Case Study 1: Reducing evening demand by implementing valves

In Figure 43, the baseline is plotted and compared with the effect the project will have on the simulation. The project achieved savings between 18:00 and 20:00. The electricity saving achieved using the simulation was 6.2 MWh, which led to an annual cost saving of R1.9 million.

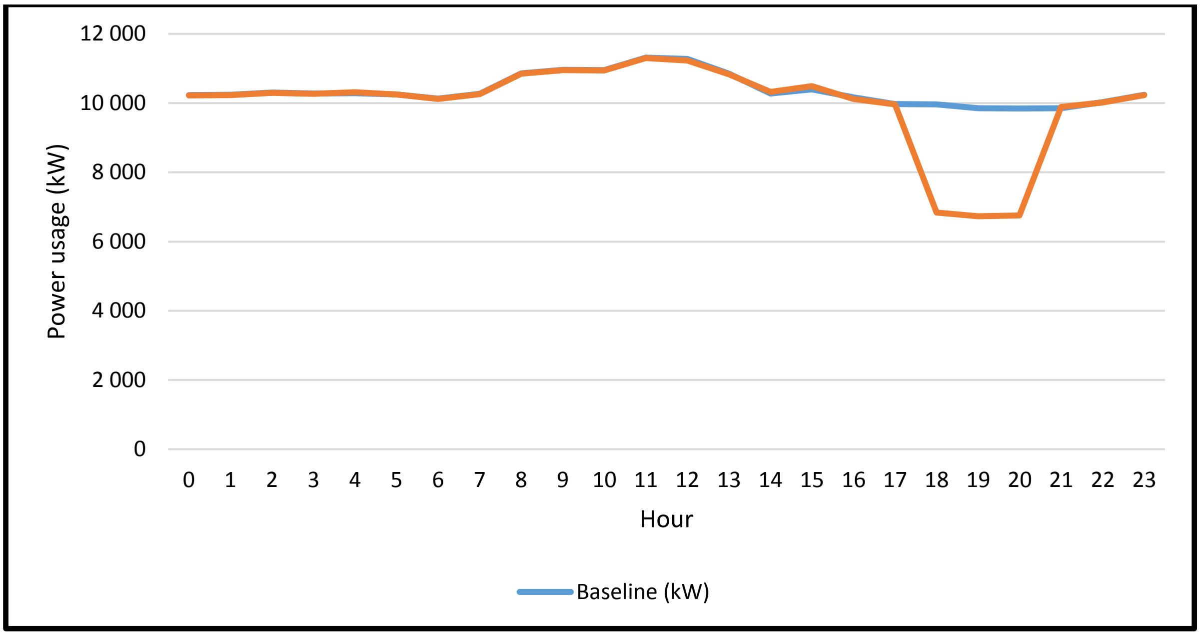


Figure 43: Baseline versus post-implementation

Table 8 shows the data of Figure 43. Between 00:00 and 17:00 the data showed that no savings were achieved, this is the same for data between 21:00 and 23:00. The maximum average saving was achieved at 19:00 with 32%.

Table 8: Baseline versus post-implementation power data

Hour	Baseline (kW)	Post-implementation (kW)	Difference (kW)	Percentage saved
0	10 229	10 217	12	0%
1	10 237	10 228	9	0%
2	10 302	10 293	9	0%
3	10 273	10 269	4	0%
4	10 287	10 316	−29	0%
5	10 247	10 245	2	0%
6	10 127	10 118	9	0%
7	10 266	10 257	10	0%
8	10 862	10 851	11	0%
9	10 964	10 949	15	0%
10	10 952	10 938	14	0%
11	11 314	11 301	13	0%
12	11 274	11 227	47	0%
13	10 849	10 836	13	0%

Hour	Baseline (kW)	Post-implementation (kW)	Difference (kW)	Percentage saved
14	10 280	10 322	−43	0%
15	10 396	10 487	−91	−1%
16	10 162	10 122	40	0%
17	9 975	9 963	12	0%
18	9 965	6 839	3 127	31%
19	9 854	6 730	3 124	32%
20	9 844	6 758	3 085	31%
21	9 852	9 886	−34	0%
22	10 031	10 020	11	0%
23	10 242	10 230	12	0%

Another parameter that should be compared is the simulated and actual flow generated by the compressors. Figure 44 compares the average compressor flow with the simulated compressor flow. The flow comparisons are accurate, although the largest difference can be seen between 17:00 and 20:00.

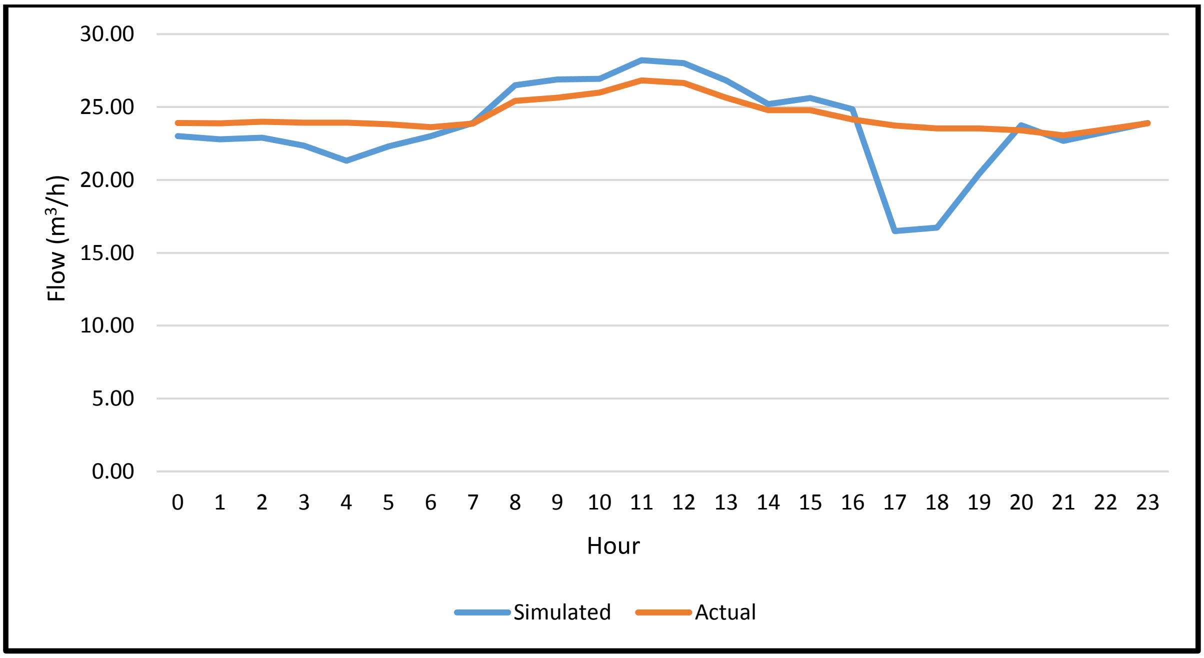


Figure 44: Simulated versus actual flow

Table 9 shows the data of Figure 44. Between 00:00 and 16:00 the data showed that the flow was similar, except for 04:00, where the percentage error was 11%. The maximum percentage error was 31% at 17:00.

