

**Developing a framework for managing
compressed air in the Platinum Group Metal
Mining Industry in South Africa**

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ABSTRACT

South Africa is home to the Bushveld Igneous Complex, the largest known platinum group metal (PGM) resource in the world, which makes South Africa the top global PGM-producing country. Unfortunately, the sustainability of the PGM mining industry in South Africa is under threat as a result of rapidly escalating costs, such as electricity and labour, in combination with a low platinum price.

PGM mining is an electricity intensive endeavour. The PGM mining industry in South Africa depends on Eskom, the parastatal electricity utility, for most of its electricity supply. This dependence is problematic because Eskom's electricity tariffs have increased annually for more than a decade at a rate significantly higher than inflation. This trend of above-inflation electricity price increases is likely to continue in future due to Eskom's ongoing financial problems. The PGM mining industry is therefore forced to implement measures to reduce electricity consumption.

The biggest electricity consumer on deep-level PGM mines is the generation of compressed air. Compressed air is used for various purposes in PGM mines and its availability is critical to prevent interruptions in the production process. Managing compressed air is important to ensure that the costs of generating compressed air and maintaining compressed air infrastructure are minimised.

The primary objective of this study was developing a framework for managing compressed air in the PGM mining sector. Two secondary objectives were also established, namely: i) developing a strategic guideline for improving and maintaining energy efficiency on compressors, and ii) developing a strategic guideline for monitoring and preventing the occurrence of events that result in increased compressor maintenance costs.

In order to achieve the objectives of the study, qualitative research was conducted through semi-structured interviews with nine experienced senior managers who manage compressed air in the PGM mining industry. The results of the qualitative research were presented in the form of six themes that were identified in the data through computer-assisted qualitative data analysis. The qualitative results were supported by quantitative

results showing that a 15% saving in compressed air generation costs could be achieved by applying measures to improve energy efficiency on compressed air networks.

A framework for managing compressed air in the PGM mining sector was developed based on the quantitative and qualitative results. The framework consists of focus areas, priorities and action steps for managing compressed air in the PGM mining sector in terms of improving/maintaining energy efficiency and the monitoring/prevention of events that result in increased maintenance costs.

KEYWORDS: Energy management, maintenance management, platinum group metal (PGM) mining, compressed air.

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LIST OF ABBREVIATIONS

Amplats	Anglo American Platinum
ARM	African Rainbow Minerals
BIC	Bushveld Igneous Complex
CPI	Consumer Price Index
GM	General Manager
HR	Human Resources
HOD	Heads of Department
IDM	Integrated Demand Management
Implats	Impala Platinum
NERSA	National Energy Regulator of South Africa
Nornickel	Norilsk Nickel
PGM	Platinum Group Metal
RBPlat	Royal Bafokeng Platinum
SCADA	Supervisory Control and Data Acquisition
USA	United States of America

LIST OF UNITS

GWh	Gigawatt-hour
kPa	Kilopascal
kV	Kilovolt
kW	Kilowatt
MW	Megawatt
oz	Ounce
v	Volt

CHAPTER 1 – NATURE AND SCOPE OF THE STUDY

1.1 Introduction

Although South Africa possesses the largest platinum group metal (PGM) reserves in the world (Ranchod, Sheridan, Pint, Slatter, and Harding 2015:287), PGM mining is limited to the Bushveld Igneous Complex (BIC). The BIC is a large layered intrusion of ingenious (magmatic) rock located in the northern part of South Africa. Figure 1-1 shows the location and layout of the BIC (Minerals Council South Africa, 2019).

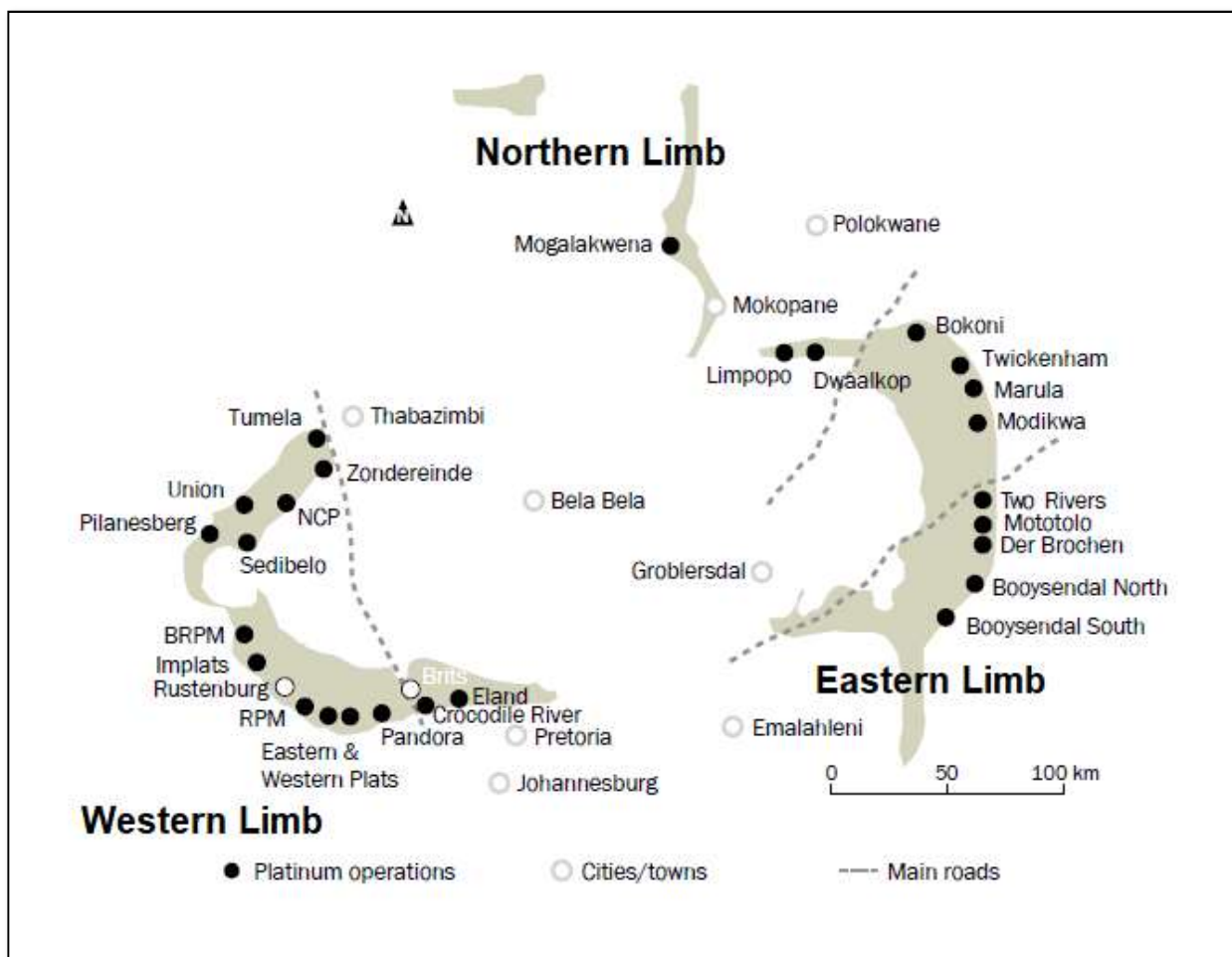


Figure 1-1: Location and layout of the BIC

Source: Adapted from Minerals Council South Africa (2019)

Three main ore bodies are mined in the BIC, namely, the Merensky Reef, the Upper Group 2 chromitite reef and Platreef (Junge, Wirth, Oberthür, Melcher, & Schreiber,

2015:41). South Africa's major deep-level PGM mines are located on the western limb of the BIC. Figure 1-2 shows the estimated distribution of the world's remaining known PGM resources (Singerling, 2019:125). The BIC is estimated to contain about 91% of the remaining PGM resources in the world.

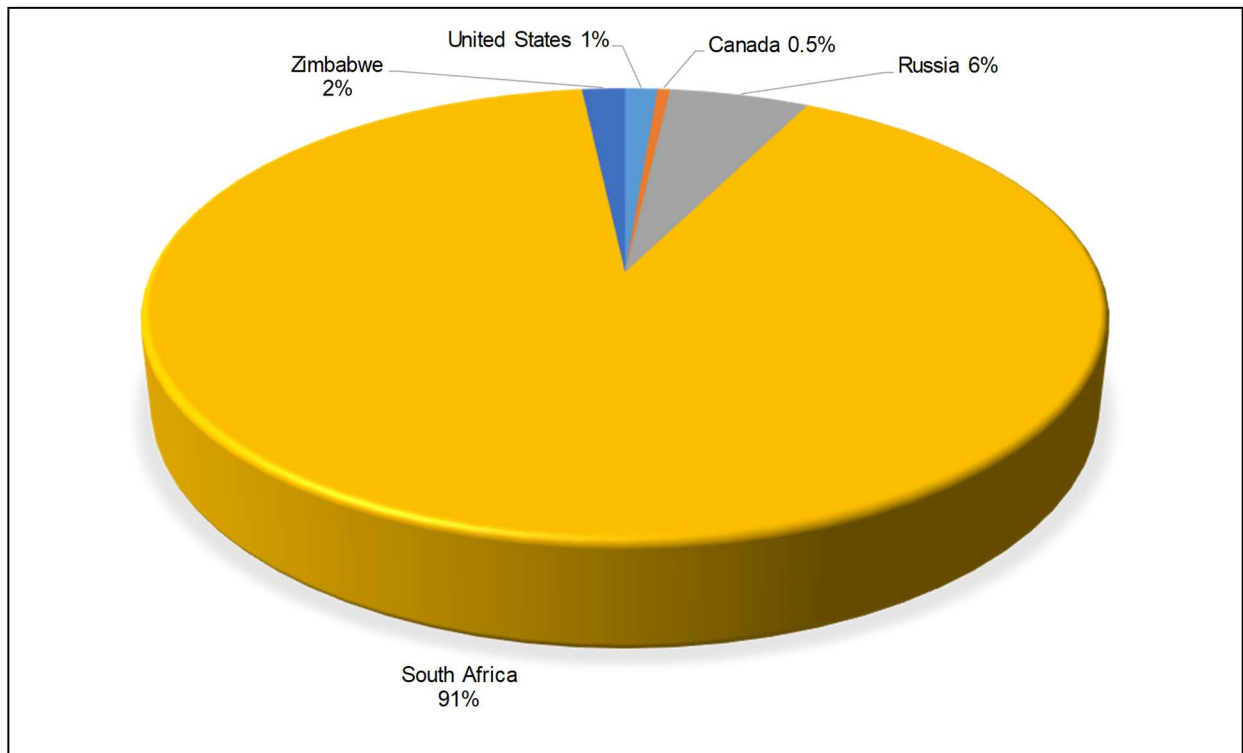


Figure 1-2: Distribution of PGM reserves

Source: Singerling (2019:125)

South Africa is the largest PGM producer in the world, accounting for 48% of global production of platinum and palladium in 2018 (Singerling, 2019:125). The PGM sector is a major contributor to the economy of South Africa. Between 1980 and 2015, 221 million ounces of PGMs were produced with a value of R1.2 trillion (Odendaal, 2019).

In 2018, the PGM sector was the largest mining employer in South Africa with more than 168 000 direct employees, representing 34% of total employment in the South African mining industry (Baxter, 2019:2). In 2018, the PGM sector earned more than R96 billion in revenue (Maeko, 2019).

The sustainability of the PGM sector in South Africa is however under serious threat due to the following challenges:

- Low price of platinum, the main PGM mined in South Africa.
- Domestic labour disputes [e.g. the Marikana Massacre (Alexander, 2013:605)].
- Costs increasing above inflation (i.e. labour and electricity).
- Declining productivity.

The combined result of the challenges listed above is that at the end of 2018, more than 65% of PGM mining operations in South Africa were marginal or loss-making (Baxter, 2019:6). These marginal or loss-making PGM operations represent 90 000 jobs that are at risk (Tshwane, 2019).

Economic growth forms the cornerstone of South Africa's National Development Plan, which is aimed at eliminating poverty and reducing inequality by 2030. The PGM industry has the potential to contribute significantly to economic growth and achieve the goals of the National Development Plan. It is therefore not only imperative that the existing jobs in the PGM industry should be preserved, but it is even more important that steps should be taken to ensure that the full potential of the PGM sector in South Africa is unlocked. The full potential can be unlocked by developing strategies to counter the challenges facing the PGM sector in South Africa.

1.2 Problem Statement

Eskom is South Africa's public electricity utility that supplies about 95% of all electricity consumed in South Africa (Jaglin & Dubresson, 2016:1). As shown in Figure 1-3, the mining industry consumed 14% of Eskom total electricity sales in the 2018/2019 financial year (Eskom, 2019a:29). This equates to 29 165 GWh, which is worth R25 billion.

The generation of compressed air accounts for between 21% and 24% of a platinum group's total electricity cost (James, 2018). When considering that the annual total electricity costs of a typical large PGM mining group exceed R1.5 billion, it is implied that a typical PGM mining group spends between R315 million and R360 million per annum on the generation of compressed air.

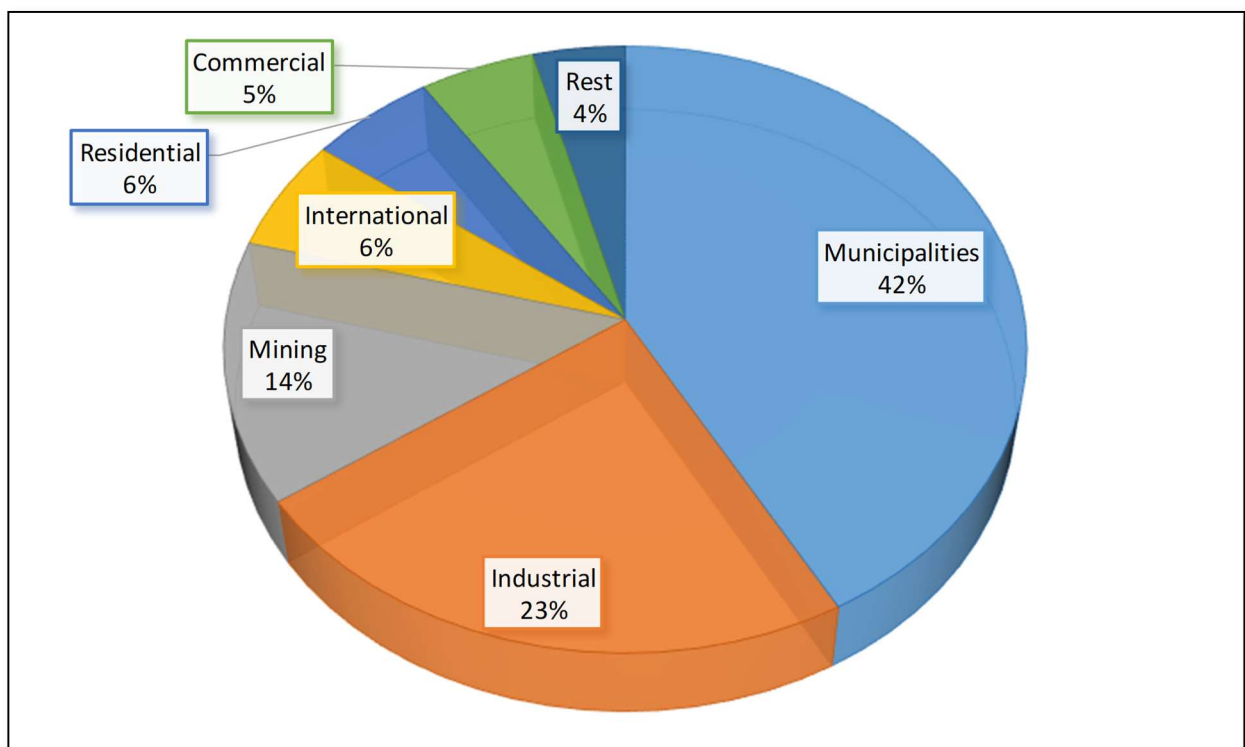


Figure 1-3: Eskom's sales for the 2018/2019 financial year

Source: Eskom (2019a:29)

Figure 1-4 shows a breakdown of the electricity costs of a typical PGM mineshaft, with compressed air consumption accounting for 38% of the total cost. A typical large PGM mineshaft currently spends more than R5 million per month to generate compressed air during Eskom's low-demand season (September to May). This amount is even higher during June, July and August when Eskom's high-demand season tariffs apply.

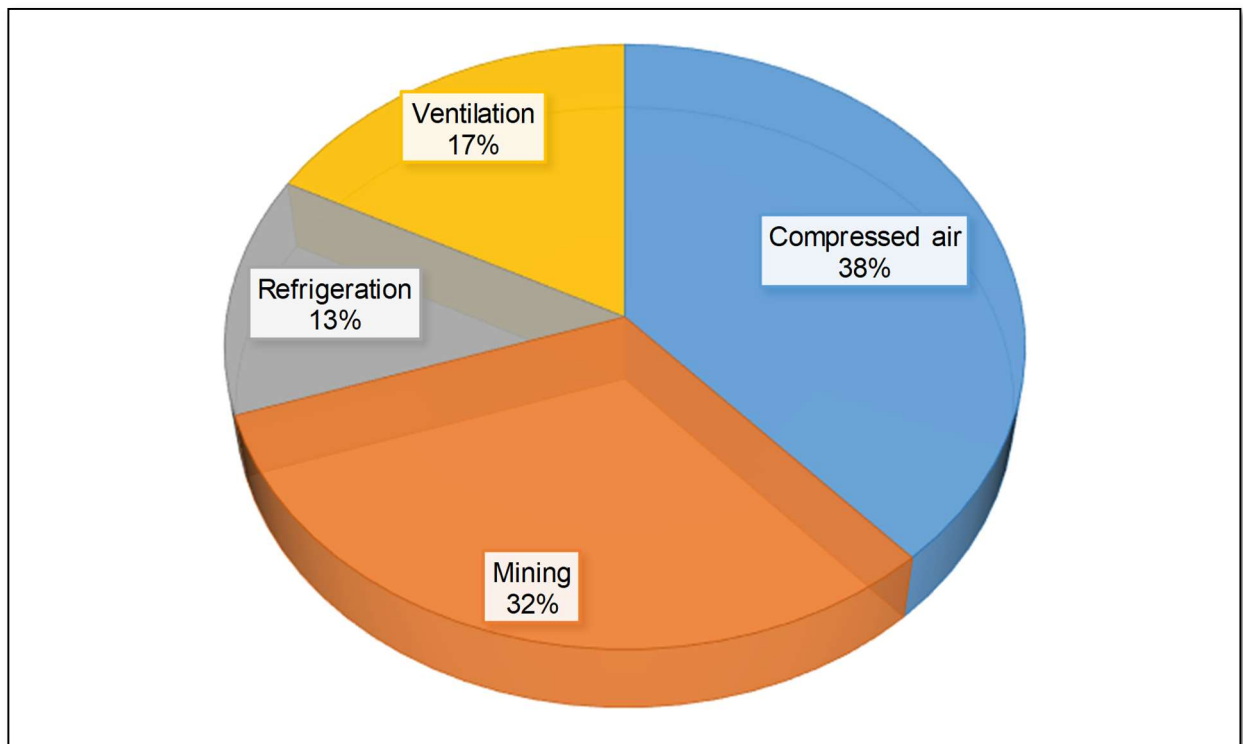


Figure 1-4: Typical breakdown of electricity cost on mineshaft level

Source: Own compilation

The fact that compressed air is the single biggest consumer of electricity on a PGM shaft motivates why compressed air consumption should be the primary target when aiming to improve energy efficiency in the PGM mining industry. As an added advantage, improving energy efficiency reduces the carbon footprint of the PGM mining industry as well. Another motivating factor is that compressed air networks are considerably less complex than the vast number of electricity consumers grouped under 'mining'. It should therefore be easier and faster to make a notable impact by reducing electricity consumption when targeting compressed air instead of 'mining' as a whole.

Energy consumption comprises 80% of the total running cost of a compressor (Booyesen, Kleingeld & Van Rensburg, 2009:1). The other 20% is made up of maintenance costs. It is imperative that correct compressor maintenance procedures are followed because the availability of compressed air is of cardinal importance to the PGM production process. Furthermore, there is a direct link between availability and energy efficiency because energy consumption tends to increase when compressors break down. It is important that energy efficiency initiatives should not affect compressor availability and maintenance

costs adversely. A framework for managing compressed air as an energy carrier in the PGM sector should therefore consider both the electricity and maintenance costs of compressors.

As stated in the previous section, a major economic challenge facing the PGM sector in South Africa is the combination of rapidly escalating costs and a declining platinum price. A significant contributing factor to escalating costs is Eskom's electricity tariffs that have on average been increasing above the inflation rate since 2007.

An analysis of the average increases in Eskom's electricity tariffs over the period from 2007 to 2019 reveals that Eskom's tariffs increased with 468%, while inflation measured according to the consumer price index (CPI) over the same period amounted to 108% (Eskom, 2019c; Inflation.eu, 2019). Figure 1-5 compares Eskom's average annual tariff increases and CPI for the period from 2006 to 2019. It is evident that Eskom's tariffs are increasing more than four times faster than the CPI.

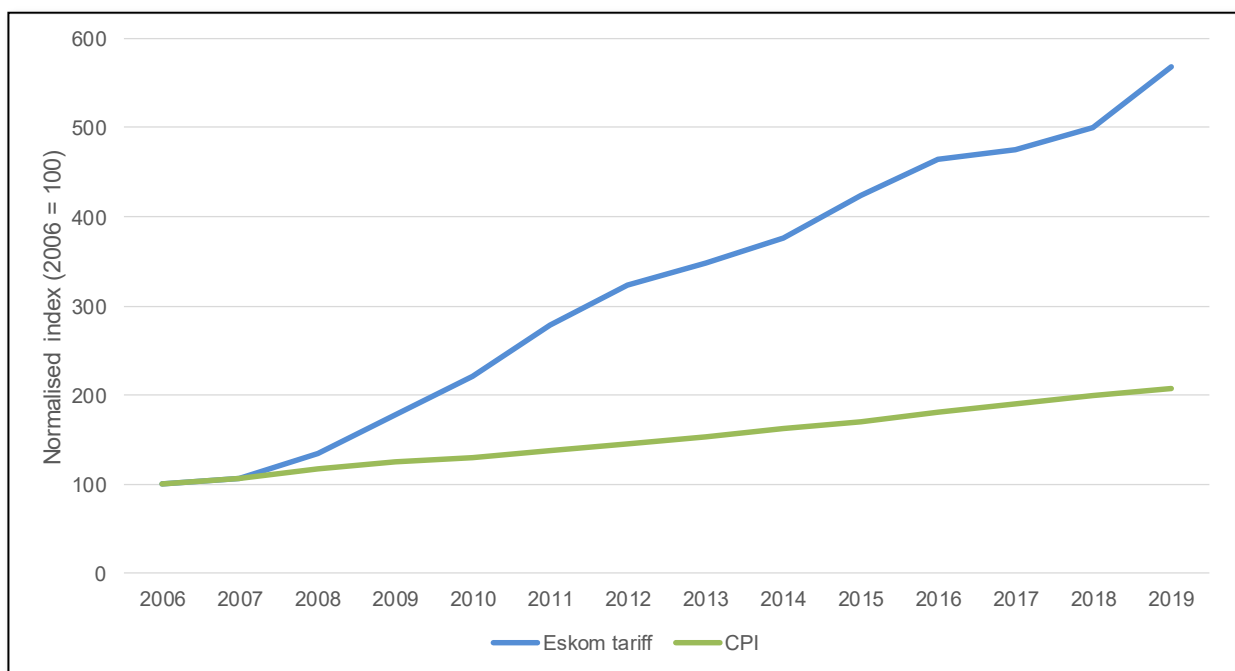


Figure 1-5: Cumulative Eskom average tariff increase vs inflation (CPI)

Source: Eskom (2019c) and Inflation.eu (2019)

Eskom is experiencing various challenges in generating enough electricity to meet South Africa's demand. This is evident from the sporadic occurrence of load shedding in 2019.

Eskom's generation problems pose a significant risk to the general economy and the PGM mining industry. According to Griffith (2019:4), chief executive officer of Anglo American Platinum (Amplats), the biggest challenge facing the mining industry in South Africa is unreliable power supply.

The Minerals Council South Africa (2019) stated that Eskom's electricity tariff increase as approved by the National Energy Regulator of South Africa (NERSA) for the period from 2019/2020 to 2021/2022 will put an additional 22 800 jobs in the PGM sector under risk. This is in addition to the 90 000 jobs that are already at risk due because 65% of PGM operations in South Africa were considered to be marginal in 2018 (Baxter, 2019:6).

Electricity is a major cost contributor in the PGM industry, accounting for between 74% and 90% of the total energy consumed (Implats, 2018c:76; Lonmin, 2017:51). For deep-level PGM mining operations in South Africa, electricity represents on average between 7% and 13% of the total cost of mining (Implats, 2018a:31; Lonmin, 2017:57).

The above-inflation electricity tariff increases in combination with electricity being a significant cost to the PGM industry motivate why the PGM sector needs to implement energy efficiency initiatives to reduce energy costs. Further motivating factors are the introduction of carbon tax in South Africa in 2019 and the fact that mining operations are becoming increasingly energy intensive when expanding to deeper mining operations.

1.3 Objectives of this Study

1.3.1 Primary objective

The primary objective of this study is to develop a framework for managing compressed air in the PGM mining sector. The intended outcome of applying the framework is a reduction in the operational costs of a compressed air network.

1.3.2 Secondary objectives

In order to achieve the primary objective, the following secondary objectives must be realised:

- Develop a strategic guideline for improving and maintaining energy efficiency on compressed air networks in the PGM sector.
- Develop a strategic guideline for monitoring and preventing the occurrence of events that result in increased maintenance costs of compressors used in the PGM sector.

1.4 Limitations of the Study

1.4.1 Coverage limitations

There are no coverage limitations because the research focuses on two PGM mining companies operating in the BIC, which is the only geological area in South Africa where PGM mining takes place.

1.4.2 Generalisability limitations

Two types of PGM mining practices are used in the BIC, namely, deep-level mining and open-pit mining. Deep-level mining consumes more compressed air than open-pit mining. Although the framework presented in this study was developed specifically for deep-level PGM mining operations, it could be applied to open-pit mining as well.

Mineshafts and concentrating/smelting plants consume compressed air on PGM operations. In terms of managing the demand for compressed air, this study only focuses on mineshafts. The concentrating/smelting plants are excluded from the scope of this study.

1.5 Definitions of Key Concepts

- **Energy management:** The monitoring and management of energy consumption to prevent wastage. In terms of a compressed air network, the idea is to reduce the electricity consumption of the compressors without negatively affecting the operation of any equipment that requires compressed air to operate.
- **Maintenance management:** The management of actions that are taken to ensure that equipment continues to function as per the original specifications.

- **Platinum Group Metals (PGMs):** Six scarce metal elements with similar properties, namely, platinum, palladium, rhodium, iridium, osmium and ruthenium (Nassar, 2015:2).
- **Compressed air:** Compressed air is used extensively as an energy carrier in deep-level PGM mining operations in South Africa. Compressed air is generated by large centrifugal compressors located on surface and distributed to the mineshafts through a pipe network on surface and underground. Compressed air is used for various purposes in PGM mining, including drilling, loading, sweeping, cleaning, and agitation.

1.6 Research Methodology

1.6.1 Research method

The research method refers to the methods or techniques used to conduct research (Bryman, Bell, Hirschon, Dos Santos, Du Toit, Masenge, Wagner, & Van Aardt, 2017:382). The methods can be qualitative, quantitative or a combination of qualitative and quantitative (i.e. mixed method). Examples of research methods include structured or unstructured interviews, questionnaires, surveys and observations.

Semi-structured interviews were conducted to collect qualitative data, which was supported by quantitative data. The quantitative data consisted of measured data, which originated from instrumentation installed on PGM mines. The motivation for choosing this research methodology was to combine the respective strengths of both quantitative and qualitative research methods to answer the research questions. Figure 1-6 indicates the sources of the data used for this study.

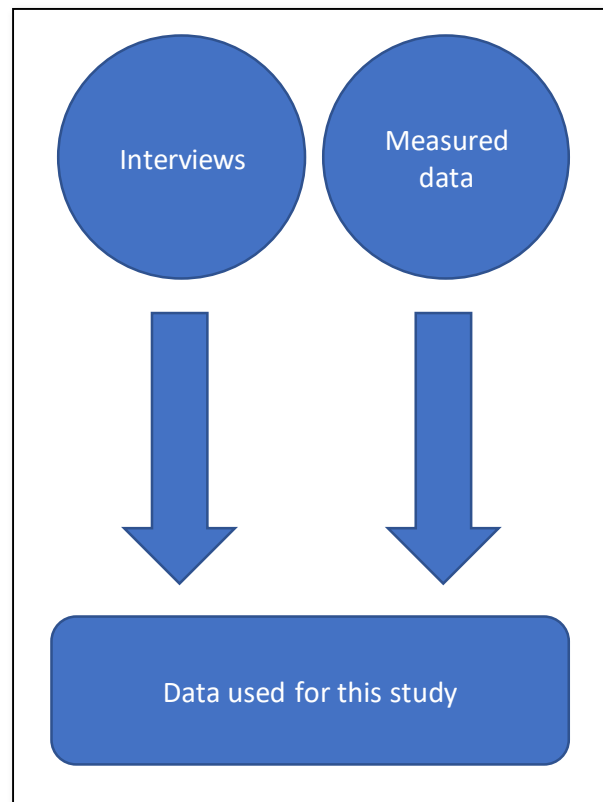


Figure 1-6: Data sources used for this study

More information about the data collection instruments are provided below:

Interviews

Interviews were conducted with senior managers employed by PGM mining companies in South Africa. The common denominator among these senior managers is that they all have some degree of responsibility in terms of managing compressed air at PGM operations.

Measured data

This study used measured data originating from instrumentation installed on compressors and other equipment at PGM mines. The data includes, but is not limited to power meter readings, vibration measurements, inlet guide vane positions, and compressed air flow meter readings. The data collected from these instruments is credible because the data is also used for other important functions such as billing and automated control of machinery on PGM operations.

1.6.2 Research design

Research design refers to the procedural plan used by the researcher to answer the research questions in a valid, objective, accurate and economical manner. The main function of the research design is to explain how the research questions will be answered (Kumar, 2011:96). Figure 1-7 depicts the research design for this study.

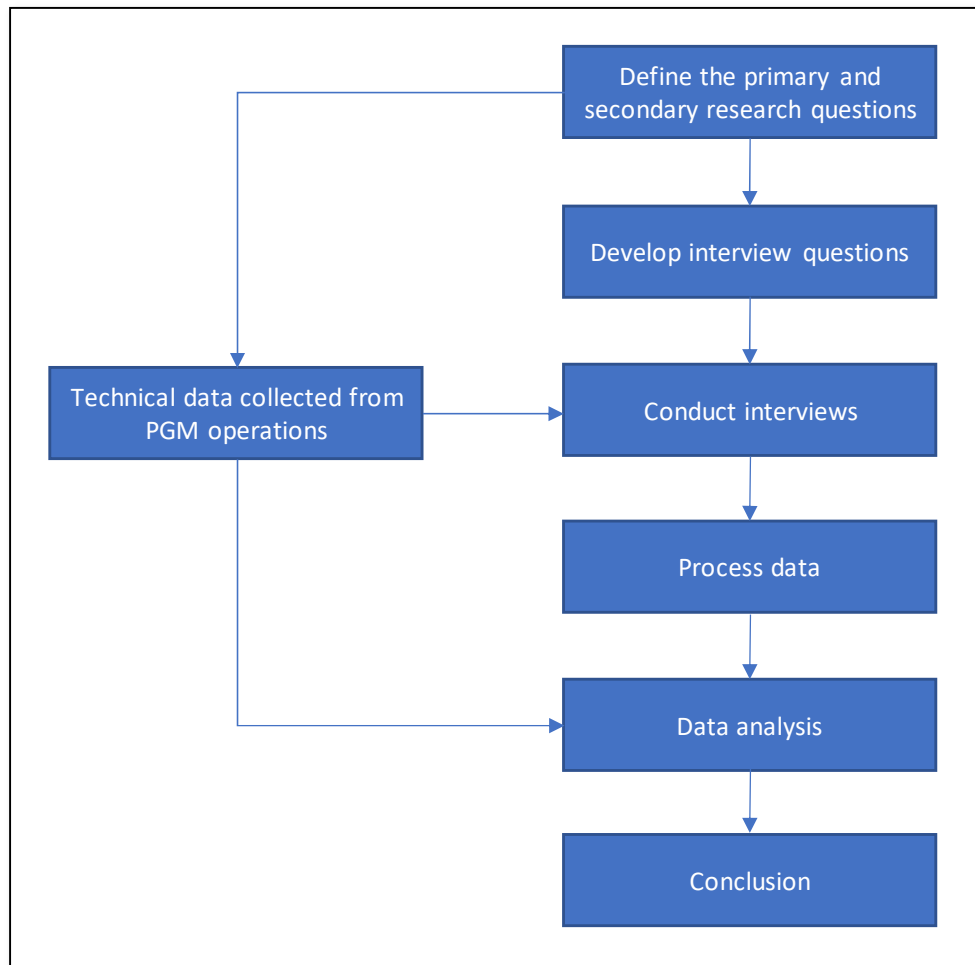


Figure 1-7: Research design

For this study, the research design started by defining the primary and secondary research questions, whereafter the interview questions were developed. The next step entailed conducting the interviews. This was followed by processing the data from the interviews. Both the data from the interviews and technical data collected from PGM operations were analysed. The final step involved reaching conclusions based on the data analysis.

1.6.3 Population

The target population of a study is defined as set of objects that holds the information that the researcher would like to obtain (Bryman *et al.*, 2017:381). The target population of this study comprised persons working at three different PGM operations, consisting of multiple mineshafts and located on the western limb of the BIC. The three PGM operations belong to two of the five largest global PGM mining companies. Senior personnel responsible for managing the compressed air networks were targeted for the interviews. For purposes of confidentiality, no reference to the names of the PGM mining companies and interviewees was made.

1.6.4 Data collection/fieldwork

The author conducted interviews to collect qualitative data. The aim of the qualitative part of the study was to determine how compressed air was managed at South African PGM operations. Quantitative data was collected from automated monitoring systems such as energy management systems and supervisory control and data acquisition (SCADA) systems. The aim of the quantitative data was to provide insight into the compressed air demand profiles of PGM operations.

1.6.5 Data coding and analysis

Qualitative data

Recordings of the semi-structured interviews were made with the consent of the interviewees. The interviews were transcribed whereafter ATLAS.ti, a qualitative data analysis software package, was used to code the transcribed interviews.

Quantitative data

The measured data collected from the PGM operations was converted to Microsoft Excel format, which enabled the creation of graphs. These graphs gave insight into compressed air demand profiles of PGM mineshafts and the impact of initiatives to reduce compressed air consumption.

1.6.6 Ethical considerations

The confidentiality of the information gathered through the interviews is guaranteed. No mining groups or names of individuals interviewed for this study were revealed. Interviewees participated on a voluntary basis and each interviewee signed an informed consent statement. Permission letters to conduct the research for this study were obtained from the two PGM mining groups.

1.6.7 Significance of the study

The outcome of this study is a framework that managers in the South African PGM sector can use to effectively manage the generation and consumption of compressed air. The anticipated result is reduced operational costs and a maintained compressed air system. This contributes to sustainability in South Africa's PGM sector. Another outcome of effectively managing compressed air in the PGM sector is that the expected reduction in electricity demand will also assist Eskom to meet South Africa's electricity needs, especially in peak demand periods.

1.7 Outline of the Dissertation

This dissertation consists of four chapters. More information about the contents of each of the chapters is provided below.

Chapter 1: Nature and scope of study

Chapter 1 provides an introduction to the study. The problem statement is provided and the research objectives are defined. An overview of the research methodology is also given.

Chapter 2: Literature review

This chapter starts with an overview of the PGM industry. Information on aspects such as the history of PGM mining in South Africa, global PGM production figures and the major role players in the industry is provided. This is followed by background information on the generation of compressed air and its various applications in PGM mining. Information on different energy savings measures on mine compressed air networks is also presented.

The chapter concludes with a literature review of research that focuses on individual energy savings initiatives implemented on mine compressed air networks.

Chapter 3: Empirical study

The purpose of this chapter is to provide information on the aspects of the empirical study. The chapter starts by providing information on the procedure and scope of the qualitative research. The results of the qualitative study are provided, starting with the demographic profile of the interviewees in terms of position, age, position and experience. This is followed by an analysis of the qualitative data, which is presented as six themes. Supplementary quantitative results are also presented, providing insight into the compressed air demand patterns of PGM operations and the impact of measures on reducing compressed air consumption. The chapter concludes with the presentation of the framework for managing compressed air in the PGM mining industry.

Chapter 4: Conclusion and recommendations

This chapter provides a summary of the entire study. Concluding remarks and suggestions for future work are given.

1.8 Conclusion

The PGM mining industry in South Africa is facing numerous challenges. Rising costs in combination with a low platinum price have resulted in the majority of PGM operations in South Africa being loss-making or marginal. Electricity supply is a major challenge due to electricity tariffs increasing above the inflation rate and Eskom's unreliable power supply. The PGM mining industry needs to become more energy efficient to ensure its sustainability in the long term. One area that should be targeted for energy efficiency improvements is compressed air systems, which is the industry's major electricity consumer. This study develops a framework for managing compressed air in the PGM mining industry. This framework contains practical strategic guidelines for managing compressed air networks on PGM mines in terms of improving energy efficiency and reducing maintenance costs.

1.9 Chapter Summary

Chapter 1 started by introducing the PGM mining sector in South Africa. The various challenges facing the PGM mining sector were highlighted. One of the challenges is rising costs, with higher than inflation electricity tariff increases being a major contributor. In addition, it was pointed out that Eskom's unreliable power supply poses a significant risk to the PGM mining industry. The generation of compressed air was established as the biggest electricity consumer on deep-level PGM mines. This motivated the primary objective of this study, i.e. the development of a framework to manage compressed air in the PGM mining sector. Two secondary research objectives were also set: i) developing a strategic guideline for improving energy efficiency in the PGM sector, and ii) developing a strategic guideline for monitoring and preventing the occurrence of events that result in increased compressors maintenance costs in the PGM mining sector. The rest of the chapter provided information on the limitations of the study, key concepts and the research design.

CHAPTER 2 – LITERATURE STUDY

2.1 Introduction

Chapter 2 begins by presenting an overview of the PGM mining industry in South Africa. The history of PGM mining in South Africa and the uses of PGMs are discussed, after which the focus moves to the historical and current PGM prices. Thereafter, the chapter provides information on different aspects of generating and using compressed air in the PGM sector. The operating principles of the centrifugal compressor, the most commonly used compressor type in the PGM industry, are explained. Information on compressed air networks and the uses of compressed air in the PGM industry are also provided. The chapter concludes with a literature study of various existing energy savings measures on compressed air networks in the mining industry.

2.2 Overview of the PGM Industry

2.2.1 History of PGM mining in South Africa

Hans Merensky identified a layer of platinum-containing rock in 1924 on the farm Maandagshoek, located north of Lydenburg in Mpumalanga (Hochreiter, Kennedy, Muir, & Wood, 1985:1). The discovery of this layer of rock, which later became known as the Merensky Reef, marks the discovery of the BIC, the richest PGM resource in the world (Cawthorn, 1999:178).

In 1925, Merensky managed to trace the Merensky Reef from Lydenburg in the east to Potgietersrus (now named Mokopane) in the north and Rustenburg in the west (Hunt, 1971:105). Merensky's discovery sparked commercial PGM mining operations near Steelpoort and Potgietersrus in 1926 (Buchanan, 1988:77). PGM mining of the Merensky Reef at Rustenburg started in 1929 (Grabe, 2002:1100; Hochreiter *et al.*, 1985:2).

The output of South African PGM mines continued to increase over the years in response to higher demand resulting from new applications being found for PGMs. PGM applications that notably increased demand included platinum jewellery in the 1960s and autocatalysts in the 1970s (Kendall, 2005:28; Morgan, 2014:217).

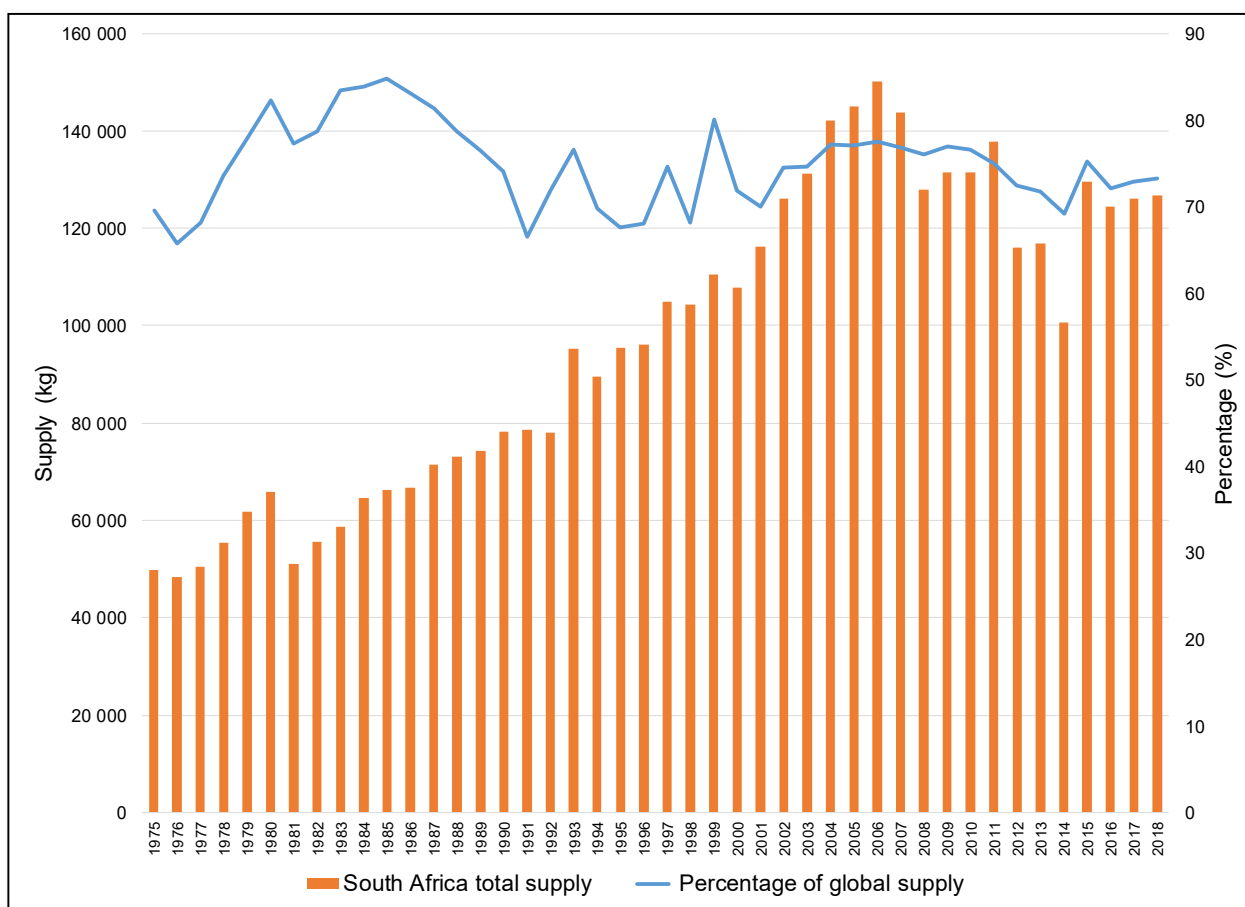


Figure 2-1: South Africa's total platinum supply and percentage of world supply (1975–2018)

Source: Compiled from Cowley (2019:1); Johnson Matthey (2015:1); Johnson Matthey (2016:1); Johnson Matthey (2019:1)

Figure 2-1 shows South Africa's total platinum supply in kilogram from 1975 to 2018 (Cowley, 2019:1; Johnson Matthey, 2015:1; Johnson Matthey, 2016:1; Johnson Matthey 2019:1). The secondary axis shows South Africa's supply as a percentage of the global supply. The supply of South African platinum peaked in 2006 at more than 150 000 kg. South Africa's highest percentage of global supply occurred in 1985 when it exceeded 85% of the global supply. In the period from 2015 to 2018, production remained stable with supply hovering around 125 000 kg per year, which accounts for 72–75% of the global supply.

2.2.2 Platinum group metals and uses

The six PGMs include platinum, palladium, rhodium, osmium, ruthenium and iridium. These metals have similar properties and often occur in the same deposits, which explains why platinum mines in South Africa also produce other PGMs such as palladium and rhodium (Schulz, DeYoung, Seal, & Bradley, 2018:N2). Platinum, palladium and rhodium are more important from an economic perspective due to their prices being higher than the rest of the PGMs. Figure 2-2 compares the 2018 global demand for five PGMs (excluding osmium) (Cowley, 2019: 1, 13, 21, 36).

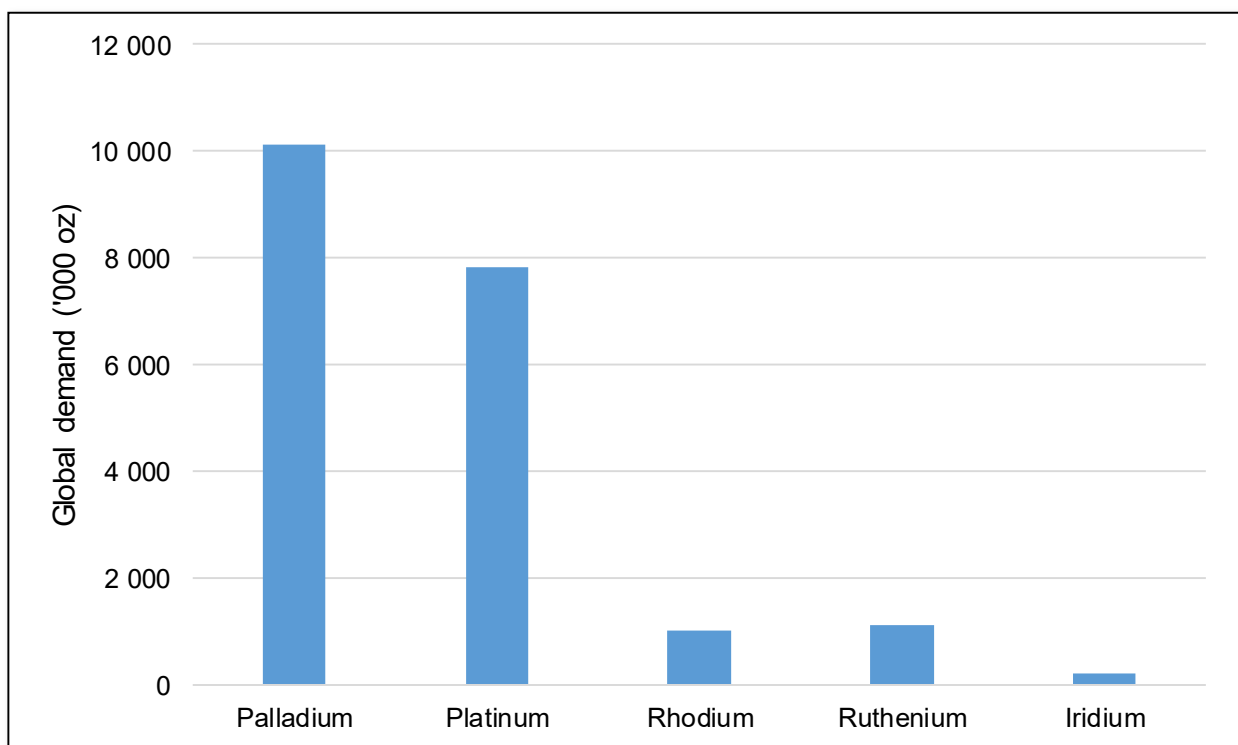


Figure 2-2: Global demand in 2018 for PGMs

Source: Cowley (2019:1, 13, 21, 36)

Palladium had the largest global demand in 2018 at more than 10 000 oz. The demand for platinum was just below 8 000 oz. Interestingly, the demand for ruthenium exceeded the demand for rhodium.