Table 9: Simulated flow data versus actual flow data

Hour	Simulated flow (m^3/h)	Actual flow (m^3/h)	Difference (m^3/h)	Percentage error
0	23.02	23.90	0.88	4%
1	22.79	23.90	1.11	5%
2	22.89	24.00	1.12	5%
3	22.34	23.93	1.58	7%
4	21.32	23.92	2.60	11%
5	22.30	23.82	1.53	6%
6	23.01	23.63	0.61	3%
7	23.92	23.86	−0.06	0%
8	26.50	25.43	−1.07	−4%
9	26.89	25.64	−1.25	−5%
10	26.94	26.00	−0.94	−4%
11	28.21	26.83	−1.39	−5%
12	28.00	26.66	−1.35	−5%
13	26.82	25.64	−1.18	−5%
14	25.19	24.79	−0.40	−2%
15	25.62	24.80	−0.82	−3%
16	24.84	24.14	−0.70	−3%
17	16.49	23.74	7.25	31%
18	16.73	23.53	6.80	29%
19	20.39	23.54	3.15	13%
20	23.75	23.40	−0.35	−1%
21	22.67	23.06	0.39	2%
22	23.29	23.46	0.17	1%
23	23.91	23.88	−0.02	0%

The large difference between 17:00 and 20:00 in compressed air flow was due to the project implementation. The flow to each compressed air user decreased when the main valves were sealed in the Eskom evening peak period. When determining if a project achieved its target savings, a more acceptable method would be to validate the results.

Validation

The results were validated by a third-party company, which is a measurement and verification (M&V) team. This company calculated and reported the energy savings that the project actually achieved. The target savings were also calculated by this specific company.

The initial calculations showed that an hourly average of 3.9 MW could be saved. The actual saving achieved was calculated as 3.1 MW, as can be seen in Figure 45. Figure 45 shows the actual power profile and the baseline power profile, where the electrical savings achieved between 18:00 and 20:00 has an average value of 3.1 MW. The savings calculated using the simulation was 3.1 MW, thus the simulation was accurate for Case Study 1. The project only achieved 79% of the original contract. This is a large difference, although the project experienced various problems.

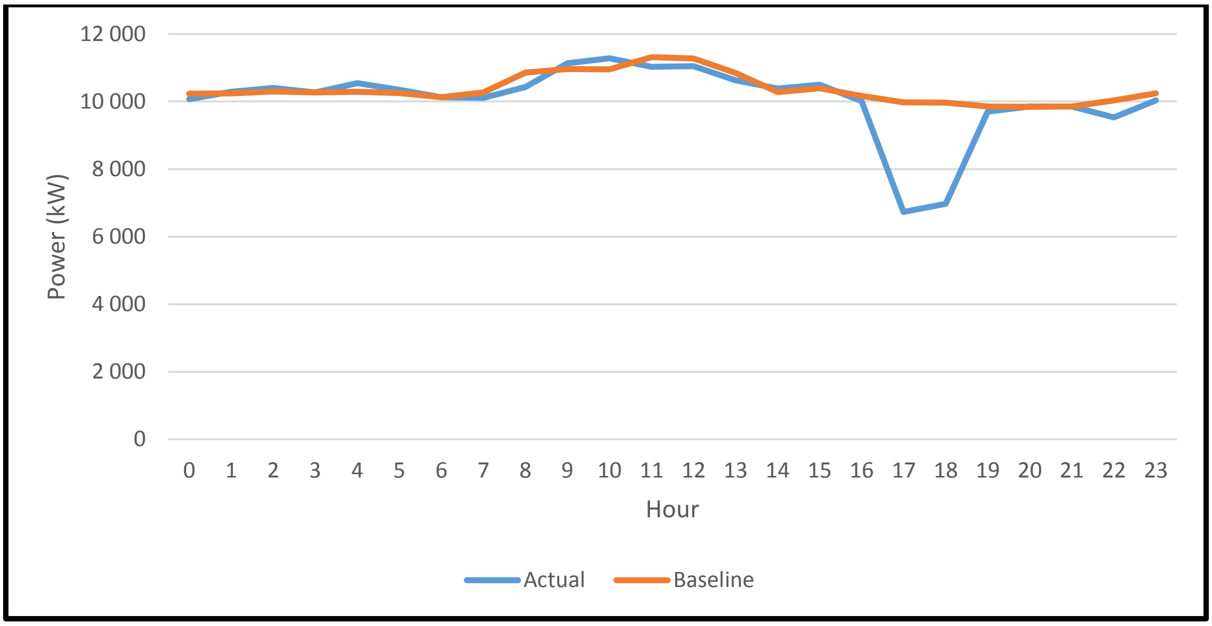


Figure 45: Actual versus baseline power

Table 10 shows the data of Figure 45. Between 00:00 and 16:00 the data showed that the power consumption was similar. The maximum percentage saved was 32.5% at 17:00. This large percentage saved is due to the effect of the project implementation on the simulation.

Table 10: Actual data versus baseline power data

Hour	Actual power (kW)	Baseline (kW)	Adjusted difference (kW)	Percentage saved
0	10 075	10 229	153	1.5%
1	10 289	10 237	−51	−0.5%
2	10 405	10 302	−103	−1.0%
3	10 273	10 273	0	0.0%
4	10 544	10 287	−257	−2.5%
5	10 349	10 247	−102	−1.0%

Hour	Actual power (kW)	Baseline (kW)	Adjusted difference (kW)	Percentage saved
6	10 127	10 127	0	0.0%
7	10 112	10 266	154	1.5%
8	10 427	10 862	434	4.0%
9	11 128	10 964	−164	−1.5%
10	11 281	10 952	−329	−3.0%
11	11 031	11 314	283	2.5%
12	11 049	11 274	225	2.0%
13	10 632	10 849	217	2.0%
14	10 383	10 280	−103	−1.0%
15	10 500	10 396	−104	−1.0%
16	10 009	10 162	152	1.5%
17	6 730	9 975	3 245	32.5%
18	6 969	9 965	2 996	30.1%
19	9 706	9 854	148	1.5%
20	9 853	9 844	−10	−0.1%
21	9 852	9 852	0	0.0%
22	9 530	10 031	502	5.0%
23	10 037	10 242	1 024	2.0%

Arising problems

The charge-up and blasting shifts coincide with the Eskom evening peak period. Three solutions could be implemented to optimise electricity savings, although problems were experienced. The solutions to these problems include:

- Operate only one large compressor
- Cut back on all compressors
- Stop one or two compressors

The solutions to these problems will be discussed next as these problems had a negative influence on the savings achieved by this project.

1. *Only two compressors could be cut back*

The first problem is that some compressors on-site are unreliable; these compressors break and need unscheduled maintenance. It is a problem, because these unreliable compressors were also not able to cut back as efficiently as initially anticipated. Some of these compressors were not able to cut back at all. Only two of the five compressors could be cut back.