When platinum mining started in South Africa in the 1920s, the jewellery market accounted for almost two-thirds of the global platinum demand. The remainder of the

global platinum demand originated from the electrical and chemical industries and dental alloys (Kendall, 2005:28).

Figure 2-3 shows the distribution of the demand for platinum in 2018 (Cowley, 2019:1). Autocatalysts represented 39% of the global demand, followed by the jewellery and industrial industries with 30% each. Only 1% of the global demand was for investment purposes as could be expected during periods with low platinum prices.

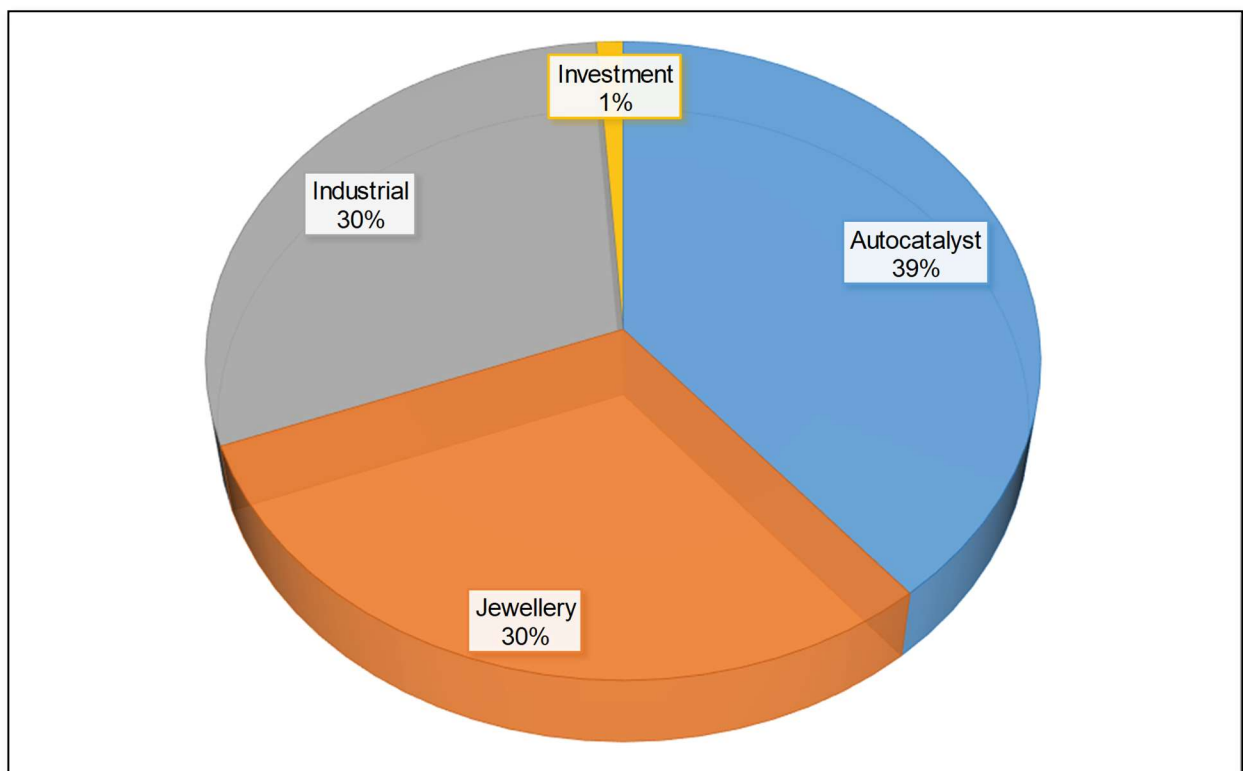


Figure 2-3: Platinum demand in 2018

Source: Cowley (2019:1)

The distribution of the industrial demand for platinum in 2018 is shown in Figure 2-4 (Cowley, 2019:3).

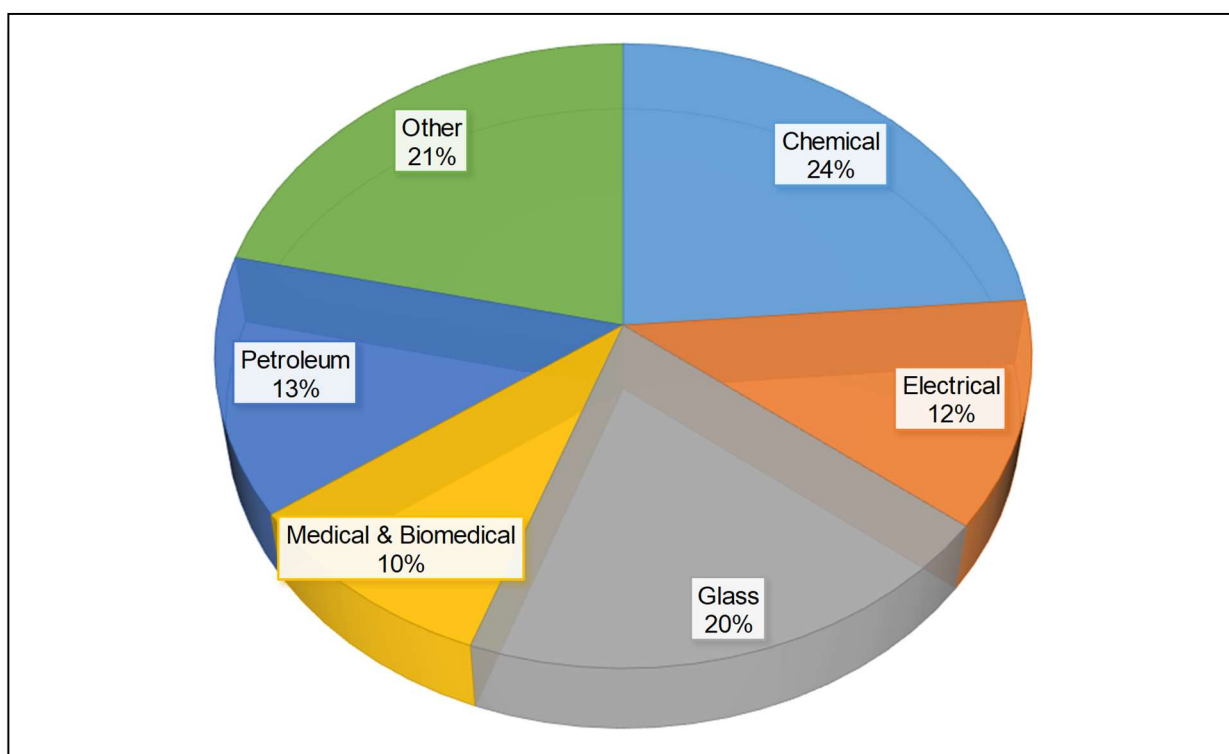


Figure 2-4: Industrial demand for Platinum in 2010

Source: Cowley (2019:3)

The automotive manufacturing industry is the biggest driver of the demand for palladium and rhodium. In 2018, autocatalysts represented 77% of the global demand for palladium and 85% of the global demand for rhodium (Cowley, 2019:19, 27). Almost all modern vehicles use autocatalysts to convert the toxic pollutants in exhaust gases to less toxic pollutants, nitrogen and water vapour (Morgan, 2014:218). Platinum is mainly used in autocatalysts for diesel-powered vehicles, while palladium and rhodium are predominantly used in autocatalysts for petrol-powered vehicles (Johnson Matthey, 2018:6).

2.2.3 Major role players

This section provides information on the major PGM mining companies. The purpose is to focus on the dominance of South African PGM companies in terms of the number of operations and production figures. The locations of the mining operations of each major PGM mining company are provided. Outside the BIC, major PGM mining operations are only located in Zimbabwe, North America, Canada and Russia.

Sibanye-Stillwater

Sibanye Gold was formed in 2012 due to Gold Fields unbundling its South African gold mining operations (Sibanye-Stillwater, 2018:30). Sibanye Gold entered the PGM mining sector in 2016 when it bought Amplats' Rustenburg operations (Sibanye-Stillwater, 2016:1). The firm's name changed to Sibanye-Stillwater after the acquisition of the North American Stillwater Mining Company in 2017 (Sibanye-Stillwater, 2017:1). Sibanye-Stillwater's latest acquisition, Lonmin, was concluded in June 2019 (Sibanye-Stillwater, 2019:1). Sibanye-Stillwater transformed from a South African gold mining company to the largest PGM producer in the world in a span of less than seven years.

Table 2-1 lists Sibanye-Stillwater's PGM-producing operations (Sibanye-Stillwater, 2018:4).

Table 2-1: Sibanye-Stillwater's PGM operations

Sibanye-Stillwater	
Operation	Location
Stillwater	51 km south of the town of Big Timber in the state of Montana, United States of America (USA)
East Boulder	
Rustenburg	Western limb of the BIC, near Rustenburg
Marikana	Western limb of the BIC, 40 km east of Rustenburg
Kroondal (joint venture with Amplats)	Western limb of the BIC, 12 km east of Rustenburg
Mimosa [joint venture with Impala Platinum (Implats)]	32 km west of Zvishavane, Zimbabwe

Source: Sibanye-Stillwater (2018:4)

Sibanye-Stillwater's Stillwater and East Boulder operations are the only PGM mining operations in the USA. Its South African operations include Rustenburg, Marikana and Kroondal, which are situated on the western limb of the BIC. Sibanye-Stillwater also owns a 50% stake in the Mimosa Mine in Zimbabwe, which is a joint venture with Implats.

Nornickel

Nornickel is the world's largest producer of palladium and nickel (Nornickel, 2018:4). In 2018, the company was also the fourth-largest producer of platinum and rhodium (Sibanye-Stillwater, 2018:29). Table 2-2 lists Nornickel's PGM-producing operations (Nornickel, 2018).

Table 2-2: Nornickel's PGM operations

Nornickel	
Operation	Location
Polar Division	Taimyr Peninsula, Siberia, Russia
Norilsk Nickel Nkomati [joint venture with African Rainbow Minerals (ARM)]	Near Machadodorp, Mpumalanga

Source: Nornickel (2018)

Nornickel's major PGM-producing operations consist of six mines that are collectively known as the Polar Division. The Polar Division is situated in the Taimyr Peninsula in Russia's Siberia province (Nornickel, 2018:29). Nornickel jointly owns and operates the Nkomati Mine, near Machadodorp in Mpumalanga, in partnership with ARM (Nornickel, 2018:88).

Amplats

Amplats was the world's largest producer of platinum until June 2019 when it was surpassed by Sibanye-Stillwater as a result of the Lonmin acquisition (Jamasmie, 2019). Table 2-3 lists the company's operations (Amplats, 2018:56).

Table 2-3: Amplats' PGM operations

Amplats	
Operation	Location
Amandelbult	Northern end of the western limb of the BIC near Thabazimbi
Mogalakwena	30 km north-west of Mokopane in the Limpopo Province

Amplats	
Operation	Location
Mototolo	30 km west of Burgersfort in the Limpopo Province
Unki	60 km south-east of Gweru, Zimbabwe
Modikwa (joint venture with ARM)	25 km west of Burgersfort in the Limpopo Province
Kroondal (joint venture with Sibanye-Stillwater)	Western limb of the BIC, 12 km east of Rustenburg

Source: Amplats (2018:56)

Amplats has multiple operations on both the eastern and western limbs of the BIC. Its Mogalakwena Mine is situated on the northern limb of the BIC. Amplats also mines in Zimbabwe at its Unki operation.

Implats

Implats was founded in 1966 when the company established its first mine near Rustenburg (Black, 2000:102). In 2018, Implats was the world biggest producer of rhodium (Sibanye-Stillwater, 2018:29). Table 2-4 lists Implats' PGM operations (Implats, 2018b:2).

Table 2-4: Implats' PGM operations

Implats	
Operation	Location
Impala	Western limb of the BIC near Rustenburg
Zimplats	Great Dyke south-west of Harare
Marula	Eastern limb of the BIC, 50 km north-west of Burgersfort
Mimosa (joint venture with Sibanye-Stillwater)	32 km west of Zvishavane, Zimbabwe
Two rivers (joint venture with ARM)	Southern part of the eastern limb of the BIC, 35 km south-east of Burgersfort

Source: Implats (2018b:2)

Implats' South African operations include ten operational shafts on the western limb of the BIC near Rustenburg as well as Marula Mine on the eastern limb of the BIC. Implats further owns 50% of the Two Rivers Mine in a joint venture with ARM. Implats mines in Zimbabwe through its Zimplats operation and Mimosa Mine, which is a joint venture with Sibanye-Stillwater.

Northam

Northam Platinum opened its first mine in 1993 (Black, 2000:102). Table 2-5 lists Northam's major PGM operations (Northam Platinum, 2018:4).

Table 2-5: Northam's major PGM operations

Northam Platinum	
Operation	Location
Zondereinde	Northern end of the western limb of the BIC near Thabazimbi
Booyseindal	Eastern limb of the BIC near Mashishing, Mpumalanga
Eland	Eastern end of the western limb of the BIC

Source: Northam Platinum (2018:4)

Northam's two flagship operations are Zondereinde and Booyseindal (Northam Platinum, 2018:4). Northam also owns the Eland Mine located on the eastern end of the western limb of the BIC. Eland was acquired from Glencore in January 2018 (Northam Platinum, 2018:10).

Royal Bafokeng Platinum

Royal Bafokeng Platinum (RBPlat) produced its first platinum in 1999 (RBPlat, 2018:64). The company owns the Bafokeng Rasimone Platinum Mine and Styldrift Mine, located on the western limb of the BIC near the town of Boshhoek.

North American Palladium

North American Palladium is a Canadian mining company that mainly produces palladium. The company's palladium production originates from the Lac des Iles mine, located in the north-western part of Canada's Ontario province. Mining at Lac des Iles

started in 1993 and comprises both open-pit and underground operations (North American Palladium, 2017:42). On 7 October 2019, Implats announced that it entered into an agreement to buy North American Palladium for US\$758 million (Implats, 2019b:1).

2.2.4 Production figures

Figure 2-5 shows the top six global platinum, palladium and rhodium producers in 2018 (Sibanye-Stillwater, 2018:29).

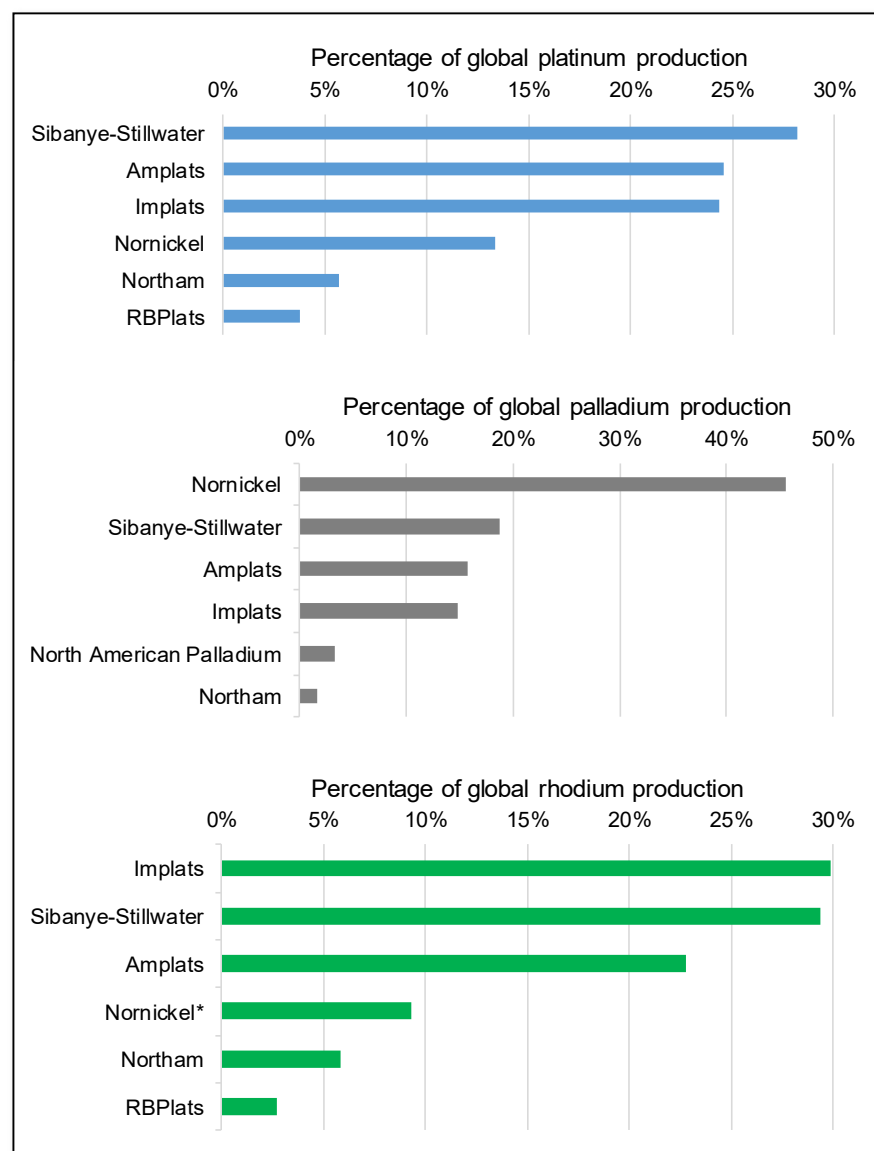


Figure 2-5: Top six platinum, palladium and rhodium producers in 2018

Source: Sibanye-Stillwater (2018:29)

Note that the production figures reported for Sibanye-Stillwater are the sum of the company's actual production and Lonmin's production figures for 2018. This was done to provide an accurate representation of the production figures of the current PGM landscape after the acquisition of Lonmin by Sibanye-Stillwater in June 2019. Sibanye-Stillwater was the largest platinum producer in 2018, followed by Amplats and Implats. Nor Nickel and Implats were the largest palladium and rhodium producers, respectively, in 2018.

2.2.5 *State of the industry*

PGM prices

Figure 2-6 shows the US dollar prices for platinum, palladium and rhodium from January 2003 to August 2019 (Johnson Matthey, 2019). It is evident that the PGM industry experienced a prosperous period from 2006 to 2008 with steadily rising PGM prices. In June 2008, the price of platinum was more than \$2 000 per ounce, rhodium exceeded \$5 000 per ounce, and palladium touched on \$1 700 per ounce. Inevitably, the global financial crisis affected the PGM industry when prices dropped significantly towards the end of 2008. PGM prices recovered somewhat in 2010/2011 but declined steadily from the end of 2011 to 2017. Although the platinum price remains low, the price of rhodium fortunately started to increase again in June 2017, with palladium following suit in September 2018.

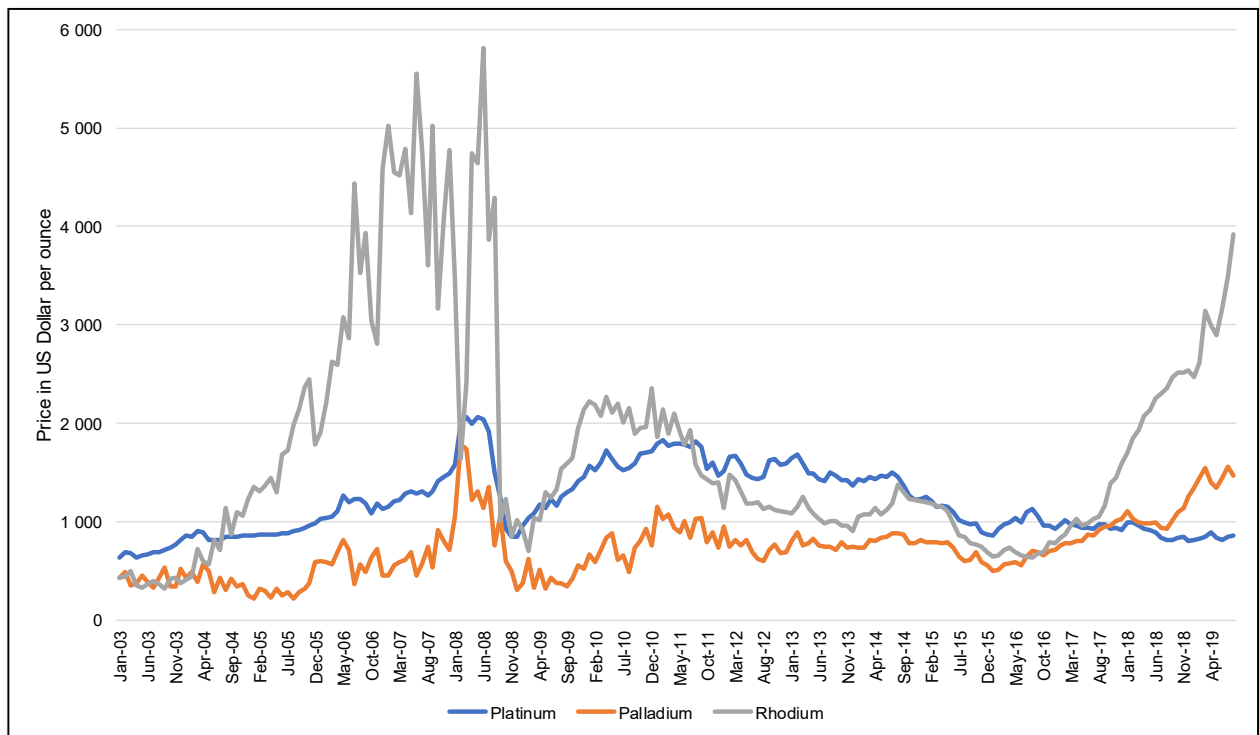


Figure 2-6: Platinum, palladium and rhodium prices in US dollar (Jan 2003 to Aug 2019)

Source: Compiled from Johnson Matthey (2019)

The depreciation of the rand against the US dollar helped South African PGM mines to stay afloat in the difficult period from 2011 to 2017. In order to obtain a better understanding of the influence of the depreciation of the rand, consider Figure 2-7 that shows the prices of platinum, palladium and rhodium from January 2015 to August 2019 (Johnson Matthey, 2019; South African Reserve Bank, 2019). The rand price of rhodium at the end of August 2019 was 274% higher than in August 2017, while the rand price of palladium was 58% higher than in August 2018. Unfortunately, the rand price of platinum in August 2019 was 13% lower than in January 2015.

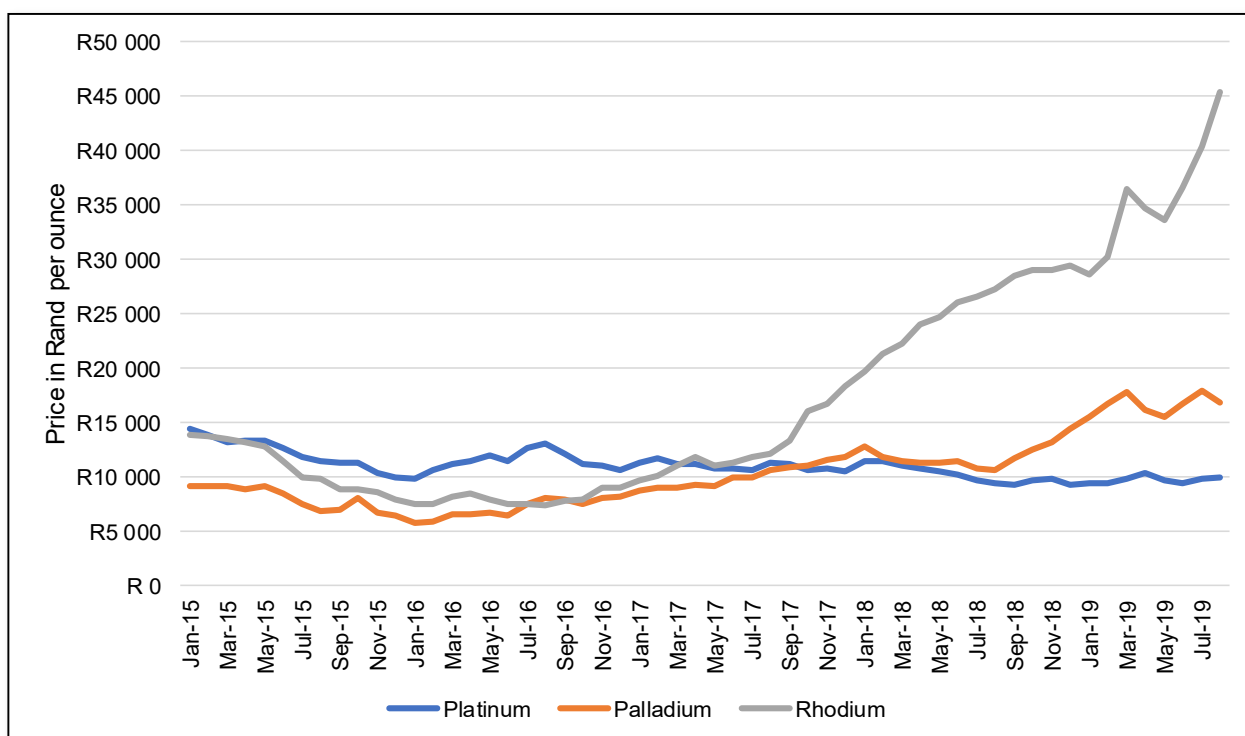


Figure 2-7: Prices of platinum, palladium and rhodium in rand (Jan 2015 to Aug 2019)

Source: Johnson Matthey (2019); South African Reserve Bank (2019)

The increase in palladium and rhodium prices have had a significant effect on South Africa's PGM producers. For example, consider the impact of the price increase on Implats. The company's production figures for the 2019 financial year are shown in Figure 2-8 (Implats, 2019a:2). Implats produced more than 1 520 000 oz of platinum in the 2019 financial year, accounting for 58% of its PGM production. The rest of its PGM production consisted of palladium (34%) and rhodium (8%).

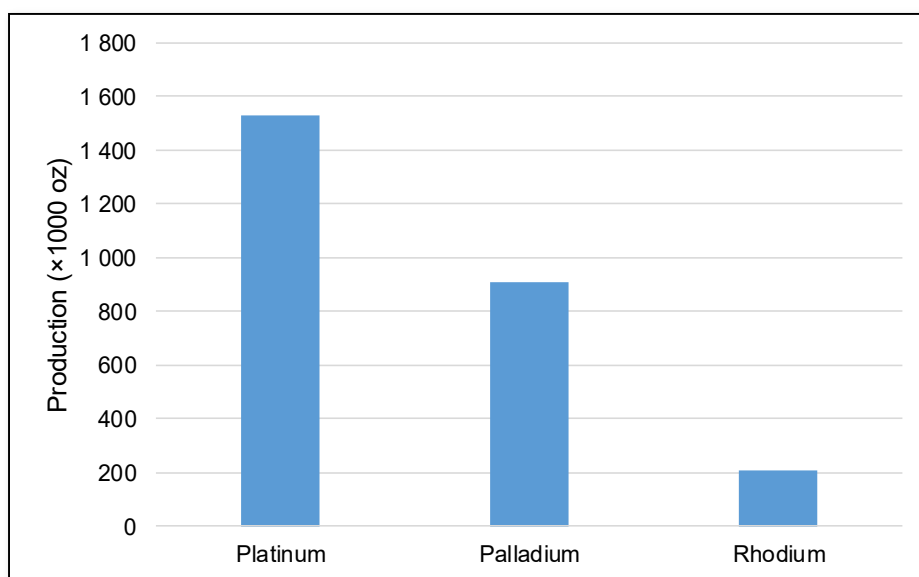


Figure 2-8: Implats' gross refined production figures for the 2019 financial year

Source: Implats (2019a:2)

Figure 2-9 shows the impact of the higher palladium and rhodium prices (Implats 2019a:2). For comparison purposes, the total rand value of Implats' 2019 PGM production is shown in terms of the average platinum, palladium and rhodium prices for the month of August from 2015 to 2019.

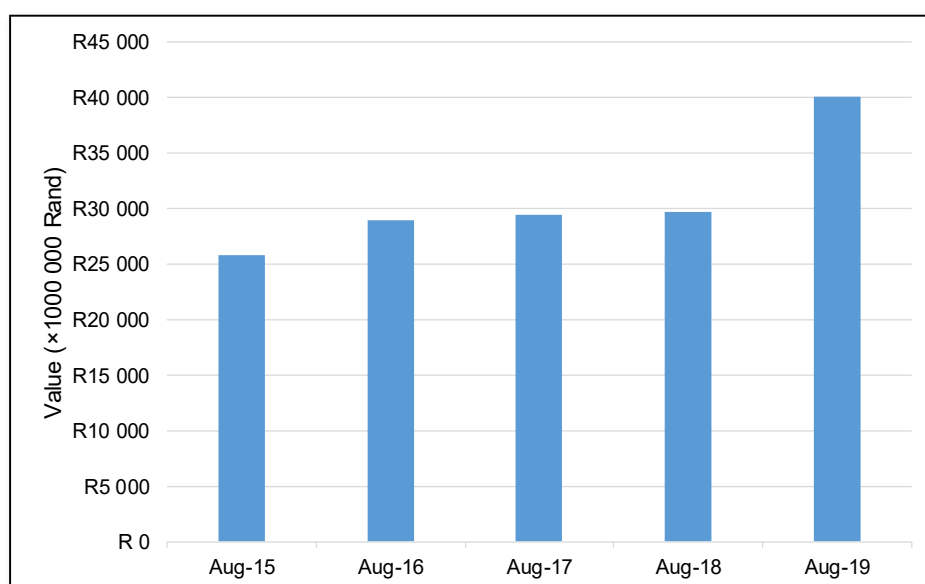


Figure 2-9: Year-on-year comparison: Impact of the value of Implats' production

Source: Implats (2019a:2)

The August 2016 value is higher than the August 2015 value due to the higher platinum and palladium prices. The values for August 2016, August 2017 and August 2018 are fairly similar. The combination of the growth in palladium and rhodium prices in the period from August 2018 to August 2019 resulted in a 35% increase in the total value of Implants' production in the 2019 financial year.

Supply and demand

The recent increases in rhodium and palladium prices and the lacklustre price of platinum can be explained by considering the global supply and demand of these metals as shown in Table 2-6 (Cowley, 2019:1, 19, 27). Platinum had the highest surplus of 373 000 oz, which explains why the platinum price has not increased. There was also a 65 000 oz surplus of rhodium, but it was much lower than that of platinum. Palladium had a deficit of 121 000 oz. The small rhodium surplus and palladium deficit motivate the current high prices of these two metals.

Table 2-6: Global supply and net demand in 2018 for platinum, palladium and rhodium

	Platinum	Palladium	Rhodium
Supply ('000 oz)	6 113	6 977	757
Net demand ('000 oz)	5 741	7 098	692
Surplus/deficit ('000 oz)	372	-121	65

Source: Cowley (2019:1, 19, 27)

As shown in Figure 2-3, the autocatalyst industry is the biggest driver of platinum demand. Platinum is predominantly used in catalytic converters of diesel-powered vehicles, while palladium and rhodium are mainly used in catalytic converters of petrol-powered vehicles (Cowley, 2019; Treadgold, 2019:27). The Dieselgate scandal had a negative effect on the demand for diesel-powered vehicles, especially in Europe with its extremely strict emissions standards (Campbell, 2016; Kassow & Braasch, 2019). The European market is therefore buying more petrol-powered vehicles. The resulting effects are a lower demand for platinum and a higher demand for palladium and rhodium.

Influence of recycling

The recycling of PGMs from autocatalysts is more cost-effective than mining (Lifton, 2016), which has made a significant impact on the demand for PGMs. Figure 2-10 shows how the amounts of recycled platinum, palladium and rhodium have increased from 2004 to 2018 (Cowley, 2019:1; Johnson Matthey, 2016:1; Johnson Matthey, 2019).

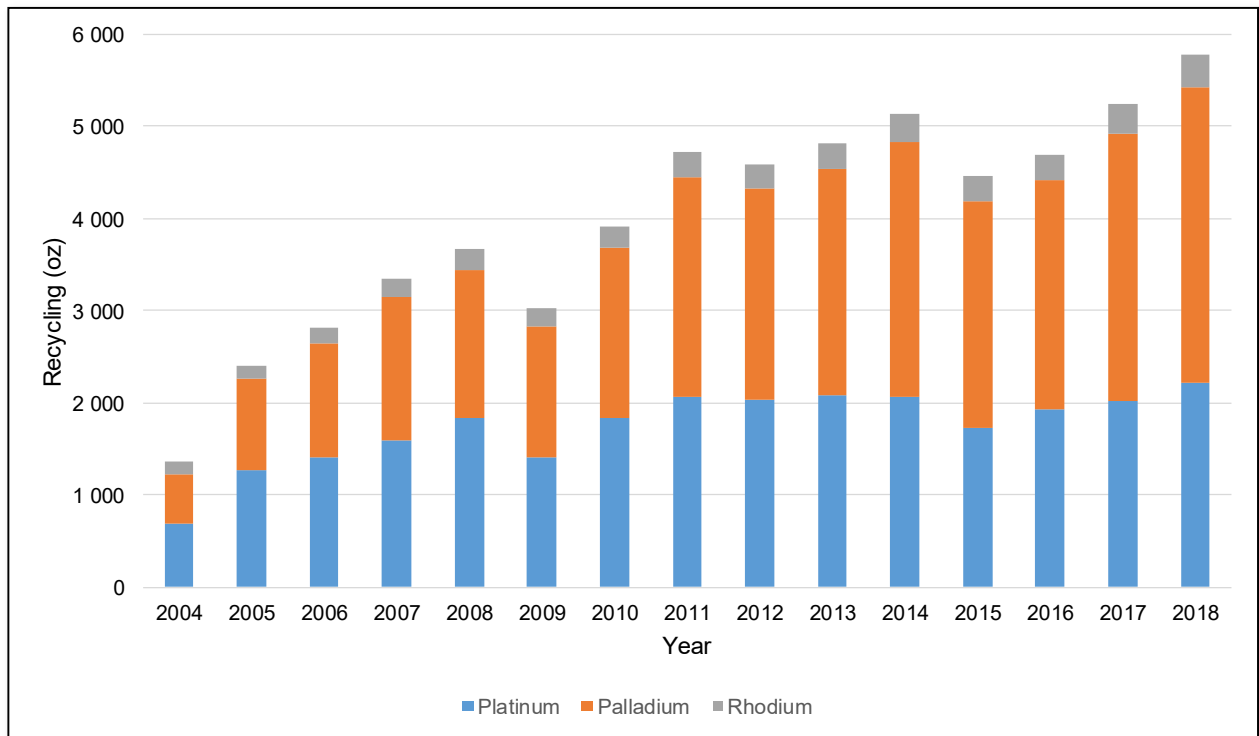


Figure 2-10: Recycling of platinum, palladium and rhodium

Source: Compiled from Cowley (2019:1); Johnson Matthey (2016:1); Johnson Matthey (2019)

Table 2-7 shows the percentages of the global demand that were recycled in 2018 (Cowley, 2019:1, 19, 27).

Table 2-7: Recycling as a percentage of global net demand in 2018

	Platinum	Palladium	Rhodium
Gross demand ('000 oz)	7 846	10 222	1 026
Recycling ('000 oz)	2 105	3 124	334
Recycling percentage	26.83%	30.56%	32.55%

Source: Adapted from Cowley (2019:1, 19, 27)

Platinum had the lowest recycling percentage with 26.83%, followed by palladium with a recycling percentage of 30.56%. Rhodium had the highest recycling percentage at 32.55%.

2.3 Compressors and Compressed Air Networks

2.3.1 Basic compressor operating principles

The purpose of a compressor is to increase the pressure of atmospheric air (or some other gas) by reducing its volume. There are three basic types of compressors:

- Reciprocating compressors
- Rotary screw compressors
- Centrifugal compressors

Figure 2-11 demonstrates the basic operation of a reciprocating compressor (Bloch & Hoefner, 1996: 33).

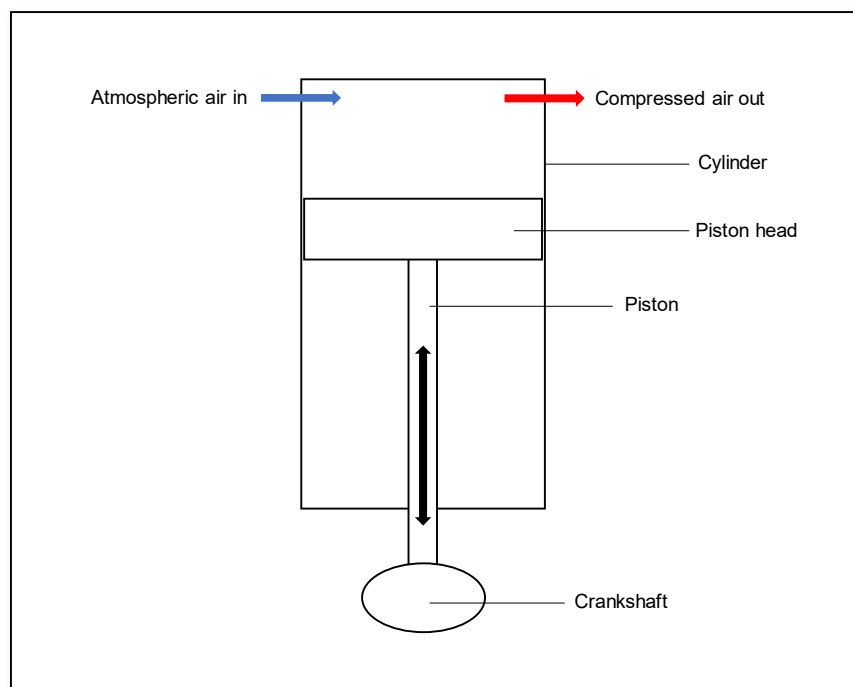


Figure 2-11: Basic operating principle of a reciprocating compressor

Source: Adapted from Bloch & Hoefner (1996:33)

It consists of a piston, which is connected to a crankshaft. The crankshaft drives the piston to compress gas. The rotating crankshaft enables the piston to move up and down inside the cylinder. When the piston head moves down, atmospheric air is drawn into the cylinder. When the piston head moves up inside the cylinder, the atmospheric air is compressed because its volume is reduced. The compressed air is released, and the cycle is repeated. Reciprocating compressors are often used in automotive workshops or at filling stations for pumping vehicle tyres.

Figure 2-12 demonstrates the basic working principle of a rotary screw compressor (Stosic, Smith, Kovacevic, & Mujic, 2011:3). It uses two rotating rotors to compress air. Atmospheric air fills the space between the two rotors. As the rotors turn in opposite directions, the space or volume between the rotors is reduced and the air is compressed (Stosic *et al*, 2011:2).

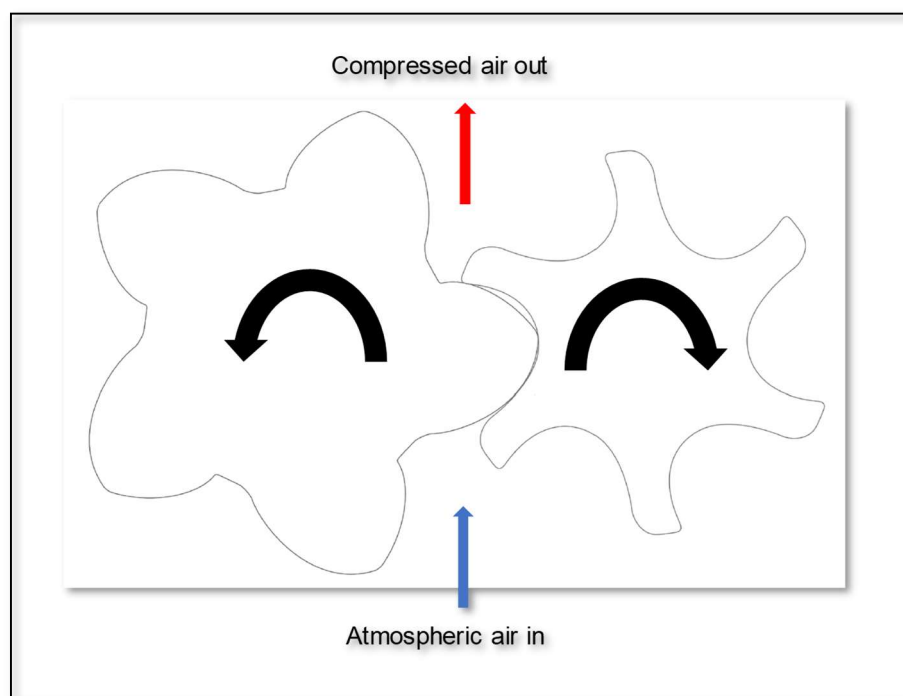


Figure 2-12: Basic operating principle of a rotary screw compressor

Source: Adapted from Stosic *et al.* (2011:3)

Figure 2-13 illustrates the basic working principle of a centrifugal compressor (Bairwa, 2017). It uses centrifugal forces to compress air. Atmospheric air enters the compressor

through the inlet pipe. The rotating impeller applies centrifugal forces on the air, pushing the air outward. The compressed air exits through the discharge pipe.

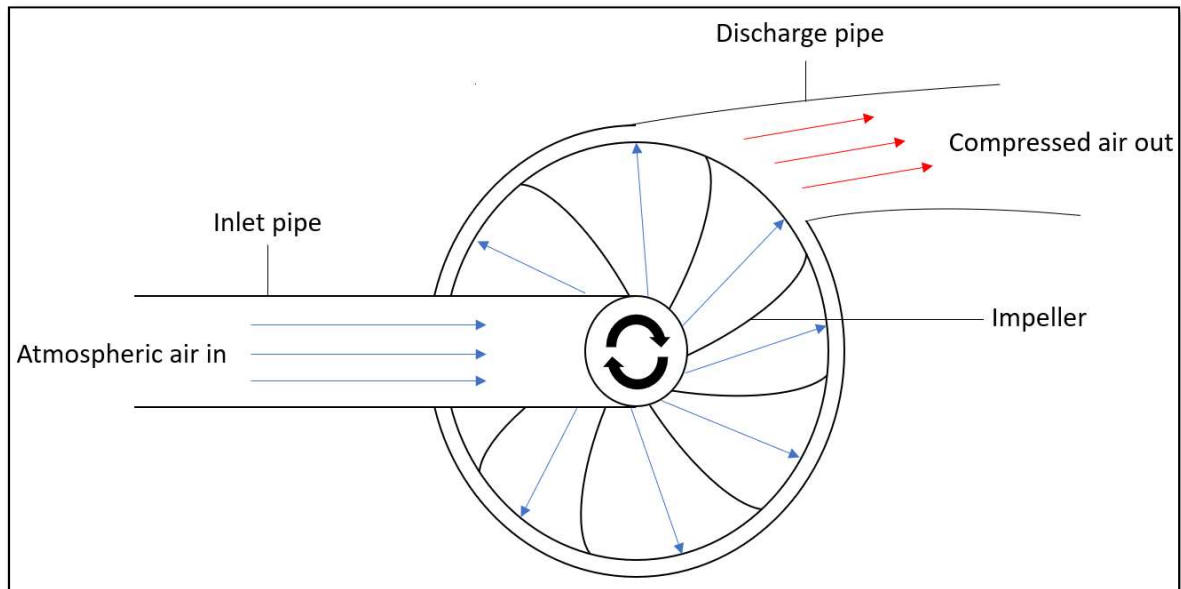


Figure 2-13: Basic operating principle of a centrifugal compressor

Source: Adapted from Bairwa (2017)

Centrifugal compressors are the most common compressor type used in deep-level mines for the following reasons:

- Centrifugal compressors supply large volumes of compressed air at relatively high discharge pressures (Kidnay, Parrish & McCartney, 2011:77).
- The output pressures and output volumes of a centrifugal compressor can be varied with inlet guide vane control. This is a useful feature in mines where the demand for compressed air in terms of pressure and volume varies throughout the different mining shifts.

The next section provides more detailed information on centrifugal compressors.

2.3.2 Centrifugal compressors

Introduction

A single-stage centrifugal compressor uses a single impeller, while a multi-stage compressor consists of more than one impeller. The advantage of multi-stage compressors is that they are more effective at producing large volumes of compressed air. Figure 2-14 shows a cutout of a centrifugal compressor with three stages (Elliot Group, 2017:9). The three impellers, one for each stage, are clearly visible.

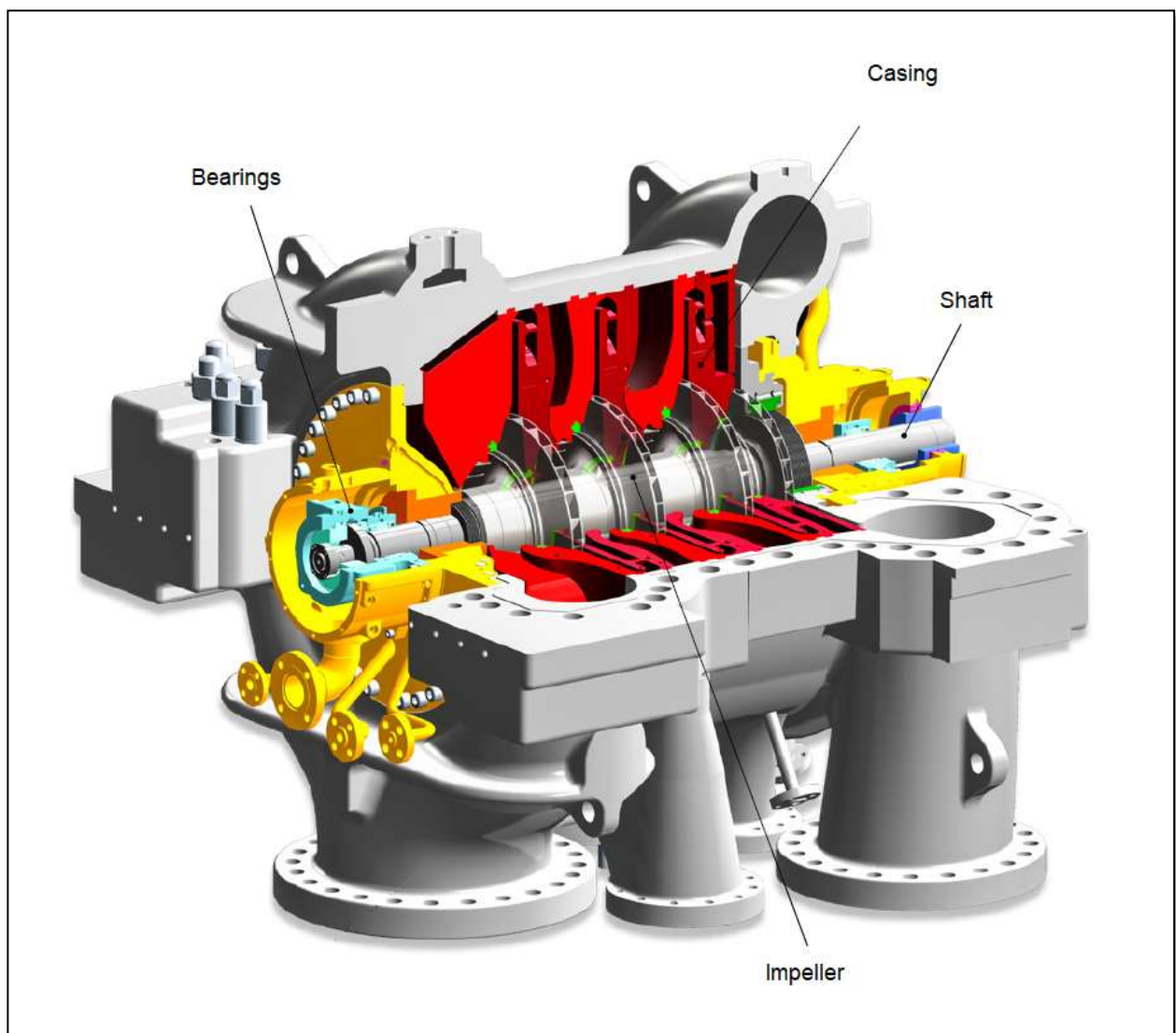


Figure 2-14: Cut-out of a three-stage centrifugal compressor

Source: Adapted from Elliot Group (2017:9)

Figure 2-15 shows a photo of a multi-stage centrifugal compressor with an installed capacity of 15 MW. This is the largest compressor that is currently being used at a South African PGM operation (Marais, 2012:2). To put the size of this compressor in perspective, it annually consumes more electricity than 15 000 average South African households (Chehore, 2014).