The effect of the problem could be minimised by cutting back the two compressors to a maximum amount and using the remaining compressors to obtain the baseload pressure. The other alternative, which proved to be more effective, was to stop the unreliable compressors and only run the compressors that could be cut back.

This solution would not be viable, because the unreliable compressors could not be stopped and started. A reason for this could be that the maintenance of these compressors was not done correctly. The larger compressor could also not supply the necessary amount of compressed air the compressed air users required in Eskom evening peak period.

2. One compressor produced too low pressures

The second problem was that a single compressor produced an insufficient amount of pressure in the evening. The mine was forced to use both compressors that could be cut back, although the electricity savings was minimised by this.

Initially only one compressor should have been used in the Eskom evening peak periods, which would have ensured higher electricity savings. Initially, one compressor could produce the required compressed air, although there was an increased in compressed air leakage. These leaks caused large losses within the compressed air network, which meant that multiple compressors were needed.

3. Increased compressed air leaks

The third problem was the increased number of compressed air leaks in the system. If the compressed air leaks could have been minimised before the project was implemented, it could have been possible to use only one compressor in the Eskom evening peak period. An example of a compressed air leak on-site can be seen in Figure 46. This leak is considered as a punch leak, with a leak size of 50 mm. When using Table 4, it was calculated that this specific type of leak results in an annual financial loss of R3.8 million. Compressed air leaks are found in active and closed-off sections. Fixing of the leaks were not part of the study. Mining personnel were informed about the leaks for repairs. The closed-off sections are also dangerous to access and specialised crews are required. Ideally the pipe section should be removed and blanked off for unused areas.

Figure 46: A punch leak in a compressed air network

The combined effect of the three problems had a significant effect on the electricity cost savings generated by the project. Theoretically, one compressor should have been sufficient to supply the required compressed air in the Eskom evening peak period, although these problems prevented this from happening.

Optimised solution

When all compressors are used in the blasting periods it would be beneficial to cut back the compressors as to their minimum to ensure maximum electricity savings. When compressors are cut back, surging could occur causing a compressor to trip. When this happens, it could lead to production loss or insufficient compressed air in the refuge bays.

The optimal solution would be the option where the most electricity savings could be achieved, while still ensuring that the required compressed air flow and pressure are generated. The implemented solution was to operate two compressors. Both compressors were cut back, although the electricity saving was not as high as expected. This led to lower cost savings.

4.2.2 Case Study 2: Exchanging compressors for energy efficiency

Average power profile

In Figure 47 an extra set of data was added to Figure 42. Figure 42 was used to compare the actual power consumption with the simulated baseline. This is the simulation data where the large compressor was exchanged with the two smaller compressors. When Figure 47 is considered, it can be seen that exchanging the large compressor would be beneficial for Mine B, as energy efficiency would be achieved.

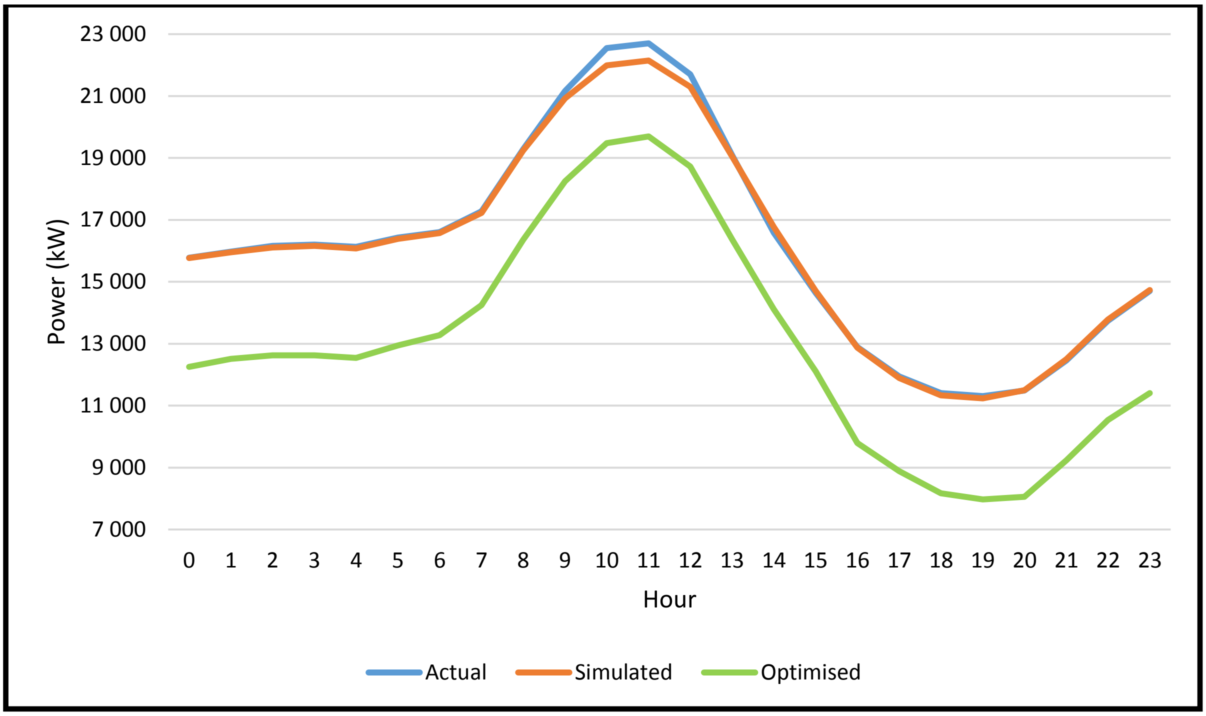


Figure 47: Case Study 2 actual versus optimised power

As this project has not been implemented yet, the simulation can provide proof that this would be a viable project to implement on Mine B. It must be considered that this would not necessarily be a viable project at every platinum mine. There are only a few platinum mines that have enough compressors, of which one is a 15 MW compressor. Table 11 shows the actual and optimised energy data. The possible energy savings were calculated for each hour.

Table 11: Case Study 2 optimised energy

Hours	Actual (kWh)	Optimised (kWh)	Difference (kWh)	Percentage saved
0	15 774	12 256	3 518	28.71%
1	15 979	12 508	3 471	27.75%
2	16 158	12 627	3 531	27.96%
3	16 206	12 627	3 579	28.34%
4	16 130	12 542	3 588	28.60%
5	16 433	12 941	3 492	26.98%
6	16 606	13 279	3 327	25.05%

Hours	Actual (kWh)	Optimised (kWh)	Difference (kWh)	Percentage saved
7	17 280	14 253	3 027	21.24%
8	19 282	16 360	2 922	17.86%
9	21 163	18 253	2 910	15.94%
10	22 555	19 476	3 079	15.81%
11	22 703	19 697	3 006	15.26%
12	21 702	18 724	2 978	15.91%
13	19 089	16 368	2 721	16.62%
14	16 589	14 110	2 479	17.57%
15	14 645	12 113	2 532	20.90%
16	12 893	9 797	3 096	31.61%
17	11 941	8 886	3 055	34.38%
18	11 409	8 168	3 242	39.69%
19	11 308	7 971	3 337	41.86%
20	11 488	8 053	3 435	42.66%
21	12 459	9 235	3 224	34.90%
22	13 741	10 536	3 205	30.42%
23	14 699	11 410	3 289	28.82%

The maximum percentage saved was 42.66% at 20:00, resulting in energy savings of 3.4 MWh. The minimum percentage saved was 15.26% at 11:00, resulting in energy savings of 3 MWh. The average percentage saved was 26.45%, resulting in an energy saving of 76 042 MWh per day, which led to an annual cost saving of R20 million.