Figure 2-15: Multi-stage compressor with an installed capacity of 15 MW

Source: Photo taken by B. Pascoe

Inlet guide vane control

Inlet guide vanes control the volume of air at the intake of the centrifugal compressor, which affects the output volume and output pressure of the compressor. Inlet guide vanes also affect the electricity consumption of a centrifugal compressor. When in the fully open position, the guide vanes are parallel to the direction of the airflow and allow maximum airflow. When in the fully closed position, the guide vanes are perpendicular to the direction of the airflow and no air is drawn into the compressor. Figure 2-16 compares guide vanes in the fully closed and partially open positions (PBN, 2019; Stasyshan & Kassin, 2019).

Under no-load conditions, the guide vanes are completely closed and the blow-off valve is fully open. A compressor consumes 40% less power when running under no-load conditions (Booyesen *et al.*, 2009:66). This is analogous to a motor vehicle that consumes more fuel when it is heavily loaded versus the same vehicle using less fuel when carrying a lighter load.

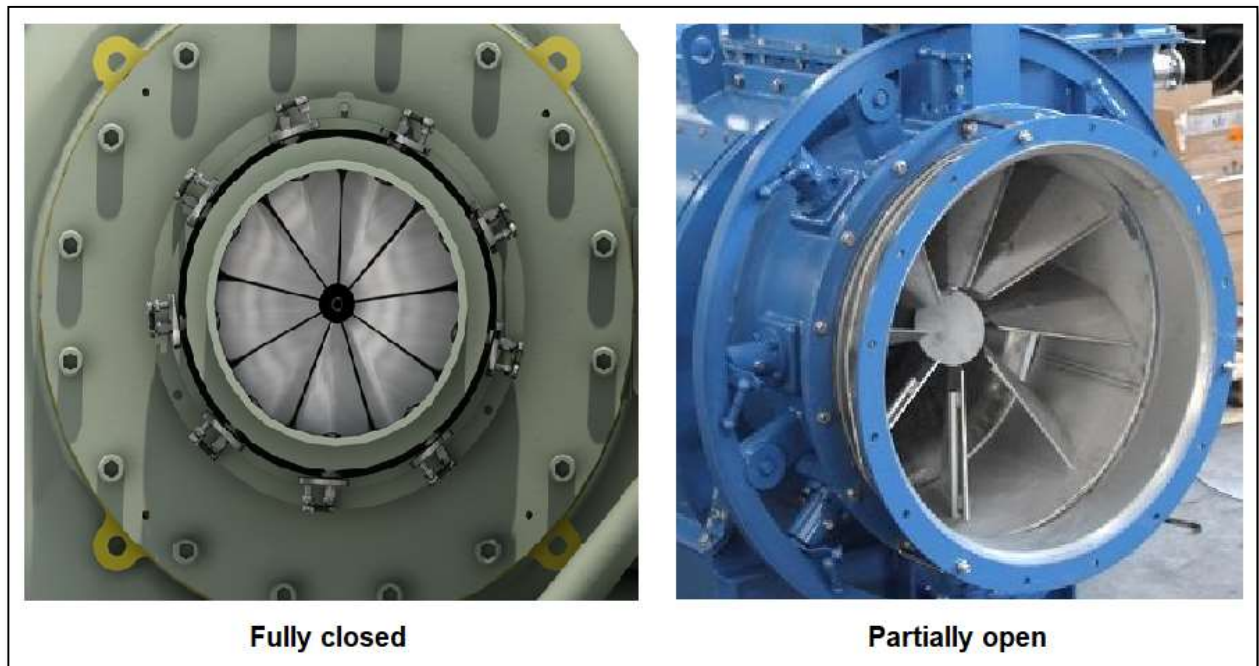


Figure 2-16: Inlet guide vanes in different positions

Source: Adapted from PBN (2019); Stasyshan & Kassim (2019)

The significance of inlet guide vanes is that they allow a compressor's output volume of compressed air and electricity consumption to be controlled according to the demand for compressed air. When the maximum volume of compressed air is required, the guide vanes should be opened fully, and the electricity consumption of the compressed will reach its maximum. When less compressed air is required, the guide vanes should be used to restrict the volume of atmospheric air at the intake of the compressor, resulting in less compressed air being delivered, which reduces electricity consumption. The magnitude of the reduced electricity consumption varies according to the guide vane position.

Compressor surge

A centrifugal compressor surges when the flow through the compressor is reversed (McLin, 2012). Surging is highly undesirable and could result in mechanical damage if it occurs frequently for extended time periods. Surging occurs when the output pressure of the compressor is lower than the pressure in the network into which it supplies compressed air. In other words, surging occurs when the output pressure of the compressor is lower than the backpressure of the compressed air network.

A compressor map is a chart that plots the operating characteristics of a centrifugal compressor in terms of the relationship between mass flow and the ratio between the discharge and suction pressure. The compressor map also indicates the surge line. An automated compressor control system monitors the operating point of the compressor on the compressor map. When the operating point nears the surge line, the automated compressor control system prevents surging by using the inlet guide vanes and blow-off valve to move the operating point away from the surge line (Kvangardsnes, 2009:9). A compressor map showing the surge line is provided in Figure 2-17 (McLin, 2017).

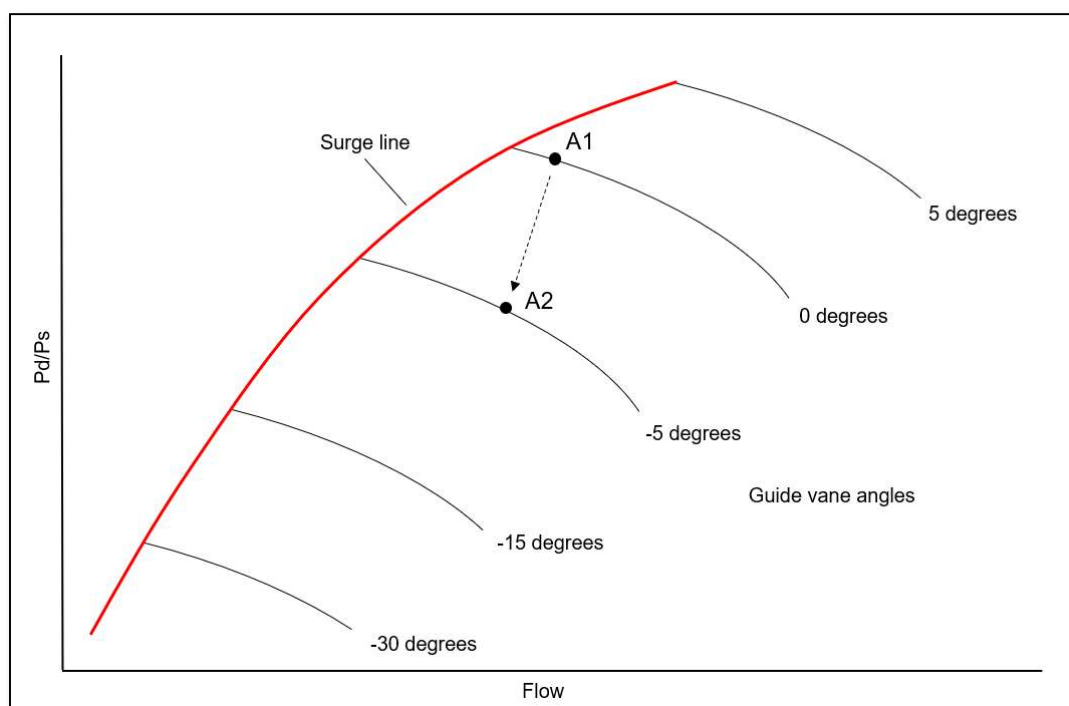


Figure 2-17: Compressor map

Source: Adapted from McLin (2012)

The ratio between the discharge and suction pressure (indicated as P_d and P_s) is shown on the y-axis and the flow is shown on the x-axis. The surge line is shown in red. Figure 2-17 can also be used to demonstrate how guide vane angles could be adjusted to prevent surging. For example, if the operating point of the compressor moves along the zero-degree guide vane angle towards the surge line (Position A1), adjusting the guide vane angle to -5 degrees ensures that the operating point moves away from surge line (Position A2).

Inlet guide vanes are the first line of defence against surging. When backpressure starts to build up, the inlet guide vanes reduce the flow of air at the inlet of the compressor. If the operating point moves closer the surge line despite the guide vanes cutting back, the blow-off valve, also known as an anti-surge valve, is ultimately used to prevent surging. When the operating point of the compressor nears the surge line despite the guide vanes cutting back, the blow-off valve opens and excess pressure is released to the atmosphere. The blow-off valve therefore ensures that excess air is released to the atmosphere before it causes a flow reversal inside the compressor.

2.3.3 Compressed air networks

Figure 2-18 shows a diagram of a typical compressed air network. One of the largest compressed air networks on a South African PGM operation spans more than 15 km between its two furthest consumers.

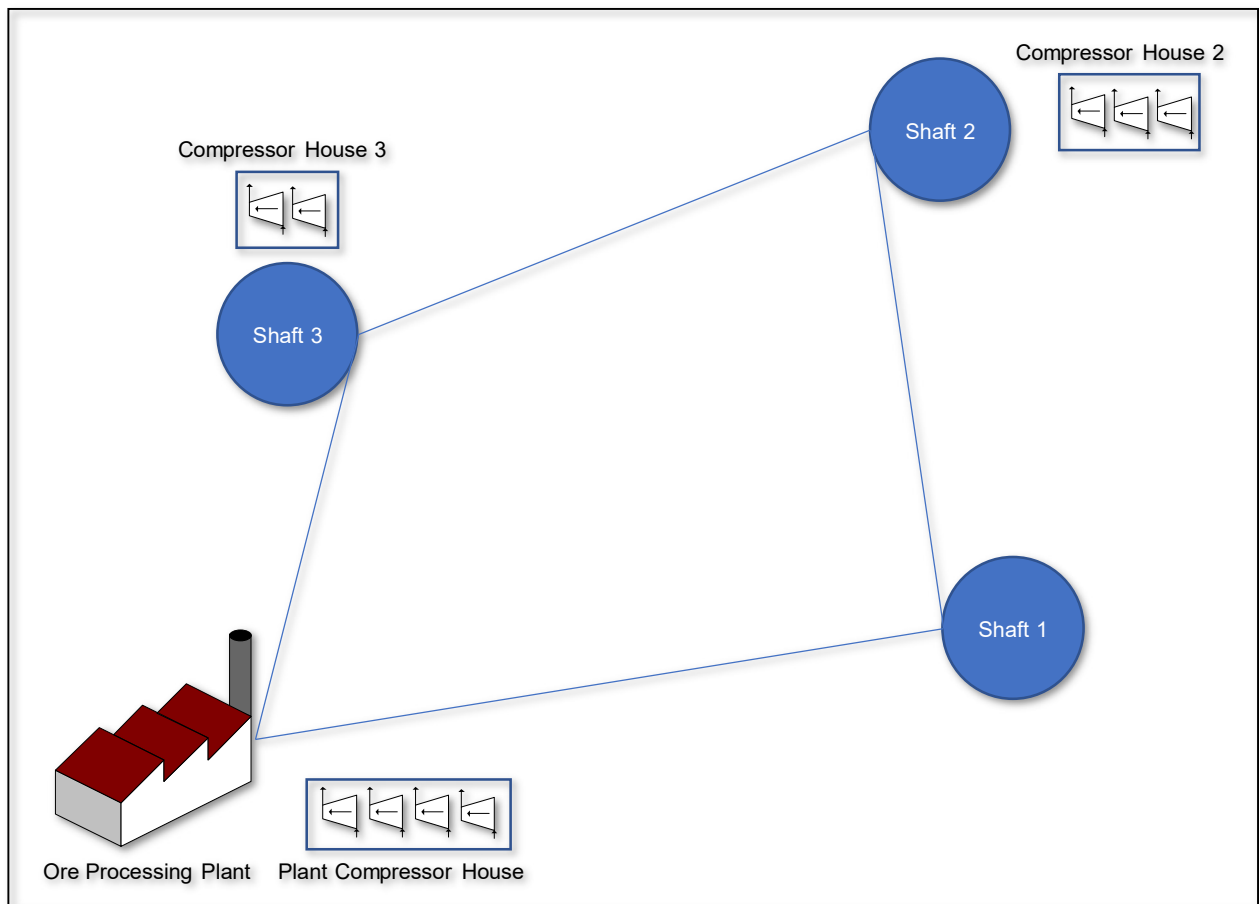


Figure 2-18: Typical compressed air network layout

On PGM mining operations, centrifugal compressors are installed in groups. Such a group of compressors is typically located inside a large enclosed structure called a compressor house. A compressor house typically contains between two and six compressors. A compressed air network, also known as a compressed air ring, consists of multiple compressor houses connected through a network of pipes. Instead of only supplying a single mineshaft, the compressors work together to pressurise the entire network. The network supplies various users such as mineshafts and mineral processing plants with compressed air.

Figure 2-19 shows a photo of compressed air piping that forms part of a large compressed air ring on a South African PGM mining operation. The advantage of a compressed air network is redundancy. If a single compressor breaks down on the network, the other compressors on the ring augment the supply of compressed air to prevent production from being interrupted.



Figure 2-19: Compressed air pipe forming part of a compressed air network

Source: Photo taken by researcher

The disadvantages of a compressed air network are the following:

- Different consumers on the network could have different compressed air requirements. The problematic aspect is that the pressure inside the compressed air ring should be kept at the pressure requirement of the highest consumer. Therefore, other consumers on the compressed air ring are oversupplied with compressed air.
- The long distances between the compressed air consumers imply an extended network of compressed air pipes that need to be maintained to prevent leaks. The extended networks also increase pipe friction losses.

2.4 Uses of Compressed Air in PGM Mining Operations

This section provides an overview of the major uses/consumers of compressed air in the PGM mineshafts.

2.4.1 Drilling

The main purpose of compressed air in the PGM mining sector is powering pneumatic rock drills. The rock drills are used to drill holes in the rockface being mined. The holes are filled with explosives and detonated to dislodge the ore from the rockface. Figure 2-20 shows a photo of a rock drill operator using a pneumatic rock drill in a South African mine (Meeran & Martin, 2016).



Figure 2-20: Rock drill operator in a South African mine

Source: Meeran & Martin (2016)

Pneumatic drills consume large volumes of air and require compressed air at high pressures (typically more than 500 kPa). The penetration rates of rock drills are directly related to the supply pressure (Bester, Le Roux & Adams, 2013:62).

2.4.2 Loaders

The blasted rock is removed from the stopes with compressed air powered loaders, also known as rocker shovels (Meek, 2009:217).

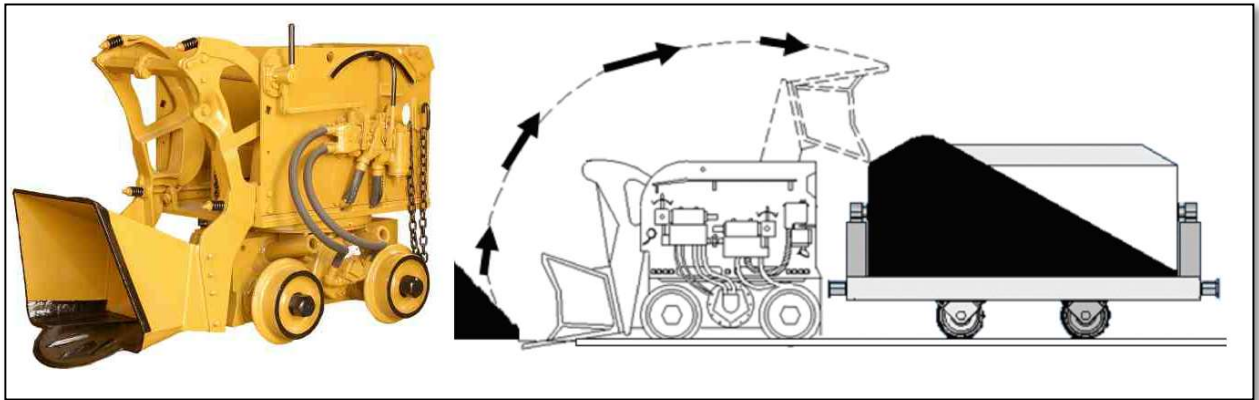


Figure 2-21: Compressed air powered rocker shovel

Source: Adapted from Meek (2009:218); Trident SA (2019)

Figure 2-21 shows a photo of a loader and a diagram that demonstrates its operation (Meek, 2019:218; Trident SA, 2019). The blasted rock is scooped up and flung overhead to load it onto a mine cart (known as a hopper at South African PGM mines).

2.4.3 Pneumatic cylinders

Pneumatic cylinders are used to power various types of equipment in the PGM industry. Examples of these equipment include:

- Loading box doors and chutes
- Scraper winches
- Stopping devices
- Valve actuators

Figure 2-22 shows a photo of a Technopost stopping device powered by a pneumatic cylinder (Deebar, 2019:1).

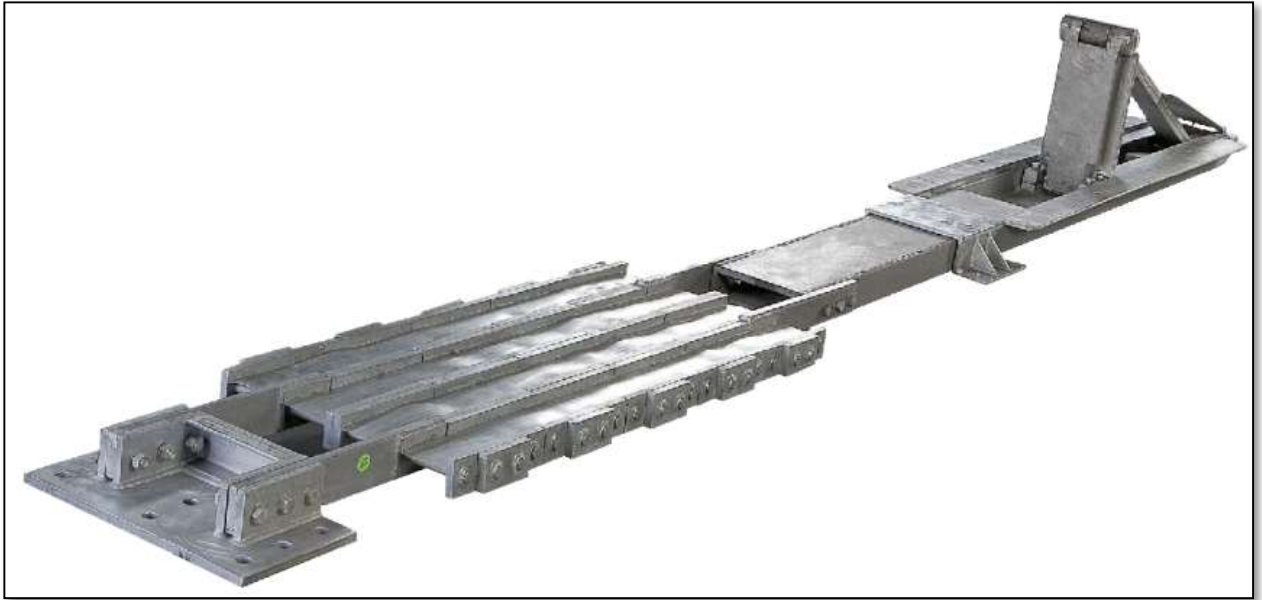


Figure 2-22: Technopost stopping device

Source: Adapted from Deebbar (2019:1)

The purpose of a Technopost is to prevent underground locomotives or hoppers from crossing the statutory boundary around the station (the area on a mining level around the shaft) and falling down the shaft (Deebbar, 2019:1).

Figure 2-23 shows a pneumatic cylinder that powers a loading box door.

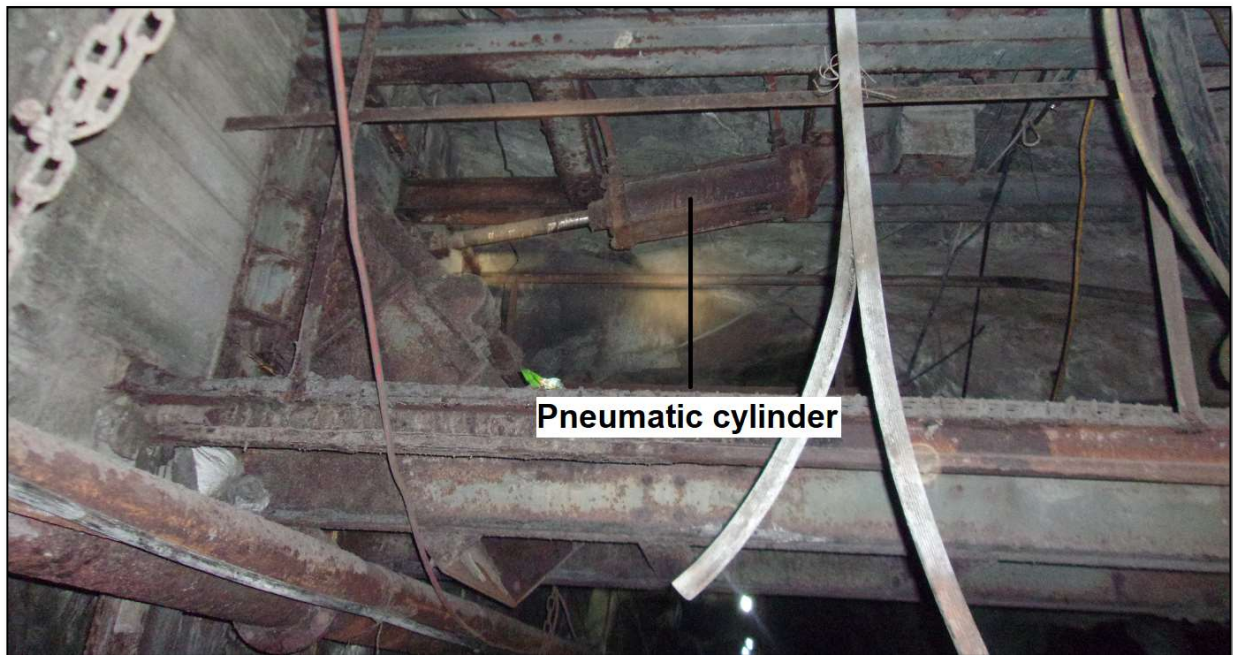


Figure 2-23: Pneumatic cylinder that powers a loading box door

Source: Photo taken by researcher

A loading box is used for vertical hauling of the blasted ore between mining levels. It forms part of the underground ore handling system that entails transporting blasted ore from the depths of the mine to the surface.

2.4.4 Refuge bays

The Mine Health and Safety Act (South Africa, 2014:5) requires that readily available refuge bays should be provided in the underground workings of mines. A refuge bay or refuge chamber is a demarcated area inside the mine where miners seek refuge during emergencies (Lehnen, Rattmann & Martens, 2015:236). Compressed air is supplied to the refuge bays on a continuous basis. Figure 2-24 shows a compressed air supply line inside an underground refuge bay.

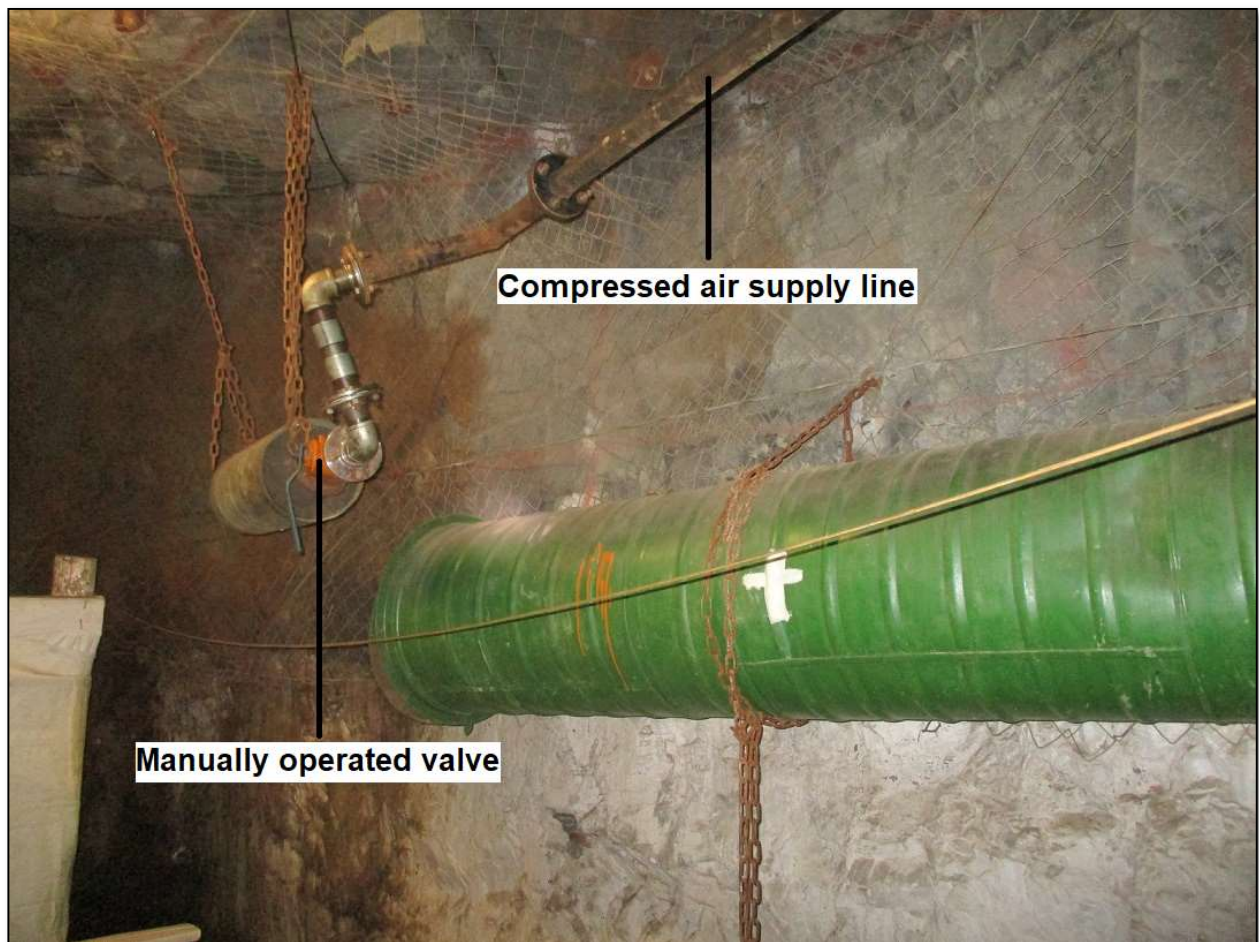


Figure 2-24: Compressed air supply in an underground refuge bay

Source: Photo taken by researcher

The compressed air supplied to a refuge bay ensures that a positive air pressure is maintained inside the refuge bay to prevent smoke and other potentially dangerous gases from entering. In case of emergency events, mineworkers can increase the supply of compressed air to the refuge bay by opening a manual valve on the compressed air supply line. The manually operated valve is clearly visible in Figure 2-24.

2.5 Electricity Savings Measures on Compressed Air Networks

This section provides information regarding energy savings measures on compressed air networks. The information is provided in two subsections:

- **Supply-side measures:** energy savings measures implemented on the compressors that supply compressed air.

- **Demand-side measures:** energy savings measures implemented at the mineshafts that consume compressed air.

2.5.1 Supply-side measures

The compressed air requirements of a mineshaft vary according to the different working hours. A mine workday consists of three distinct shifts, each with different compressed air requirements:

- **Drilling shift:** The drilling shift entails using pneumatic rock drills to drill holes in the rockface being mined.
- **Blasting shift:** Explosives are placed inside the holes drilled in the rockface during the drilling shift. The explosives are detonated remotely once all workers have evacuated the stope areas. Compressed air consumption reaches its lowest point during the blasting shift, because the only compressed air consumers in the period are the refuge bays and leaks.
- **Cleaning shift:** The cleaning shift entails collecting the blasted ore and moving it through ore passes into loadings bins, from where the ore can be hoisted to surface. During the cleaning shift, compressed air is required to power equipment such as rocker shovels, scraper winches and loading boxes.

Figure 2-25 illustrates the variation in compressed air pressure and flow throughout a workday. Maximum compressed airflow is required during the drilling shift, minimum airflow is required during the blasting shift, and intermediate airflow is required during the cleaning shift.

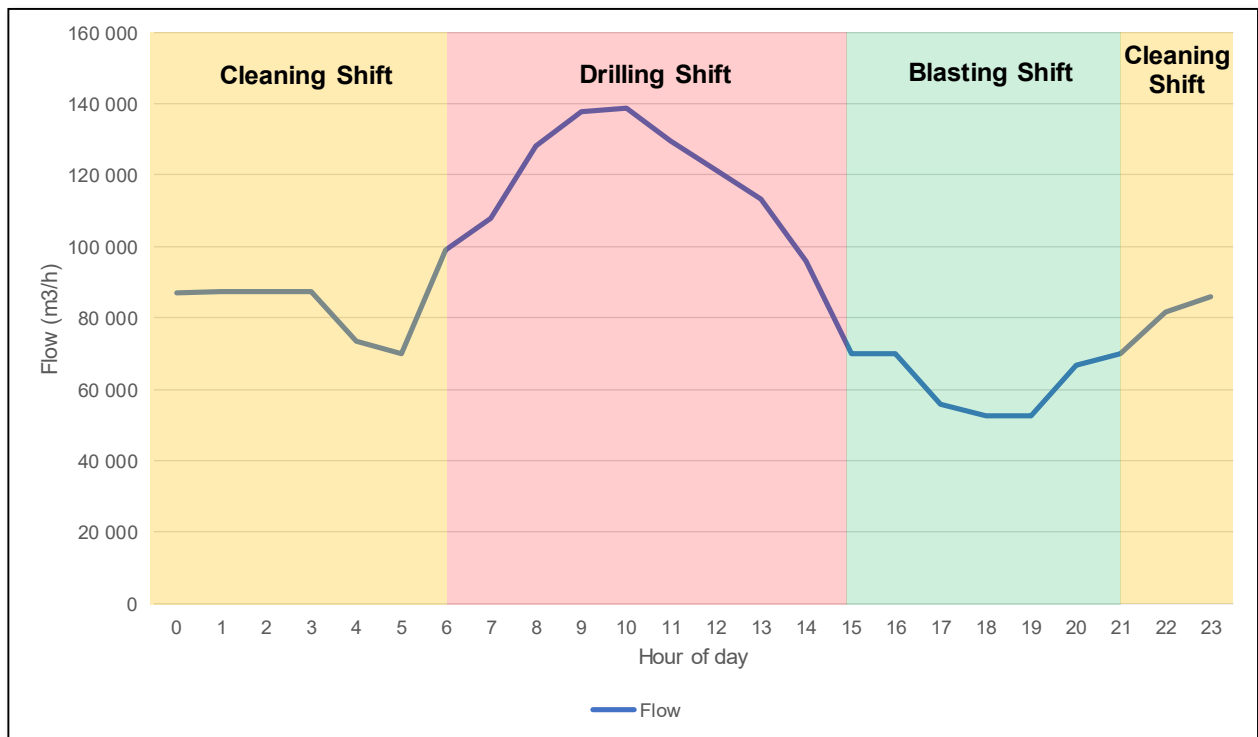


Figure 2-25: Typical compressed airflow requirements during different shifts

Source: Own compilation from data obtained from PGM mine included in this study

PGM mines often tend to oversupply compressed air during the blasting and cleaning shifts. Significant energy savings can be achieved by matching the compressed air demand requirement accurately with the supply during the blasting and cleaning shifts. This is achieved through a combination of the following three actions:

- Switching off compressors that are not required. This is the most effective way of matching supply with demand and ensures that maximum energy savings are achieved. Intermittent stopping and starting of compressors should however be avoided because it results in unnecessary wear.
- Off-loading of compressors, which entails closing the inlet guide vanes and opening the blow-off valve. This ensures that the compressor does not run under any load and that its electricity consumption is reduced to around 60% of its installed capacity. Although off-loading realises energy savings, it is still deemed an inefficient practice as it wastes energy. Off-loading compressors is however a viable option on mines with large variations in compressed air demand because

off-loading is preferred above intermittent stopping and starting, which result in unnecessary wear and tear.

- Implementing inlet guide vane control is suitable for situations where supply and demand cannot be matched by switching off compressors. For example, in the event that three compressors do not supply enough compressed air to meet demand, and four compressors would oversupply, the solution is to run four compressors at reduced output levels using inlet guide vane control.

The three basic supply-side measures discussed in this section are generally easier to implement than demand-side measures. The reason is that the compressors at PGM operations are often remotely controlled from a single, central control room, as opposed to demand-side measures that are implemented at multiple PGM mining shafts. The implementation of supply-side measures should therefore be prioritised over the implementation of demand-side measures.

2.5.2 Demand-side measures

Shaft control valves

A control valve can be installed in the main compressed air column that feeds a mineshaft. This valve is controlled to limit the supply of compressed air during periods when less compressed air is required (Fouché, 2017:12). Figure 2-26 shows a photo of a control valve with an automatic actuator installed on the main supply line of a PGM mine.



Figure 2-26: Automatically actuated valve installed on a compressed air line

Source: Photo taken by researcher

The disadvantage of a shaft control valve is that different mining levels or even different parts of the mine could have differing compressed air requirements, thereby making it difficult to develop an optimised control philosophy that satisfies the compressed air requirements of all the users. This is especially problematic in a mineshaft where a combination of conventional and mechanised mining methods is used.

The control philosophy describes the control parameters of a device such as the output set points of the valve for different time periods. The output set points are based on compressed air flow or pressure, depending on the preferences of the shaft.

Table 2-8 shows the weekday control philosophy of a surface control valve that controls the supply of compressed air to a PGM shaft.

Table 2-8: Control philosophy of a compressed air surface valve

Start time	End time	Flow set point [m³/hr]	Typical cost for Eskom low-demand period
14:30	17:00	70 000	R17 098
17:00	20:00	35 000	R10 259
20:00	22:30	70 000	R17 098
22:30	04:00	85 000	R45 675
04:00	06:00	70 000	R13 678
06:00	14:30	150 000	R124 569
			R228 377

Source: Own compilation from data obtained from PGM mine included in this study

This control philosophy entails controlling the valve according to a particular flow set point, i.e. the valve is automatically actuated to supply the shaft with the flow set points in the table. For example, between 17:00 and 20:00 in the blasting shift, the valve supplies 35 000 m³/h of compressed air to the shaft. Between 06:00 and 14:30 in the drilling shift, the valve is opened fully to ensure that the maximum flow of compressed air is supplied to the shaft. The approximate costs of the compressed air for each period, according to the Eskom low-demand season tariffs, are also shown in Table 2-8.

Level control valves

Control valves are installed on individual mining levels to control the compressed air supplied to the levels (Marais, 2012:47). The advantage of level control valves is that the control philosophies of the valves can be optimised to fit the compressed air requirements of the individual levels. This makes level control valves a better option than shaft control valves. Figure 2-27 shows a control valve installed at the start of an underground mining level.

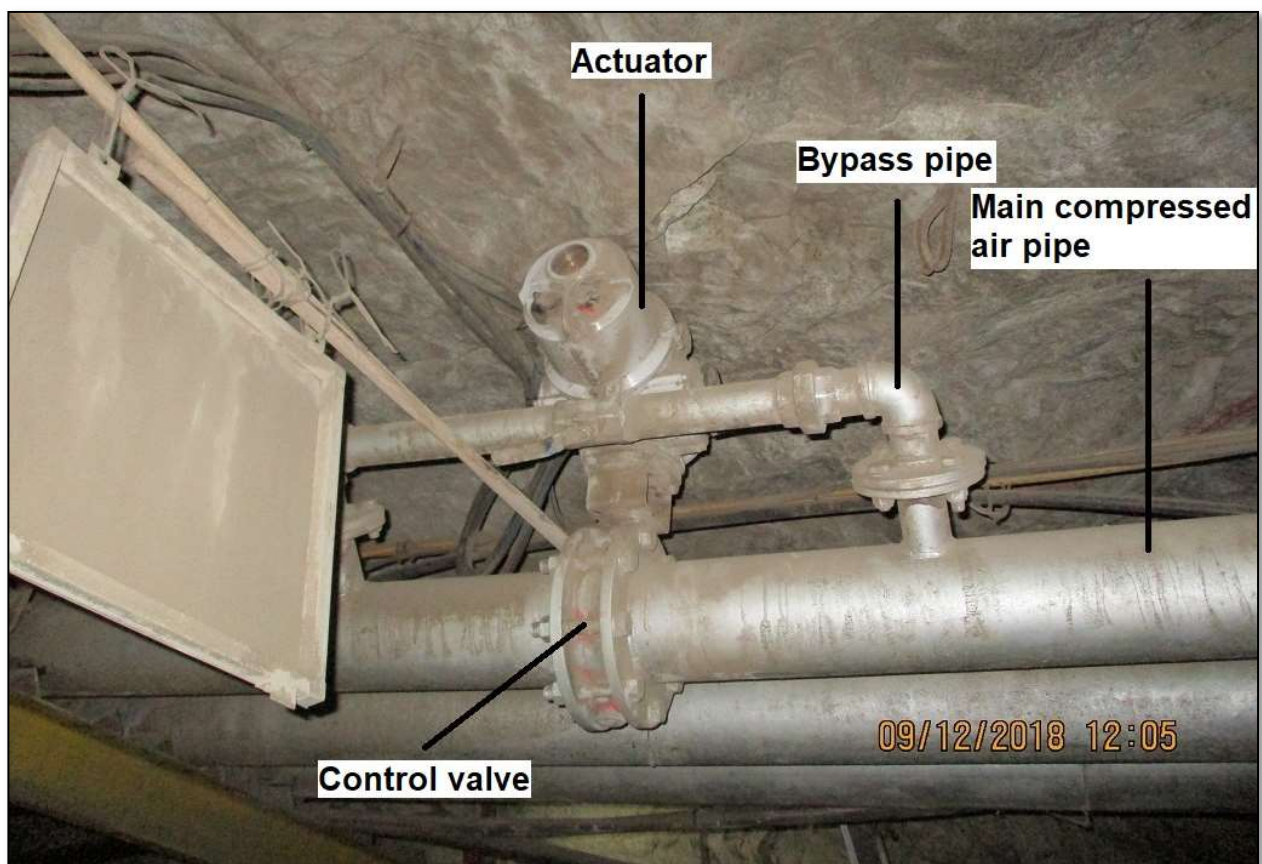


Figure 2-27: Control valve installed in underground mining level

Source: Photo taken by researcher

A bypass pipe was installed over the control valve to ensure that the refuge bays on the mining level are always supplied with compressed air even if the control valve is in the fully closed position.

Stope isolation valves

Stope isolation valves are used inside stope areas to isolate the supply of compressed air in periods when no mining activities take place (Nel, 2019:15). The location of the stope valves inside the stope areas makes stope isolation valves more difficult to maintain than level control valves, which are typically more easily accessible due to being situated at the start of mining levels. The result is that stope isolation valves are prone to developing leakages.

Prevention of compressed air wastage

The practice of using compressed air to cool down areas with inadequate ventilation is a common practice in deep-level mines in South Africa (Bester *et al.*, 2013:3). However, using compressed air to augment ventilation is an ineffective practice, especially when considering the high cost of generating compressed air. Open pipe ends, leaks and supplying compressed air to inactive mining areas contribute to compressed air wastage. In certain circumstances, open compressed air pipe ends are permitted. Examples include ventilating mining areas with high levels of methane or using compressed air to help get rid of explosive gas residue.

Figure 2-28 shows a punch leak in a compressed air pipe on surface (Pascoe, 2016:71).



Figure 2-28: Punch leak in compressed air pipe on surface

Source: Pascoe (2016:71)

Figure 2-28 is also evidence of a poorly repaired leak. A better solution would have been to rather replace the entire pipe section. Although this solution is more costly, it would have been more cost-effective in the long term.

2.6 Compressor Maintenance

The reliable operation of compressors is important to ensure that PGM production is not affected by a shortage of compressed air. Performing correct maintenance procedures on compressors is therefore an important aspect of managing compressed air supply. Unplanned maintenance or breakdowns can result in shortages of compressed air, which may affect production negatively. The advantage of a compressed air ring is that the other compressors on the ring augment the supply of compressed air to shafts affected by the breakdown. The problematic aspect is that this is often not an ideal solution from an energy efficiency perspective. For example, consider the compressed air ring shown in Figure 2-29.

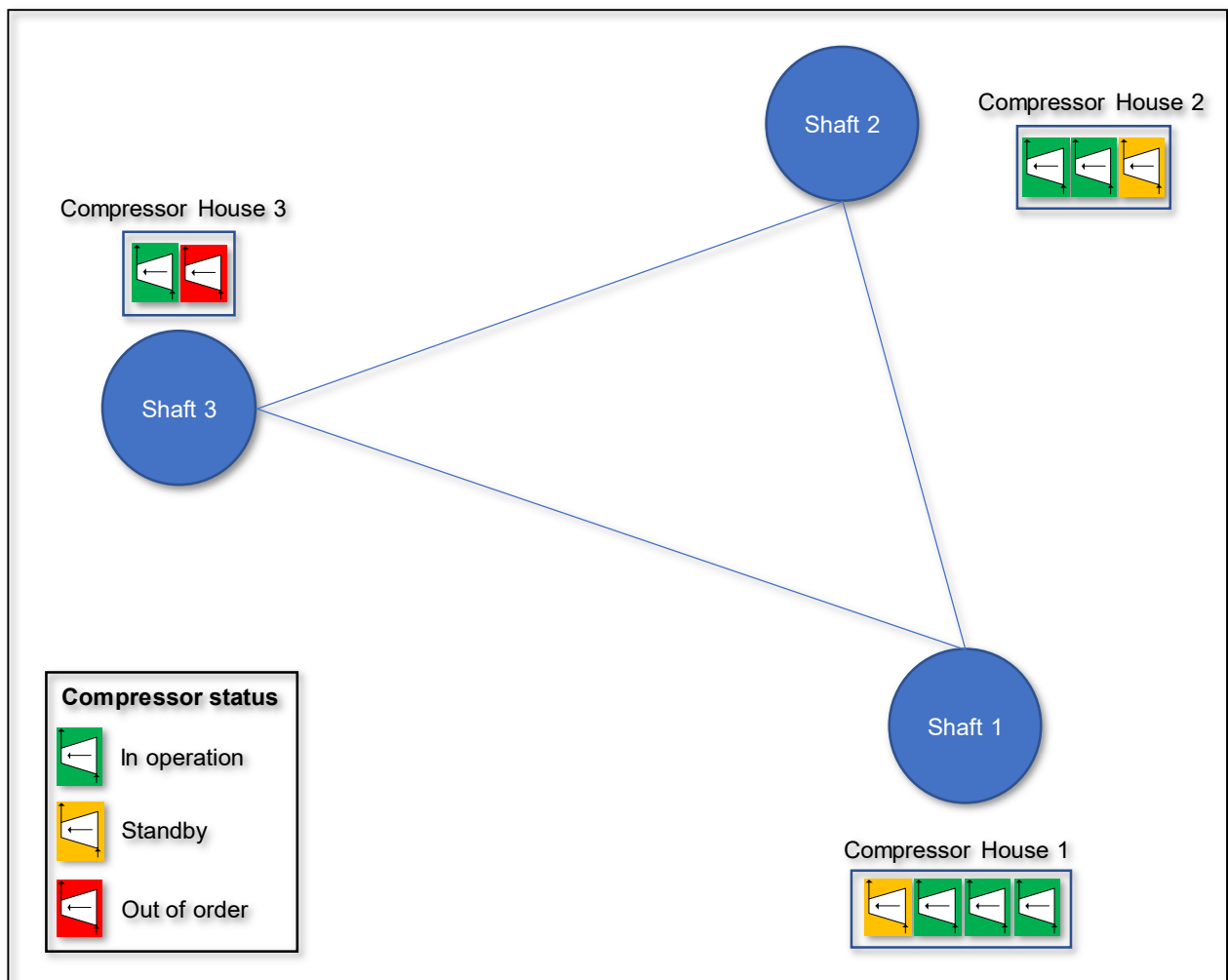


Figure 2-29: Example of compressed air ring

If one of the compressors in Compressor House 3 fails, the spare compressors at the other two compressors houses would have to be started to ensure that Shaft 3's supply of compressed air is not affected. The net result is that one extra compressor is used in comparison to normal operation. The use of the additional compressor is necessary to compensate for the the friction and other transmission losses of supplying compressed air over a longer distance. Although using an additional compressor ensures that production is not interrupted, it is not an effective solution from an energy management perspective because more electricity is consumed.

More information on three different maintenance types or approaches that are commonly used on South African PGM operations are provided below.

Breakdown maintenance

Breakdown maintenance entails running a machine until it fails (Manney, 2017). This is a risky maintenance approach because it is difficult to predict when a failure will occur. Breakdown maintenance is therefore not suited for production-critical equipment.

Time-based maintenance

Time-based maintenance involves performing maintenance tasks according to a predetermined time-based schedule (Ahmad & Kamaruddin, 2012:136). The advantage of time-based maintenance over breakdown maintenance is that the maintenance activity can be scheduled to occur outside peak production periods.

Condition monitoring

Condition monitoring requires the availability of instrumentation to measure certain parameters such as temperatures and vibrations on equipment (Carden & Fanning, 2004:355). The principal idea is that a change in a parameter value indicates that a potential fault is developing that could cause a breakdown and/or damage. For instance, an increase in the frequency of a vibration could be indicative of an imminent bearing failure.