Flow comparison

Figure 48 plots the compressed air flow of the actual consumers against the simulated flow after the simulation was adjusted. The simulated flow is lower between 09:00 and 16:00, because the two 4 MW compressors were not able to generate the maximum flow as generated by the 15 MW compressor.

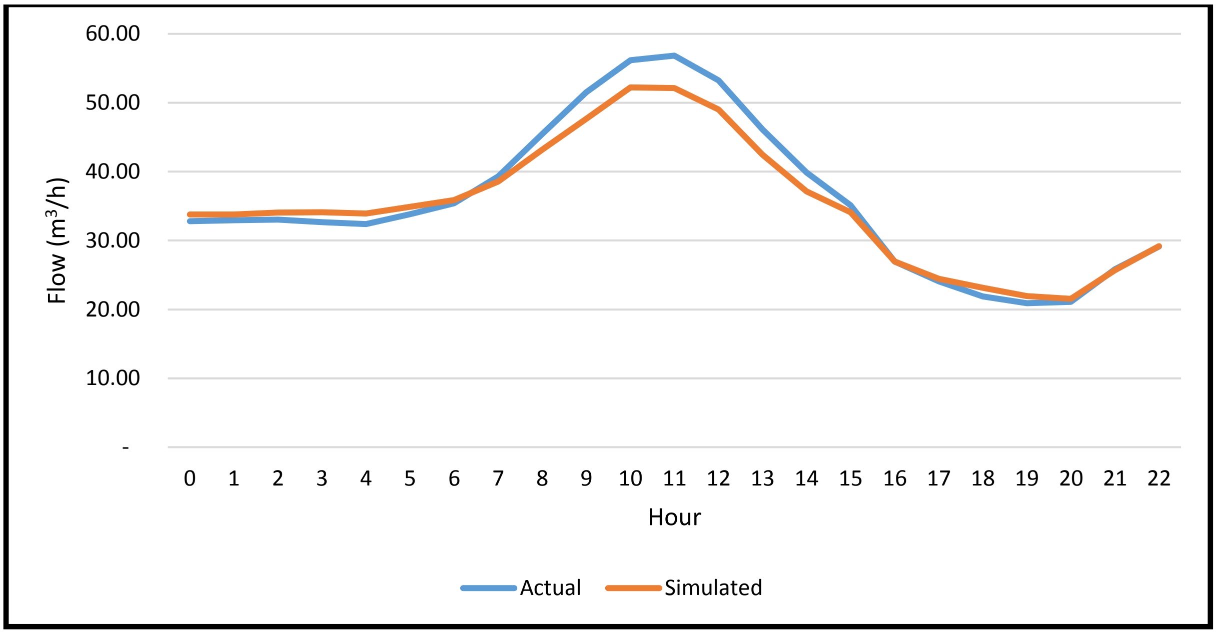


Figure 48: Simulated versus actual flow for Case Study 2

The maximum difference between these two lines are 9.07% at 10:00. Table 12 shows the values that were used to create Figure 48. The actual and simulated flows only represent the summation of the total compressed air consumption. Table 12 compares the actual and simulated flow results for Case Study 2 after the simulation was adjusted to include the two new compressors. Another parameter that needs to be compared is the system pressure of the compressors.

Table 12: Simulated versus actual flow for Case Study 2

Hour	Actual (kg/s)	Simulated (kg/s)	Percentage error
0	32.81	33.79	2.48%
1	32.93	33.77	3.00%
2	33.02	34.04	4.14%
3	32.68	34.09	4.60%
4	32.38	33.94	3.02%
5	33.84	34.89	1.27%
6	35.41	35.87	1.92%
7	39.30	38.56	5.34%
8	45.51	43.21	8.10%
9	51.53	47.67	7.53%
10	56.16	52.23	9.07%
11	56.84	52.11	8.62%

Hour	Actual (kg/s)	Simulated (kg/s)	Percentage error
12	53.25	49.03	8.63%
13	46.13	42.46	7.35%
14	39.88	37.15	2.95%
15	35.13	34.12	0.10%
16	26.96	26.93	1.60%
17	24.06	24.45	5.39%
18	21.88	23.13	4.61%
19	20.90	21.91	2.14%
20	21.08	21.54	0.42%
21	25.81	25.71	0.02%
22	29.16	29.16	0.50%
23	31.04	31.20	2.48%

Pressure comparison

Figure 49 compares the actual system pressure data with the simulated system pressure data. The actual data was retrieved from a SCADA on-site. Pressure data for three consecutive months were used. The blue line represents the simulated data and the orange line represents the actual data.

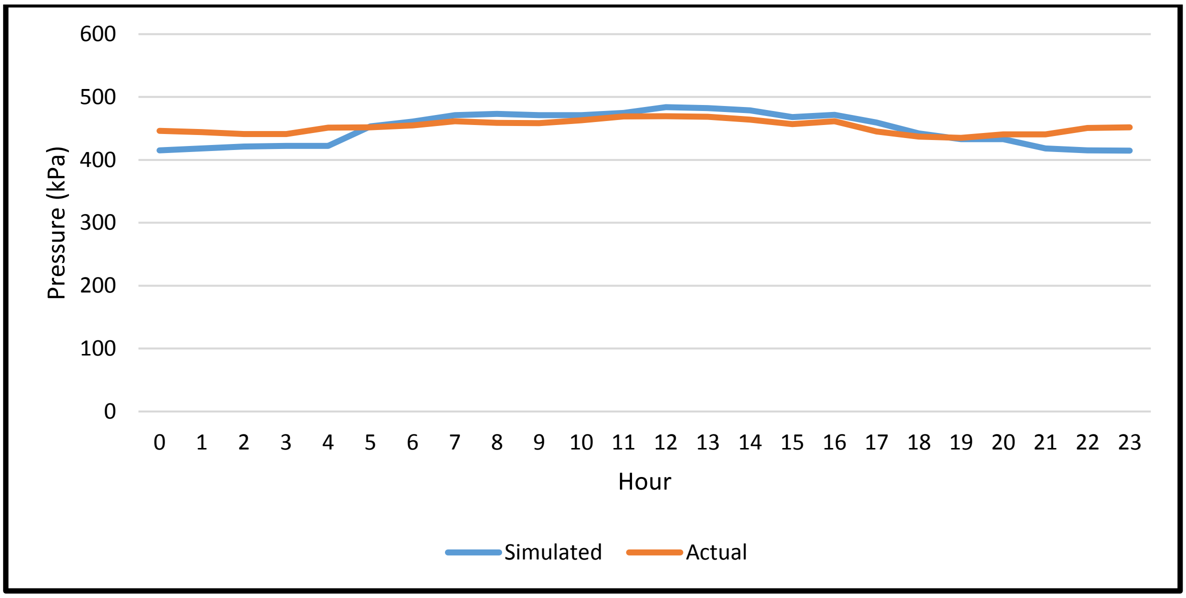


Figure 49: Pressure comparison

Figure 49 is used to indicate that the optimised compressor configuration would have negligible effect on the average system pressure. The simulated pressure and actual pressure are similar. Table 13 the actual and simulated pressure results for Case Study 2 after the simulation was adjusted and the two new compressors were added to the simulation. The maximum percentage error was 8.19% at 23:00.