Compressor failures could have a significant negative effect on the production of a PGM operation. The maintenance type or approach to be followed by a PGM operation on its

compressors is a crucial decision since it directly affects the availability factor of the compressors. The availability factor of a compressor is defined as the amount of time that it is able to produce compressed air over a certain period, which is divided by the amount of the time in the period (Kumar, Dasari & Reddy, 2018:72).

2.7 Previous Compressed Air Studies

Managing a large electricity utility such as Eskom is a balancing act between supply and demand. The ideal is that the reserve margin (i.e. the difference between electricity supply and consumption) should be maintained at a level of at least 15% to meet peak demand (Burillo, Chester, Ruddell, & Johnson, 2017:267). A low reserve margin is risky because it could result in load shedding or even a total collapse of the grid. A very high reserve margin is also undesirable because it is not cost-effective.

Eskom's reserve margin fell from 27.1% in 1999 to below the recommended level of 15% in 2004 (Skinner, 2012:9). This was due to a combination of increasing demand and inadequate generation planning. The long-term solution was to build more power stations, but it was evident that an interim solution was required to manage electricity demand in the short term. One interim solution was Eskom's Integrated Demand Management (IDM) programme that incentivised large industrial consumers such as gold and platinum mines to reduce electricity consumption.

The Eskom IDM programme gained momentum in 2004 when the first demand-side management projects were signed (Hansen, Langlois & Bertoldi, 2009:118). The Eskom IDM programme further stimulated research in energy efficiency on mine compressed air networks. This research focused mainly on individual initiatives or projects that were funded through Eskom's IDM programme. Some of the research findings are discussed below.

Booyesen *et al.* (2009:65-68) studied the optimisation of compressor control strategies. The optimised control strategy entailed lowering the output pressures of compressors using guide vane control in periods when mining operations have a lower demand for compressed air. The reduced output pressures decrease the power consumption of the compressors. The optimised compressor control strategy was implemented successfully

at a South African gold mine. The advantage of this strategy is that energy savings could be achieved without the need for expensive infrastructure upgrades.

Marais (2012:1-171) performed a study to develop simplified guidelines for evaluating energy savings opportunities on mine compressed air networks without the need of using complex equations and simulation software. Marais (2012) further developed an integrated approach that consisted of combining the guidelines with a strategy to isolate users requiring high-pressure compressed air on surface and underground from users with varying pressure requirements. Limitations of this study include that the guidelines oversimplify the situation in some case as they do not consider the impact of aspects such as line friction and autocompression on the performance of energy savings initiatives on compressed air networks. The strategy further requires the installation of expensive automatically actuated control valves, which might not be feasible in the case of marginal mines.

Bolt, Venter and Van Rensburg (2012:1-6) developed an automated compressor control system that incorporated both simulation and control capabilities. This control system, namely Dynamic Compressor Selector, dynamically selects compressors based on their efficiency and position in the compressed air network. The problematic aspect of an automated compressor control system is that it is not suitable for situations beyond normal operating parameters such as emergencies or if there are additional production shifts that require compressed air outside the normal mining schedule.

Bredenkamp, Van der Zee and Van Rensburg (2014:1-8) studied the reconfiguration of mine compressed air networks for electricity cost savings. They found that compressed air networks on South African mines are often substantial and inefficiencies could arise due to changes that occur over time. The study reported on the results of a compressed air network reconfiguration that was implemented on a gold mine comprising three shafts. The reconfiguration entailed the installation of a surface pipeline with a length of 4 km between two shafts. The resulting electricity cost saving was R8.1 million per year. The cost for the pipeline was kept low by using salvaged pipe sections. The project would however not have been feasible if new pipe sections had to be used.

Pascoe, Groenewald and Kleingeld (2017:1-5) implemented a combination of improved compressor control and demand-side strategies to realise electricity savings on

compressed air networks. The demand-side initiatives entailed using automated control valves located on mining levels to reduce the supply of compressed air according to the demand of the mining operations. Using automated control valves is a proven mechanism for reducing the demand for compressed air. However, due to the high cost of installing control valves, it unfortunately implies that it is not always a feasible solution.

A study by Du Plooy, Maré, Marais, and Mathews (2019:126-135) resulted in the development of a methodology to locate inefficient compressed air usage in an underground mine. The methodology entailed benchmarking different mining levels in terms of a correlation between compressed air consumption and production. It was found that high compressed air consumption in combination with low production is a good indication that inefficiencies exist.

Literature on the maintenance of centrifugal compressors is limited. An explanation is that different compressor original equipment manufacturers have different maintenance recommendations. Compressor maintenance comprises mostly routine tasks, which are not attractive as a research topic. Literature around compressor maintenance therefore rather focuses on overhead maintenance strategies such as using automated condition-monitoring algorithms to predict failures before they result in breakdowns (Safiyullah, Sulaiman, Naz, Jasmani, & Ghazali, 2018:485-494; Xenos, Kopanos, Cicciotti, & Thornhill, 2016:117-131).

The literature review presented in this section indicated that Eskom's IDM programme stimulated a fair amount of research on energy savings initiatives on compressed air in the South African mining industry. Unfortunately, the Eskom IDM programme is currently hampered by a lack of funding. With the added pressure of escalating electricity tariffs and other costs, the PGM sector needs to implement electricity cost saving initiatives without funding and support from Eskom IDM.

The motivation for this study is that the existing work on improving energy efficiency on compressed air networks in the South African PGM sector consists of scattered projects implemented in isolation. There is no single framework that prioritises the different energy efficiency initiatives in terms of expected impact versus the implementation cost. There is also a lack of information available on the impact of energy efficiency measures on the maintenance costs of compressors.

2.8 Conclusion

South African PGM mining companies dominate the global PGM mining industry. These companies are significant contributors to the economy of South Africa. The PGM mining industry is suffering from a low platinum price, but due to increased demand from the autocatalyst industry, recent increases in the prices of palladium and rhodium have made a positive impact on the balance sheets of PGM mining companies.

Compressed air plays an indispensable role in PGM production and is also the highest electricity consumer on PGM mining operations. Compressed air powers rock drills and numerous other mining equipment. It further plays a role in safety as compressed air is used to pressurise refuge bays. Sound compressor maintenance practices are essential for ensuring an uninterrupted supply of compressed air to mining operations. Eskom's IDM programme has stimulated research in energy efficiency on mine compressed air networks.

2.9 Chapter Summary

This chapter presented background information about the PGM mining industry and compressed air consumption on PGM mines. The chapter started with an introduction to the PGM mining industry. It was shown that South Africa is the number one global supplier of platinum in the world. The major global PGM mining companies were also introduced.

The section on compressed air usage in the mining industry introduced the basic compressor operating principles. The uses of compressed air in the PGM mining industry were discussed. The most important use of compressed air is to power pneumatic drills, which are of central importance to the production process. A high-level overview of basic energy savings measures on both the supply and demand side of mine compressed air networks was provided. The chapter concluded with a literature review of energy savings measures that were implemented as part of Eskom's IDM programme on mine compressed air networks.

CHAPTER 3 – EMPIRICAL STUDY

3.1 Introduction

The aim of this chapter is to provide information on the research methodology used to achieve the research objectives listed in Chapter 1. This chapter commences with the procedure and scope of the qualitative research. Information about the data gathering process, data processing procedures, sample group, sample size and demographic information about the interviewees is provided. The results of the qualitative study are presented according to different themes identified during the data analysis phase. This is supported by quantitative results that show the impact of various initiatives for reducing compressed air consumption at the PGM mining operations included in this study. The chapter concludes with a description of focus areas, priorities and action steps that comprise the framework for managing compressed air on PGM mining operations.

3.2 Procedure and Scope of the Qualitative Research

3.2.1 Data gathering

The qualitative data used in this study was collected through semi-structured interviews. Semi-structured interviews entail using a precompiled list of questions to guide the interviews, which is supplemented by ad hoc questions. The purpose of the ad hoc questions was to get more information about certain topics as they arose during the interview. The list of precompiled questions is provided in Appendix A.

Most interviews were conducted in the interviewees' offices, located on-site at PGM mining operations situated in the western lobe of the BIC. An interview protocol was followed during each of the interviews, which is provided in Appendix B. The researcher conducted all interviews in a face-to-face manner. The interviews were recorded in electronic audio format, which were transcribed by the researcher using Microsoft Word. The transcribed interviews were coded using the ATLAS.ti, which is a computer-aided quantitative data analysis software. Coding entails categorising the transcribed data to facilitate analysis (Bryman *et al.*, 2017:336).

3.2.2 Sample group and size

The target population was experienced senior managers who manage aspects of compressed air on South African PGM operations. The participants were selected using non-probability sampling and convenience sampling techniques (Bryman *et al.*, 2017:171, 178). The further following criteria were used to select the participants:

- Their level of involvement in managing compressed air on PGM operations.
- Their level of seniority in terms of managing compressed air on PGM operations.
- Their experience and expertise in managing compressed air on PGM operations.

Nine interviews were conducted. The number of interviews was determined by the saturation point (Saunders, Sim, Kingstone, Baker, Waterfield, Bartlam, Burroughs, & Jinks, 2018:1893). It was evident after the ninth interview that the saturation point was reached because no new information or themes were observed during the coding process.

3.2.3 Thematic analysis

The transcribed data was analysed using the thematic analysis technique. The goal of thematic analysis is to identify, analyse and describe patterns or themes that occur in the data set (Bryman *et al.*, 2017:350). Braun and Clarke (2006) identified thematic analysis as a six-phase process:

1. Familiarising yourself with the data
2. Generating initial codes
3. Searching for themes
4. Reviewing the themes
5. Defining and naming the themes
6. Producing the report

The six phases of Braun and Clarke (2006) were followed by the researcher. The researcher familiarised himself with the data by conducting the interviews in person and transcribing each interview without any assistance. The durations of the interviews ranged between 20 and 70 minutes. The nine transcribed interviews comprised 29 741 words.

The researcher coded the first three interviews using the open coding methodology (Khandkar, 2009:1). Thereafter, the existing codes were applied to the remaining interviews. Where necessary, new codes were created when the existing list of codes was deemed insufficient.

3.2.4 Demographic profile of interviewees

Figure 3-1 shows the distribution of the interviewees' designations. The two departments concerned were the compressed air supply management department and the instrumentation department.

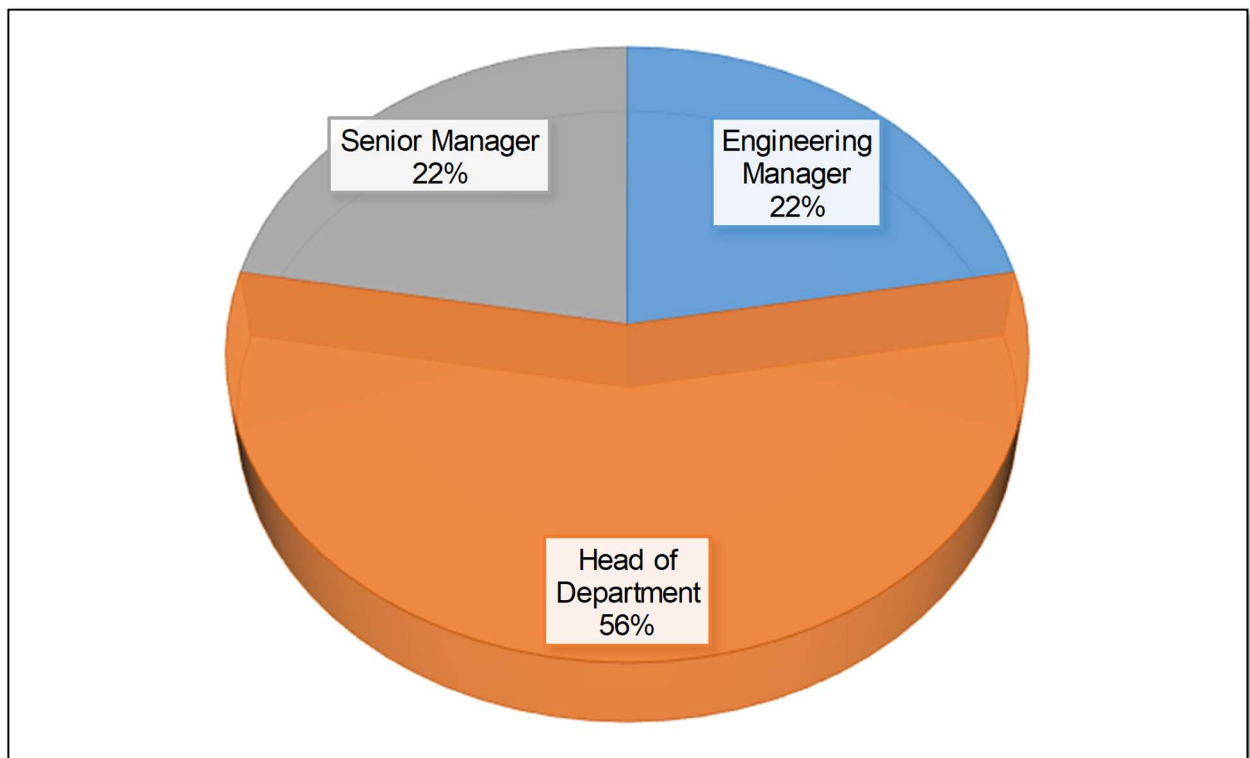


Figure 3-1: Distribution of the positions of the interviewees

Of the interviewees, 56% were heads of departments (HODs); 22% were senior managers who report directly to the HODs; and the remaining 22% were engineering managers. An engineering manager oversees engineering activities at multiple shafts. Shaft engineers report to directly to the engineering manager. On South African PGM operations, each PGM shaft has at least one shaft engineer depending on the size of the shaft. Larger shafts have two or more shaft engineers, with each shaft engineer being responsible for a different section of the shaft.

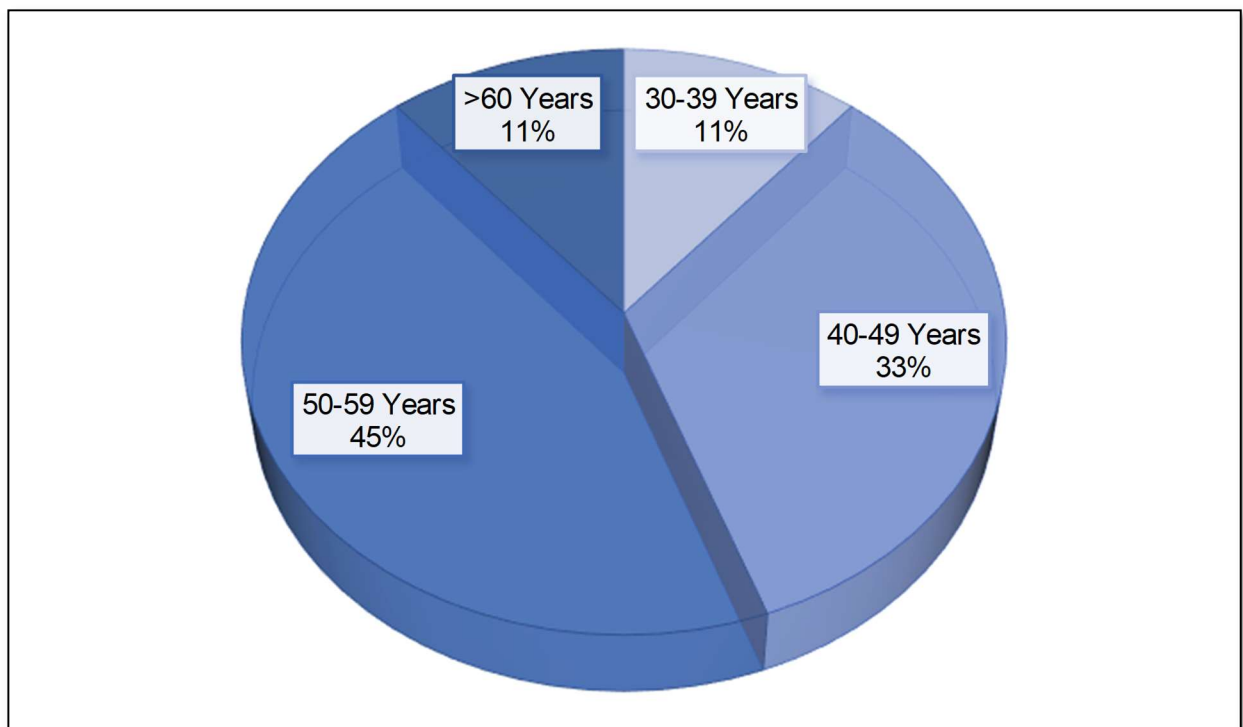


Figure 3-2: Age distribution of the interviewees

Figure 3-2 shows the distribution of the interviewees' ages. The data shows that 45% of the interviewees fall in the category '50–59 years'; followed by 33% in the category '40–49 years', with 11% in each of the categories '> 60 years' and '30 39 years'. The fact that 56% of the interviewees were older than 50 years was expected, because the target population for the study was experienced senior managers. This also points out a potential risk area, because it shows that the majority of experienced compressed air managers in the PGM industry is nearing retirement age, which may result in a future skills shortage.

Figure 3-3 shows the distribution of the PGM mining experience of the interviewees. The graph shows that 90% of the interviewees had more than 10 years' experience working on PGM operations.

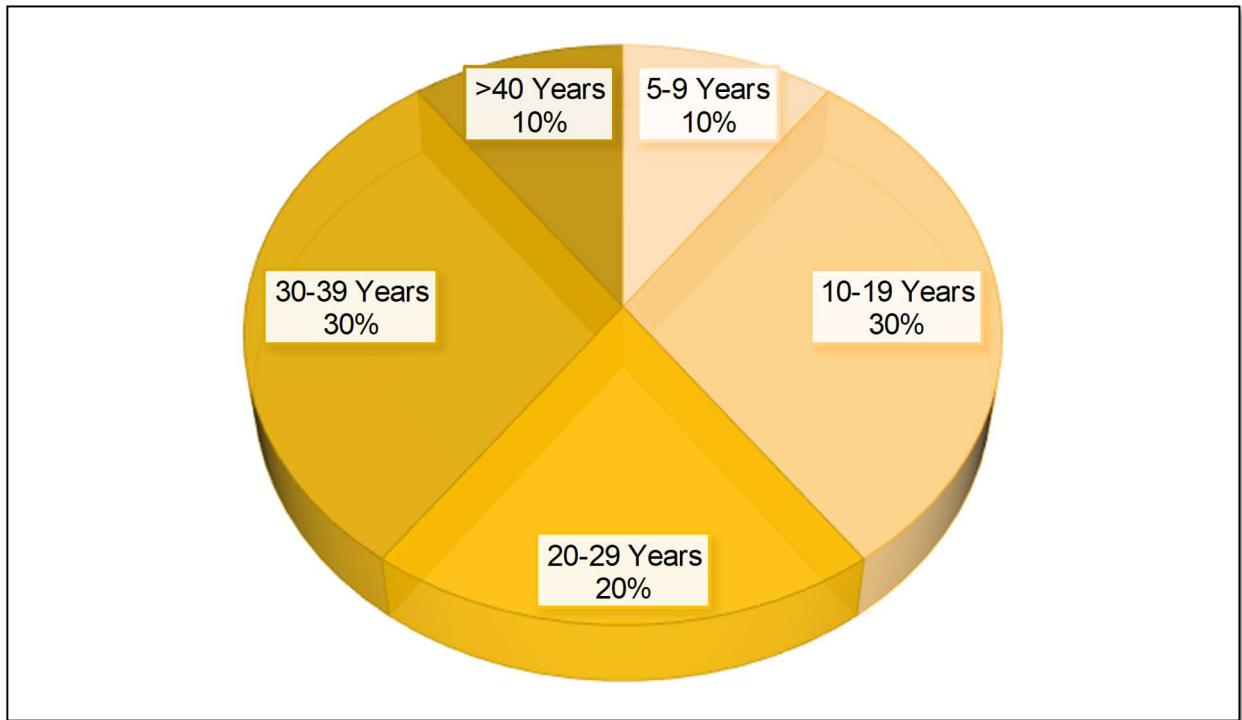


Figure 3-3: PGM experience of the interviewees

Figure 3-4 shows the experience of the interviewees in terms of managing compressed air on PGM operations. Most interviewees (55%) had more than 10 years' experience in this regard. This bears testimony to the vast compressed air management experience of the interviewees.

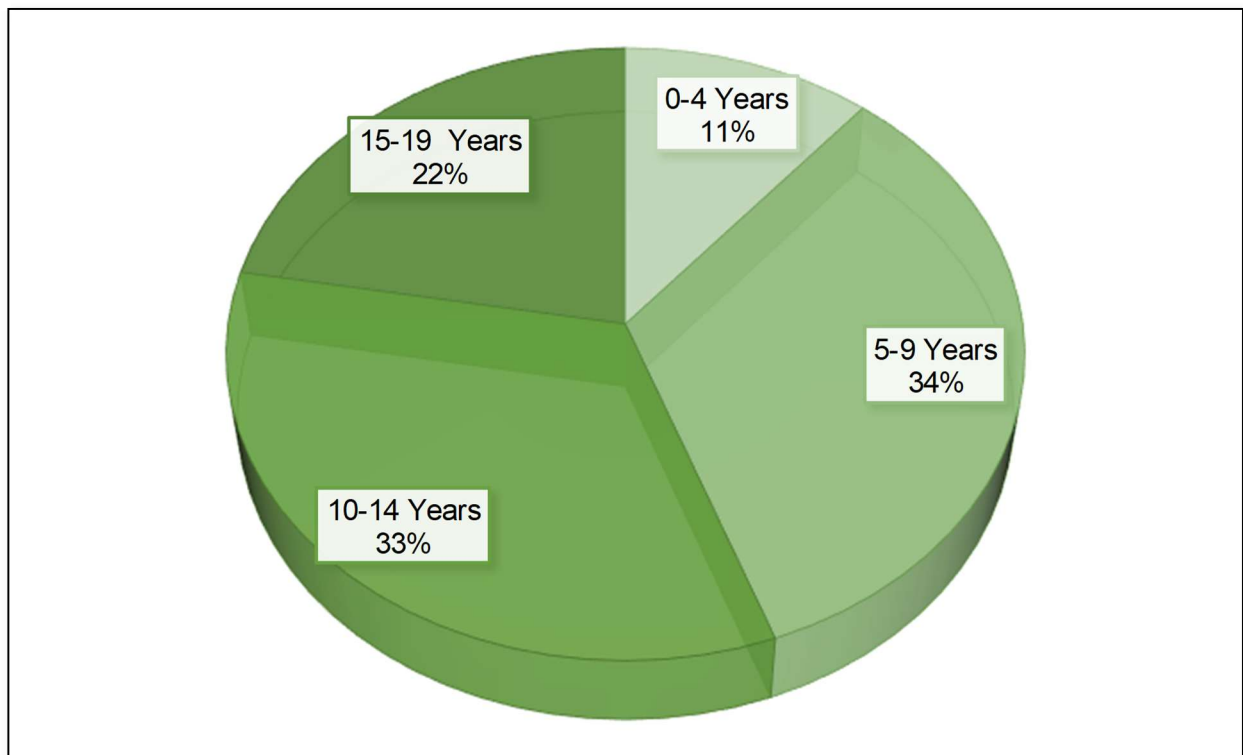


Figure 3-4: Compressed air management experience of the interviewees

3.3 Results of the Qualitative Study

This section discusses the results of the qualitative study in terms of themes identified in the data. The coding of the interviews in the ATLAS.ti software resulted in 46 unique codes, which were grouped into six themes. Each theme consisted of two or more subthemes, while certain subthemes were divided into categories. The following six themes were identified:

- Importance of compressed air
- Compressor challenges
- Maintenance challenges
- Demand-side challenges
- Efficiency
- Information

Figure 3-5 shows a network diagram of the six themes. Each of the themes has been colour-coded to make it easier to distinguish.