Table 13: Pressure comparison

Hour	Actual (kPa)	Simulated (kPa)	Percentage error
0	446.41	415.25	6.98%
1	444.40	418.31	5.87%
2	441.19	421.18	4.53%
3	441.11	422.33	4.26%
4	451.47	422.54	6.41%
5	451.74	453.62	0.42%
6	455.08	461.15	1.33%
7	461.33	471.22	2.14%
8	459.20	473.00	3.00%
9	458.48	471.36	2.81%
10	462.86	471.28	1.82%
11	469.05	474.70	1.20%
12	469.51	483.93	3.07%
13	468.68	482.40	2.93%
14	464.08	478.62	3.13%
15	457.00	468.18	2.45%
16	461.34	471.87	2.28%
17	445.46	459.38	3.12%
18	437.09	442.19	1.17%
19	435.14	433.29	0.42%
20	440.93	433.09	1.78%
21	440.84	418.07	5.17%
22	451.03	415.19	7.95%
23	451.82	414.81	8.19%

Optimised solution

In Case Study 2 only one solution was considered – where one large compressor would be exchanged with two smaller compressors. This could be a viable option for Mine B, although this solution would have high initial costs. This option entails purchasing and installing new compressors, which would also ensure higher efficiencies on the network. For two new 4 MW compressors, the purchasing costs could be between R90 million and R170 million [85]. This implies that the project would have a payback period of between 4.5 and 8.5 years.

This option would also ensure that a backup compressor was available in case of emergencies and when regular maintenance was done on compressors. When new compressors are installed, they should also be able to cut back more efficiently than the 15 MW compressor. This should ensure increased electricity savings on the compressed air network.

A simulation was built to determine the viability of this solution. After safety, production would be the most important factor in this project. When comparing the simulated and the required pressure, it can be seen that the production of the mine would not be influenced. If the project influences production in a negative manner, other means of electricity savings should be investigated.

4.3 Application to industry

A study done in 2010 found that industrial compressors in South Africa consume 9% of the total power consumption [35]. The total available electricity, which was distributed in the year 2015/16, was 238 599 GWh [5], thus a total of 21 473.91 GWh was consumed by compressed air networks in South Africa. An assumption is made that the total compressed air consumption is still 9% of the total energy consumed in South Africa.

In Case Study 1 it was calculated that the project achieved 30% electricity savings in the Eskom evening peak period. An average value is calculated on the total power generated in 2015/16 and used as a 24-hour baseline. If this project could be implemented on all compressed air networks in South Africa, and if each compressed air network would be able to achieve electricity savings of 30% in the Eskom evening peak period, the total electricity savings could be calculated. Equation 8 can be used to calculate the total electricity consumption of the compressors.

$$\text{TC} = \text{TP} \times \frac{9}{100}$$

Equation 8: Total compressed air network consumption

The components of Equation 8 are:

- TC: Total compressed air network consumption
- TP: Total power generated

When the total compressed air consumption is calculated, it can be used as a baseline to measure the effect on the electricity consumption. The average electricity consumption is calculated per hour for a 24-hour profile using Equation 9.

$$\text{AV} = \frac{TC}{24}$$

Equation 9: Hourly average for the total compressed air network consumption

The components of Equation 9:

- AV: 24-hour average for total compressed air network consumption
- TC: Total compressed air network consumption

The final step would be to calculate a 30% electricity saving in the Eskom peak period and to calculate the cost savings using 2016/17 Megaflex tariffs. The electricity saving of this process could be 536.85 GWh in the Eskom evening peak period, which could lead to annual cost savings of nearly R165 million for all compressed air consumers.

4.4 Conclusion

In Chapter 4 the results were explained for each case study. It can be seen that each simulation's results are accurate. The simulations can be used to simulate the effect of future projects on these compressed air networks. Unfortunately, if the mine makes any changes to the compressed air network, the simulation must be altered using the steps discussed previously.

4.4.1 Case Study 1

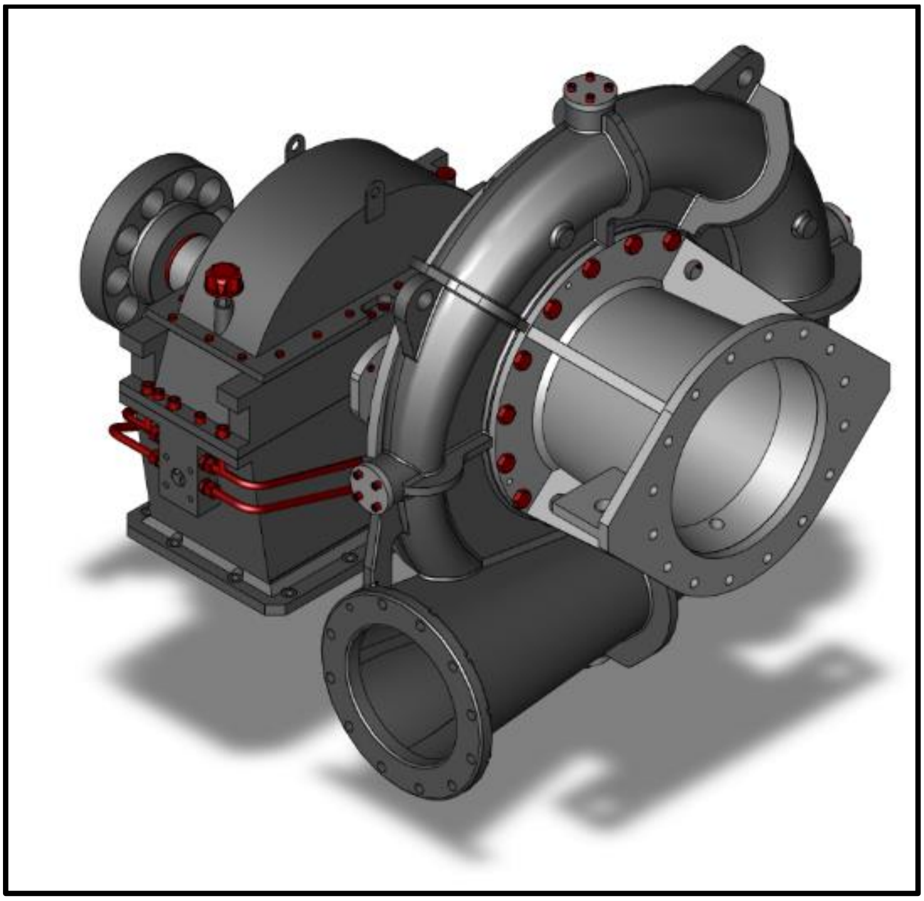
The initial target for this project was 7.8MWh electrical savings each day, the actual electrical savings achieved was only 6.2MWh each day. The project was not successful as the project underperformed by 21%, although many unforeseen problems arose that was not part of the scope of the project. The problems caused the project not to achieve the target savings, although great insight was achieved that can be applied to future projects. If compressed air leak repairs were included in this project, the target could probably have been achieved. This project can lead to an annual cost savings of R1.9 million.

4.4.2 Case Study 2

This case study is only a theoretical project and will not necessarily be implemented. If this project is implemented, it has a potential energy efficiency saving of 76 042 MWh per day. Flow and pressure are the parameters that were compared. This comparison included actual parameters and simulated parameters before adjustments were made on the simulation. The financial expenses for this project will be large, especially when two new compressors must be purchased. This project could lead to an annual cost saving of R20 million. If this project is implemented, it will have a minimum payback period of 4.5 years. Unfortunately this project could not be validated.

The conclusion of this study will be discussed in the next chapter. Lessons were learned which will also be discussed in Chapter 5. Afterwards, recommendations will be made on how to minimise the probability of unforeseen problems arising which caused Case Study 1 not to reach its target.

5 Conclusion and recommendations



Simulation model of a centrifugal compressor [86]

"In engineering, that only is great which achieves. It matters not what the intention is, he who in the day of battle is not victorious, is not saved by his intention."

Henry Ward Beecher

5.1 Summary

In Chapter 1 background information was given on the current state of Eskom and the company's electricity generating capabilities. In 2014, the maximum electricity generation capacity was lower than the electricity demand in winter. Eskom's solution was the New Build Programme, which commenced in 2005, and the use of OCGTs. Initially it was planned to use the OCGTs only in the evening peak periods, although they were used extensively. The diesel used as combustion is more expensive than the coal used by power stations. These solutions caused the high tariff increases in South Africa.

Information was also given on the current situation of the platinum mining industry, which included the platinum price. The platinum price has decreased by nearly 42% since the year 2010. Another factor which has a large influence on the platinum mining industry is the shares of these companies that have been decreasing significantly.

The problem statement and objectives of this study were discussed in Chapter 1. The problem statement included that the platinum mining industry is under pressure as the platinum price and the company shares have decreased. It was seen that electricity is an expenditure that can be lowered without compromising productivity of the mine. This means that there is potential for implementing a DSM initiative on platinum mines.

Objectives were discussed where opportunities were identified to reduce the pressure – the compressors were controlled to reduce the flow generated and solutions were simulated. These solutions were implemented and results were verified and validated.

In Chapter 2, background information was given on compressed air networks. This information included compressed air networks configurations, types of compressor and compressed air users. There are two compressed air configurations, namely, a stand-alone system and a ring feed system. The optimal choice would be the ring feed system, because of redundancy of compressors. Two types of compressor were discussed, namely, axial and centrifugal compressors. Centrifugal compressors were the optimal choice, because these compressors are efficient over a large operating range. Compressed air users were discussed and how the mining schedule can be used to identify which periods in a day mines require lower pressures and flows.

Compressed air leaks were also discussed. It was seen that compressed air leakage can result in large financial losses annually, thus compressed air leak detection methods were discussed.

The optimal method included a computer-based method. This method can be used to identify the size of the leak and its location. Different saving opportunities and DSM techniques were also discussed and more information was given regarding each technique. Finally, previous research was discussed, where information was given to how each of these studies were done on compressed air networks.

The purpose of Chapter 3 was to discuss the methodology of two case studies. In Case Study 1, control valves were installed on the surface main compressed air pipeline towards each compressed air user. This valve configuration included a main valve that was used to seal the pipe in the Eskom evening peak period. Another smaller valve was installed in a bypass pipeline and controlled to deliver the optimal amount of flow and pressure to each compressed air user.

In Case Study 2, a large 15 MW compressor was replaced by two 4 MW compressors in a simulation. This was only a theoretical project as the financial expenses to purchase two 4 MW compressors were too high. Each case study's discussion included background information regarding the mine and the improvement of each case study's strategy to reduce compressed air consumption. A simulation was developed and verified for each case study.

In Chapter 4, the results of each case study were discussed. Each simulation was adjusted to calculate the effect the implementations had on the compressed air network. Case Study 1 was validated using actual data, which included the electricity consumption of the compressed air network. This was a peak clipping project with an initial target of 7.8 MWh electricity savings. This project achieved 6.2 MWh, although there were problems which reduced the savings significantly. This project under performed with 21%. If compressed air leak repair was included in the scope of the project, it would have been possible to achieve the target. The annual electricity cost savings for this project were calculated as R1.9 million.

Case Study 2's results included flow and pressure comparisons. The actual flow and pressure values were compared with the simulation's values after it was adjusted to simulate the project. Calculations were done after the simulation was altered, where the target for this theoretical project was calculated as 76 042 MWh per day. This can result in electricity cost savings of R20 million per year, with a minimum payback period of 4.5 years. These results excluded validation as this was a theoretical project. The financial impact was calculated if the valve strategy from Case Study 1 could have been implemented on every industrial compressed air network in South Africa.

5.2 Objectives reached

The subsections that follow describes the objectives that have been reached.

5.2.1 Identify opportunities to reduce airflow and/or pressure to decrease electricity costs

In Case Study 1, opportunities were identified when it was seen that the pressure set points in the compressed air ring were not lowered sufficiently in the Eskom evening peak periods. This was seen as an opportunity for implementing a DSM project.

In Case Study 2, the large 15 MW compressor oversupplied the compressed air network. It was identified that the flow generated by the compressors could be lowered to match the supply without using the large compressor, thus it was replaced with two 4 MW compressors in the simulation.

5.2.2 Controlling the compressors to generate the lower required flow and/or pressure

In Case Study 1, the compressors were controlled according to the demand side of the compressed air network. In Case Study 2, compressors with large cut-back capabilities were acquired theoretically. Each of these compressors were controlled to match the supply of the compressed air users.

5.2.3 Simulating solutions for reducing electricity costs

A simulation was built for each case study, where it was seen that there was a possibility of reducing the electricity consumption. In Case Study 1, solutions were implemented on the simulation before implementations were done on the compressed air network. The electricity consumption decreased, which led to a reduction in electricity costs.

In Case Study 2, a simulation was built where a large 15 MW compressor was replaced by two 4 MW compressors. This simulation’s results indicated that the electricity consumption of the compressed air network would be decreased, which would reduce electricity costs.

5.2.4 Implementing the solution for reducing the compressed air consumption in the Eskom evening peak period

In Case Study 1, control valves were implemented on the main compressed air line towards each compressed air user. There were two valves installed towards each compressed air user, one large valve to seal the main pipeline and one in the bypass pipeline to control the flow through the pipe. Case Study 2 had no implementation as this is a theoretical project.

5.2.5 Verifying the results

In both case studies, the simulation’s accuracy was verified with actual data. This actual data was obtained on the database of each mine individually. The simulated results before alterations were made to simulate the effect of the project were compared to the actual data. This process was done for each case study.

5.2.6 Validating the electricity cost savings

Case Study 1 could have been verified and validated as this was an actual project. In Case Study 2, the baseline simulation results were verified before the simulation was adjusted to simulate the effect of the theoretical project.

5.3 Recommendations for future work

5.3.1 Case Study 1

A future project that can be implemented on Mine A is a flap-valve project, which shifts the control of the compressors to the intake valve of each compressor. This flap valve will be installed at the intake of the compressor to control the amount of compressed air that enters the compressor. If the flow at the intake is reduced, the compressor should be able to cut back more efficiently and more electricity savings could be achieved. In theory, this alteration to the intake of the compressor would improve the efficiency of cutting back the compressor.

A maintenance contract should be considered with Mine A to ensure that the project will achieve the target savings. This will ensure that no deterioration takes place that will cause the project to lose the possible savings that can be achieved. Compressed air leakage detection and repairs should be added to the maintenance of the project. When focussing on leakages a viability study should be conducted to seal the older section.

A DCS could be investigated on Mine A. A DCS can be implemented as a project where optimal compressors are selected for real-time compressed air requirements. The DCS will monitor the flow of each compressed air user constantly and predict what each compressed air users' flow will be in 30 minutes. The DCS will use this information to choose the optimal compressor selection. This selection will depend on the flow and pressure needed by each compressed air user and its location. The possible DCS project could extend the lifetime of the compressors by choosing an optimal schedule for stopping and starting of compressors, where maintenance schedules developed by the DCS can be used to further improve the compressed air network.

5.3.2 Case Study 2

Case Study 1's implementation of control valves can be a future project on Mine B and similar electricity savings can be achieved. Leak detection and repairs can be included to ensure the same mistake will not be repeated as in Case Study 1. Mine B has more compressors and more compressed air users, which could mean that a larger savings target can be achieved. Lastly, DCS can be implemented on Mine B. It should have the same effect as discussed, thus optimal compressors would be chosen to operate according to the demand at that specific time. This could extend the life time of the compressors.

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Appendix A: Case Study 1 simulation layout

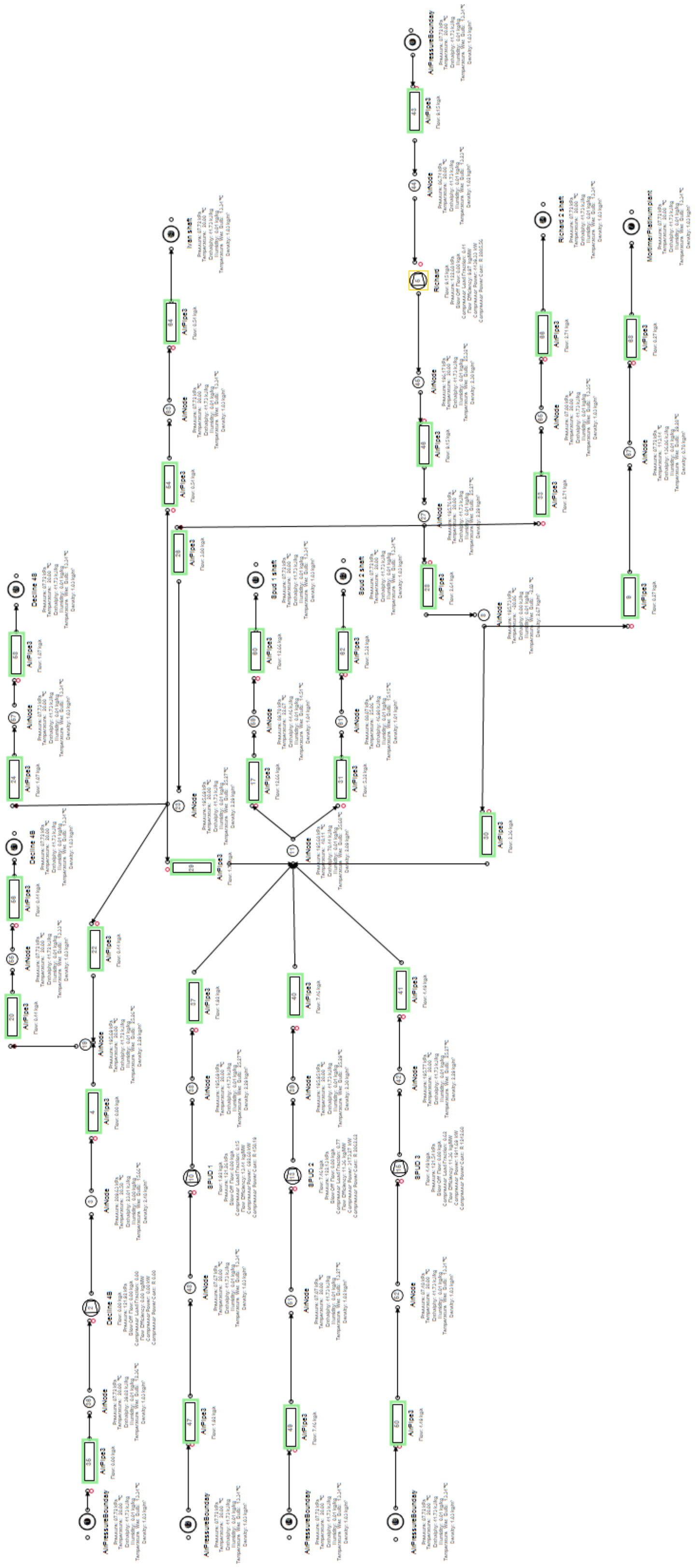

Figure 50: Case Study 1 simulation layout

Appendix B: Case Study 2 simulation layout

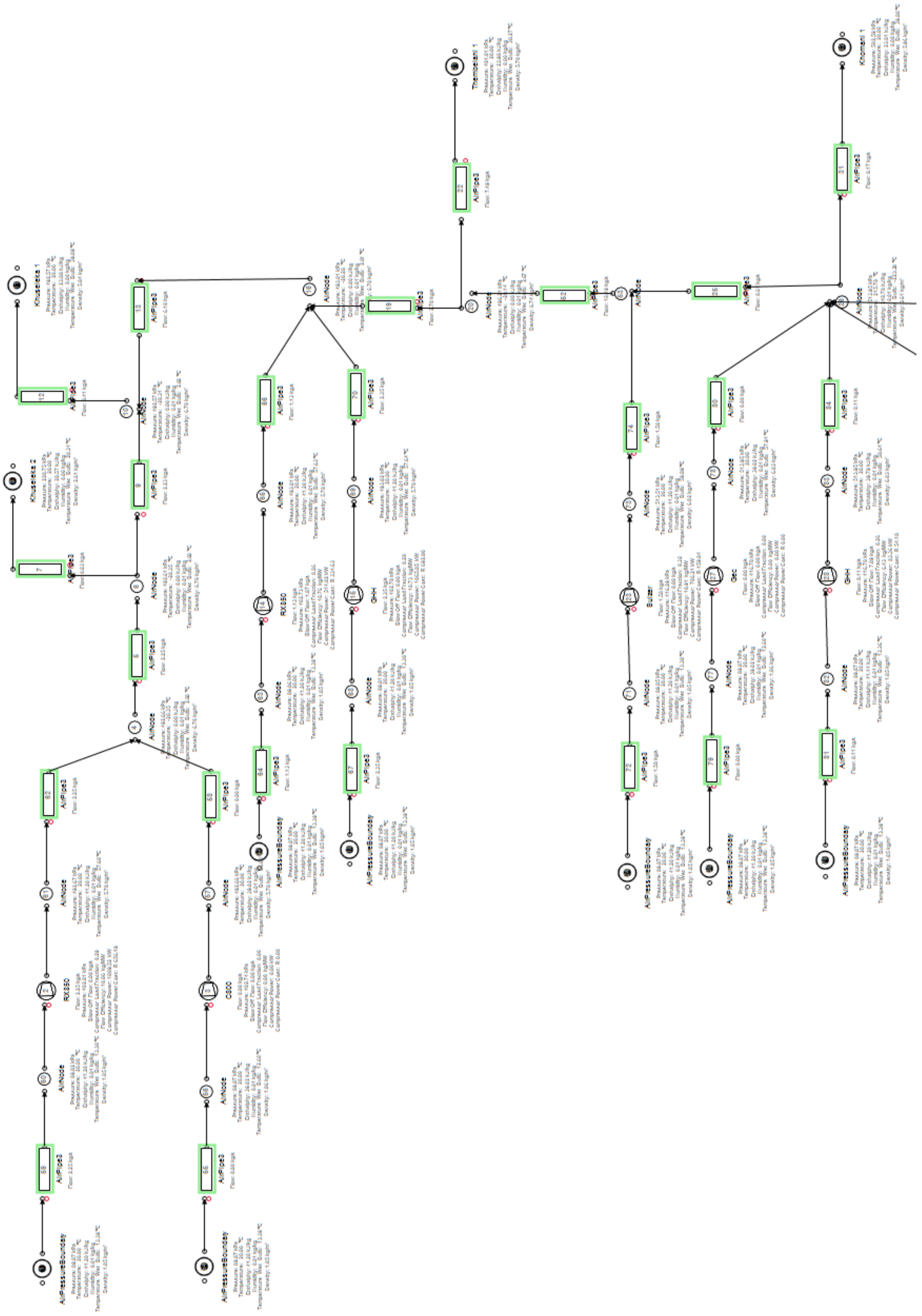

Figure 51: Case Study 2 simulation layout

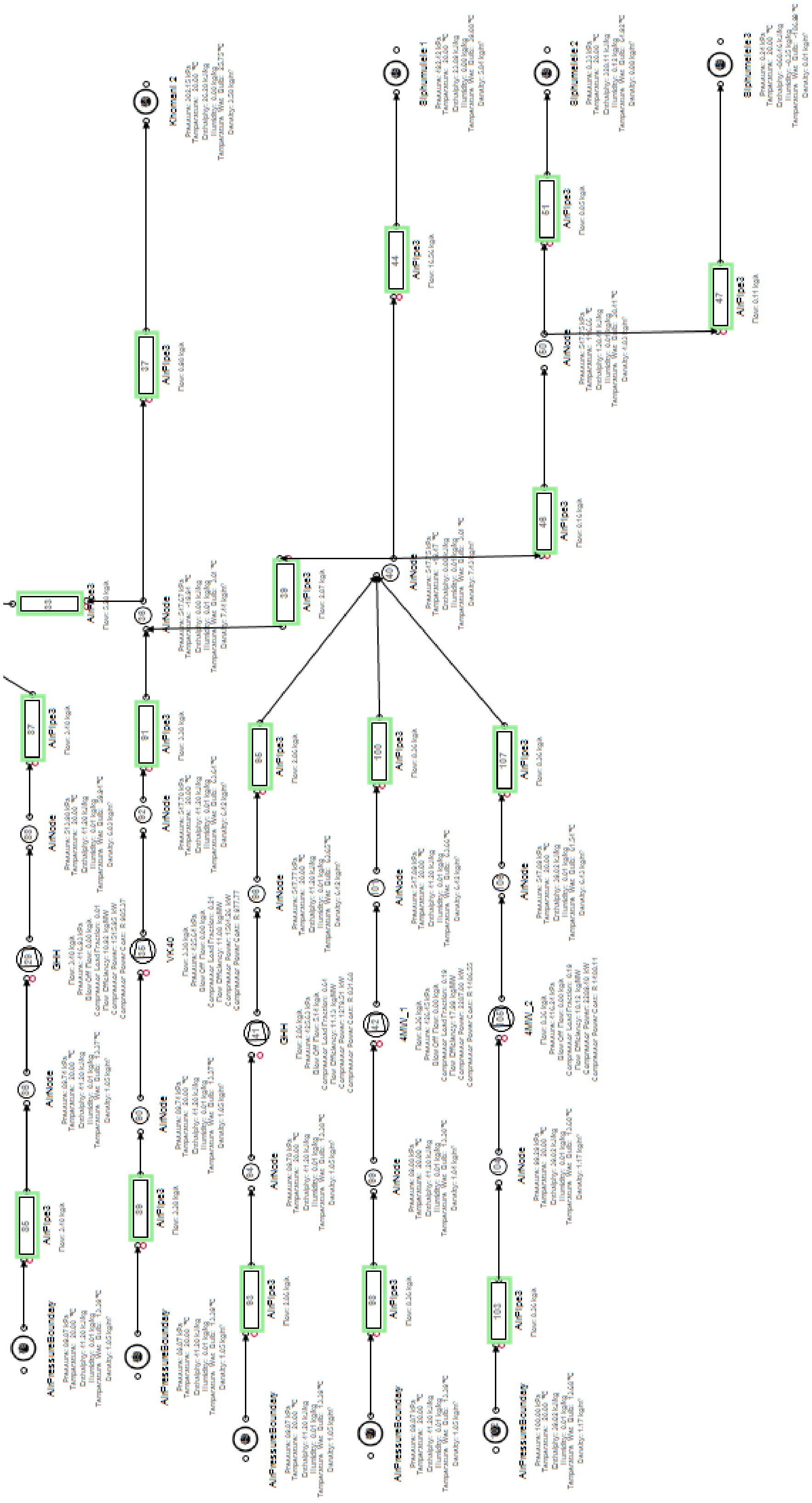

Figure 52: Case Study 2 simulation layout (continued)