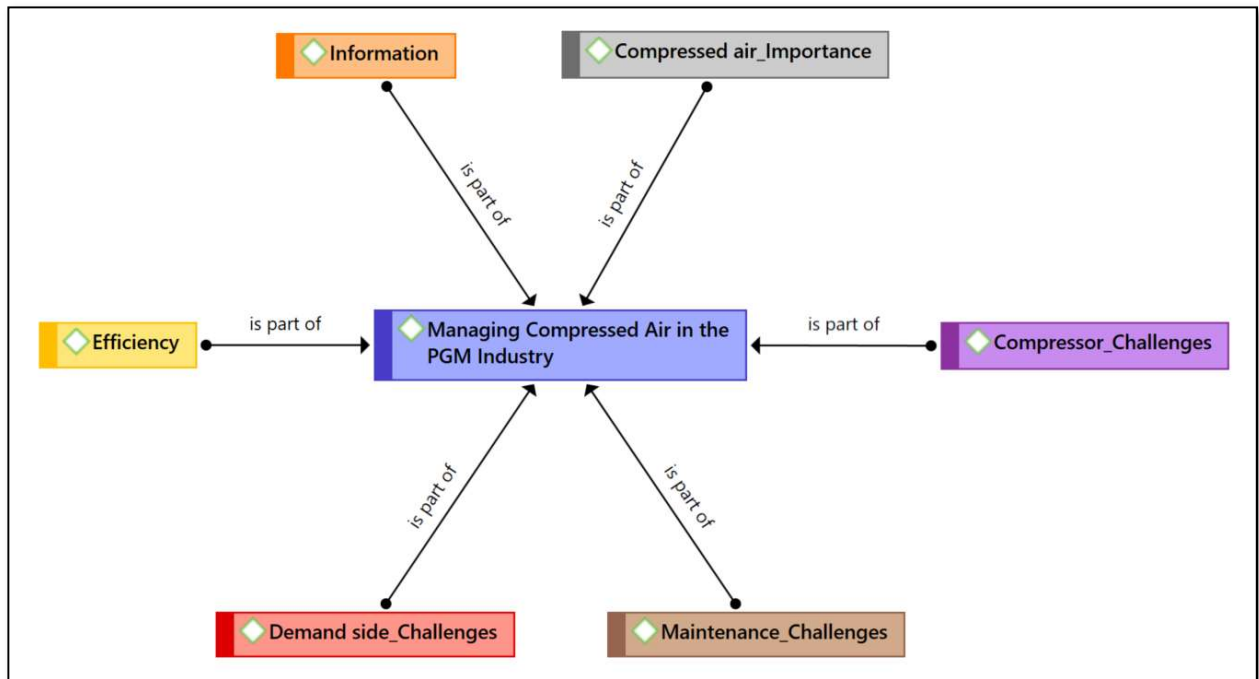


Figure 3-5: Themes of the qualitative study

Hereafter, each theme is discussed starting with a network diagram that shows the different subthemes and categories. A three-tier approach was followed: every theme was divided into subthemes, while certain subthemes were divided further into categories, as shown in Figure 3-6. The frequency count of each code is shown next to the letter 'G'. For example, 'Category 2' has a frequency of 2, which indicates that the code occurred twice in the transcribed interviews. The density of each code is shown next to the letter 'D'. The density indicates how many times the code is linked to other codes. 'Subtheme 2' in Figure 3-6 has a density of 3, which shows that it is linked to three other codes.

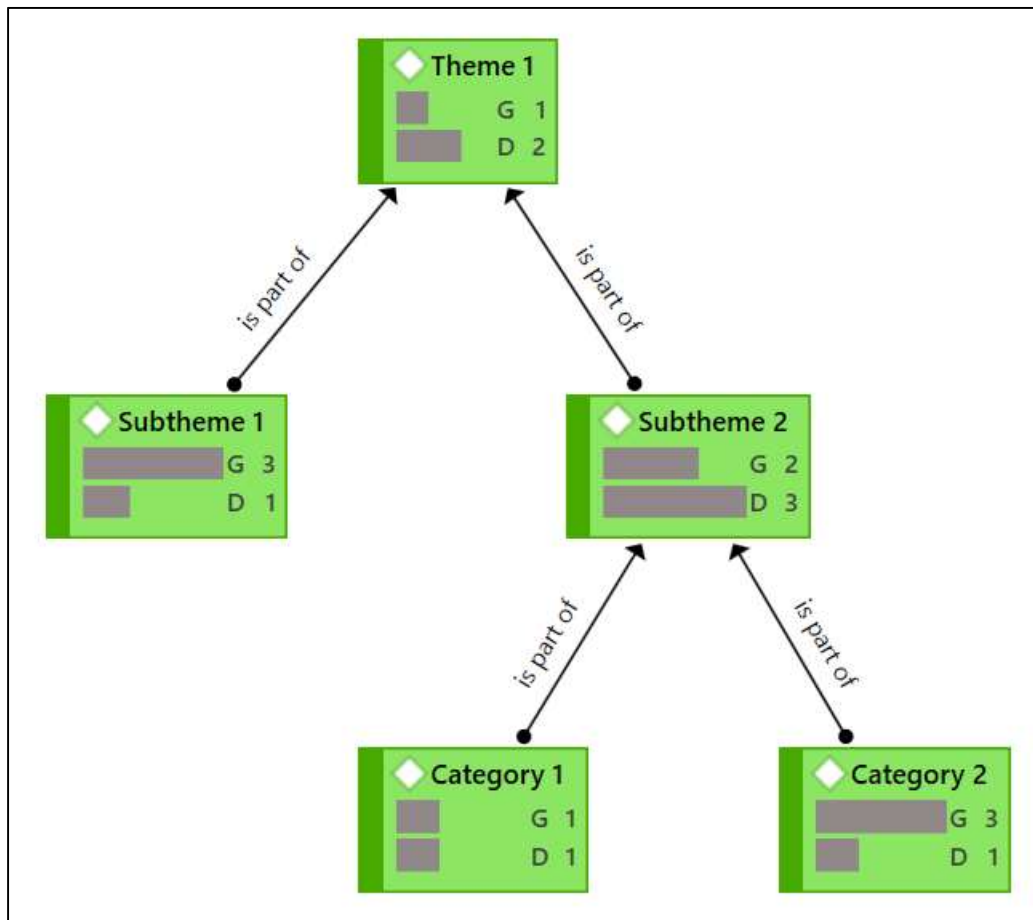


Figure 3-6: Three-tier approach

Quotes from the interviews are shown in italics. Confidential information in the quotes is hidden with three asterisks: ***.

3.3.1 Importance of compressed air

Figure 3-7 shows the network diagram of the 'Importance of Compressed Air' theme. This theme consists of two subthemes, namely 'Function' and 'Saving'.

3.3.1.1 Function of compressed air

The important functions of compressed air in terms of production and safety in PGM mines were confirmed, as shown in the two responses below:

"Look, knowing that compressed air plays a very big role. For starters, the importance of compressed air, because our production is entirely dependent on compressed air."

(Participant 4)

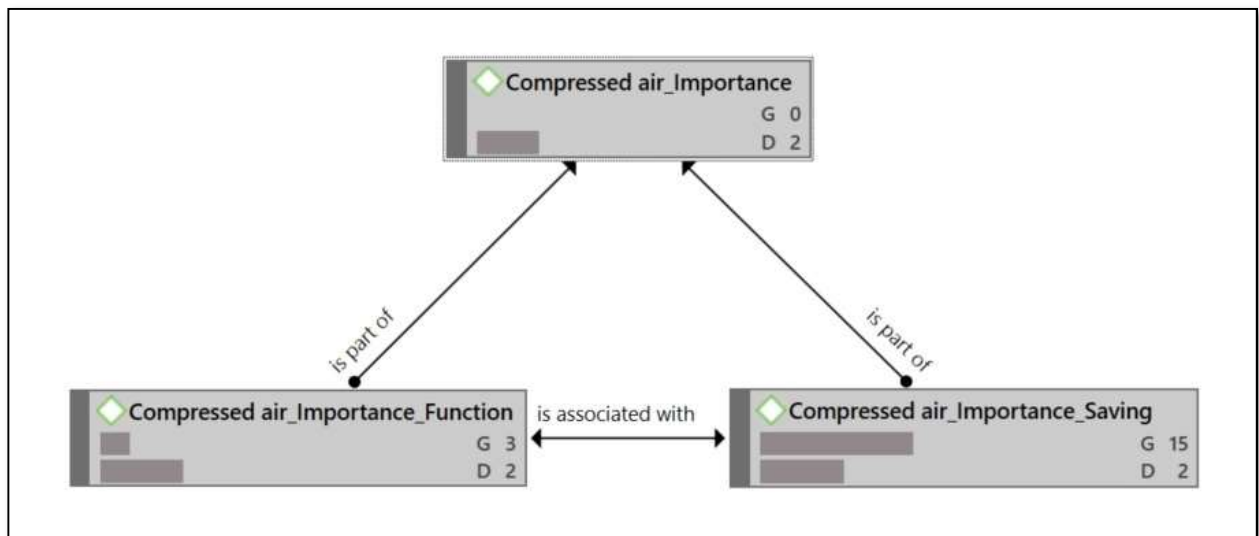


Figure 3-7: Network diagram: Importance of compressed air

“Compressed air is a necessity for daily mining. It is a necessity because it allows you to drill and blast. It is also a necessity because it supplies fresh air to the refuge bays.

And it is used for opening and closing chutes that you use for controlling and transporting the ore from one hole to another. It is important because it is a source of energy, but it is also something that gives your air to breathe in the mine, although it is not primarily a source of clean air, but it does contribute to it.” (Participant 2)

3.3.1.2 Saving compressed air

In terms of saving compressed air, all interviewees unanimously agreed that saving compressed air should be an important priority for PGM operations:

“Yes, it is important. Why do you need to waste? If you can save, why do you want to waste. Reduce, reuse, recycle. If you apply those principles, besides the financial advantages, there are other advantages. Not always direct, but indirect savings or other things that you gain.” (Participant 3)

“If you go and look at the total running cost of the mine. Labour cost is a big chunk. Energy is also a big chunk. If we speak about energy, we say we have a smelter. The ovens consume large amounts of electricity. Our smelters are our biggest single consumer of electricity. Compressed air is very close to or on par with the smelters. If all our ovens are running, they consume a bit more electricity than compressed air. If one

*of the ovens are switched off, compressed air is the biggest electricity consumer. What are energy costs in terms of the total bill of ***? I think it is just over 10%. Now if you start thinking that energy costs contribute to more than 10% of ***'s total operational cost, then it gets to a large amount. We pay more than R240 million per month for power. This is enormous.” (Participant 2)*

The question about the importance of saving compressed air was asked in the context of whether the benefit is justified when considering the effort that saving compressed air requires and whether the potential electricity cost saving is significant in comparison with the large turnover of a PGM operation. The responses indicated the benefits of saving compressed justify the effort and potential electricity cost saving:

“For me it is a no-brainer. It's like, if you have a lot of money, will you now just leave your electric bill running? One must save where you can. If you can save, why not? The economy works that way, you need to save. You say now when the price is good ... we cannot work with ‘maybes’. If you are working for a company, you must make good decisions for that company. You do not make half-baked decisions; it is meaningless. Whatever you do, go all out, do it right. It doesn't help us to operate on the principle of now the prices are good, now we don't have to save, we can waste. It does not make sense. Another dry year is coming, another low price is coming. It is up and down. Our vision is to save costs, do it as safe and cheap as possible.” (Participant 8)

“Yes, and perhaps it is small in comparison to the ‘platinum basket’. My view is that every bit matter.” (Participant 9)

The link between the two categories of the ‘Importance of Compressed Air’ theme was also established. Reducing the wastage of compressed air is not only important from the perspective of electricity costs savings, but it is also important in the sense that it results in more compressed air being available for its intended functions, namely, powering equipment used in the production process and pressurising refuge bays.

“The bigger picture is that the moment you save, the guys can drill quicker, they can actually open other avenues to say maybe we can have more faces that we can drill so your IMF, which is your immediate mineable faces, can be attended to. And then of

which it will bring more production for the company. Unlike the guys are just struggling with what they are currently having.” (Participant 4)

3.3.1.3 Summary

To summarise, the main findings of the ‘Importance of Compressed Air’ theme are:

- Compressed air is an indispensable resource in the PGM mining industry. Compressed air powers equipment used in the production process. Furthermore, compressed air is important from a health and safety perspective because it is used to pressurise underground refuge bays.
- Saving compressed air should be an important priority of PGM mining operations. The effort spent on implementing measures to reduce the wastage of compressed air is justified when considering the electricity costs savings and the fact that it results in more compressed air being available for its intended purpose.

3.3.2 Compressor challenges

The network diagram of the ‘Compressor Challenges’ theme is shown in Figure 3-8.

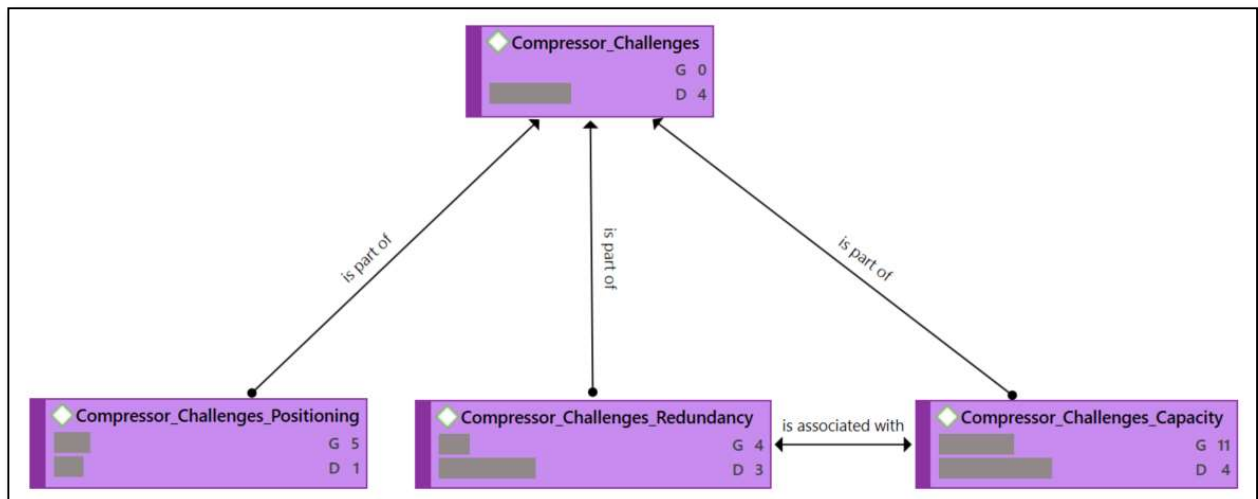


Figure 3-8: Network diagram: Compressor challenges

This theme consists of three subthemes namely, ‘Positioning’, ‘Redundancy’ and ‘Capacity’.

3.3.2.1 Positioning

The positioning of compressors was found to be a problematic aspect on all the PGM operations included in this study. Compressors are not always positioned near the shafts that consume the compressed air. This results in compressed being supplied over large distances, which is an inefficient process due to transmission losses:

“Another thing is the distribution, the positional efficiencies of the compressors, because many of them are located far away from the shafts and your transmission losses are extremely high”. (Participant 7)

The compressor positioning problems experienced by PGM operations are the result of gradual changes in the demand for compressed air over the lifetime of a shaft. A new shaft's demand for compressed air increases over time until it reaches its planned production peak. Thereafter, production starts to decrease gradually as it nears the end of life. This varying demand for compressed air over the life of a shift makes the optimal positioning of compressors quite challenging. The problematic aspect is that it is expensive to move compressors between different locations:

*“I would say the other challenge is the restructuring of the mine. The locations of our compressors are not necessarily ideal. For example, there are two compressors at *** Shaft, which we really do not run you know. Even if we run them, the pipes connecting the compressors with the shafts are not large enough and those compressors are located far from the other shafts, so you will have significant friction losses. We will have to move those compressors, but it costs a lot of money. You do not just load a compressor on the back of a bakkie and move it quickly, it costs a lot of money.”*
(Participant 6)

3.3.2.2 Redundancy

It was found that one of the PGM operations had no redundancy. During the drilling shift when compressed air consumption is at its highest level, all the available compressors were required to run in order to satisfy the demand for compressed air. This is a serious problem, because in the event of a breakdown, the shafts cannot be supplied with enough compressed air, which has a negative impact on production:

“Well ... the biggest challenge is that we do not have any redundancy. We have no spare capacity, we run basically all the machines every day. If there is one machine standing it is a crisis.” (Participant 1)

3.3.2.3 Capacity

Although redundancy and capacity are two closely related concepts where compressors are concerned, there is a difference. Redundancy refers to having spare compressors available in the event of a breakdown or scheduled compressor maintenance. Capacity refers to being able to supply enough compressed air to meet the demand. The PGM operation that suffered from a lack of redundancy also experienced problems in terms of capacity:

“I cannot supply enough air; I just do not have it.” (Participant 1)

*“Yes, you could get away when one machine broke down, but not a second one. Sometimes, in critical places such as *** Shaft, we could simply not stop a single compressor on weekdays. If you stop, the pressure drops dramatically and then you must evacuate the miners from underground.” (Participant 7)*

3.3.2.4 Summary

The main findings of the ‘Compressor Challenges’ theme are summarised as follows:

- The optimal positioning of compressors at PGM operations is challenging because each shaft’s demand for compressed air varies over its lifetime. The result is that compressors installed to supply compressed air to a particular shaft will become obsolete as the shaft approaches the end of its live. Unfortunately, the relocation of compressors is a costly exercise.
- Redundant compressors should be available to prevent production losses in the event of a breakdown.
- The output capacity of the compressors should exceed the demand for compressed air during the drilling shift.

3.3.3 Maintenance challenges

Figure 3-9 shows the network diagram for the 'Maintenance Challenges' theme. The theme consists of five subthemes, with the 'Strategy' subtheme consisting of two categories:

- Quality
- Old equipment
- Strategy
 - Condition monitoring
 - Routine procedures
- Breakdowns
- Standardisation

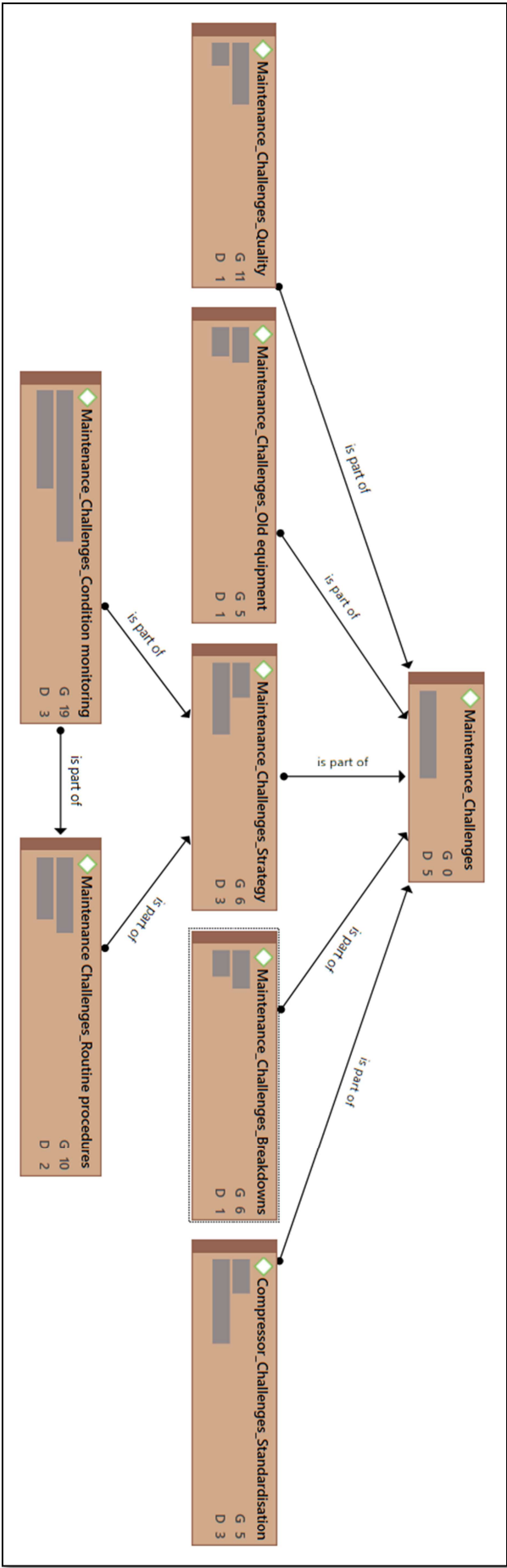


Figure 3-9: Network diagram: Maintenance challenges

3.3.3.1 Quality

The 'Quality' subtheme is concerned with the quality of the maintenance work conducted on the compressors. It is important to execute routine maintenance procedures correctly:

"... we depend on the artisans to do regular checks. The issue comes when procedures are not followed or when not enough maintenance is being done. Proper maintenance is where the focus should be." (Participant 3)

Two interviewees said that they are concerned about the quality of their maintenance personnel:

"Also, the quality of the maintenance staff has reduced dramatically over time."
(Participant 7)

"We are lucky because we still have experienced artisans. But I am worried about the future; I am very worried about the future. The quality, and I am not only talking about artisans, the quality of the entire trade is going backwards." (Participant 1)

3.3.3.2 Old equipment

The oldest compressors and electric motors at the PGM mining operations included in this study date from the 1960s and 1970s. In terms of reliability, the age of the compressors is not such an important factor as the age of the electric motors:

"If you look at the age of the machines, when they were installed, the age of the motors, and that type of thing. You get motors where the insulation cracks, it flashes, and you lose the motor. If you take that motor and send it in for a rewind, when you get it back it is still a refurbished motor, not a new one. You can also just refurbish it so many times. Somewhere along the line you need to start thinking about replacing a motor."
(Participant 3)

"Apart from that, electrical problems on the motors, you know some of those motors also originated from the sixties. You can keep a mechanical thing going, but over time, an electrical motor becomes completely worn out." (Participant 7)

3.3.3.3 Strategy

The maintenance strategy followed at all the PGM operations included in this study is a compromise between cost and functionality:

“Your maintenance strategy can always be changed. For example, when flying an aeroplane, the number of monitoring systems, proactive systems are a different strategy in comparison to when you need to keep a machine running in the middle of Johannesburg where the neighbour has more of those machines in stock. Versus when you need to operate something in the middle of the Congo or the Sahara Desert where you do not have parts readily available. You devise a strategy that works for you.”

(Participant 2)

“Look, it is a challenge to see where to cut off that line. What do we spend on the machine and what should we not spend on the machine? We want to do it as economically as possible without affecting reliability.” (Participant 8)

Routine procedures

All the PGM mining operations included in this study follow a time-based routine maintenance schedule:

“We do planned maintenance every month on every machine. And then from the mechanical side we stop all the machines for a ‘yearly’, a ‘three yearly’ and a ‘five yearly’. The ‘five yearly’ is the big overall; then the machine is stopped, opened up, it is looked at, opened, tested, it’s a big operation. It costs us a lot of money, but it is something that needs to be done to stop us from having to spend more money ...”

(Participant 8)

“... we have a three-month maintenance plan that is generated by SAP to go through all the instrumentation.” (Participant 9)

Condition monitoring

All the PGM operations included in this study follow a condition-monitoring strategy consisting of two parts. The first part of the condition-monitoring strategy entails installing instrumentation on the compressors such as temperature and vibration sensors. Alarms

are sounded or the compressor is tripped if the output values of the temperature and vibration sensors exceed certain predetermined threshold values.

“... we measure vibrations and temperatures on the machines. We often trip the machines well in advance and then we prevent significant damage. This happens quite a lot.” (Participant 3)

The second part of the condition-monitoring strategy entails using third-party service providers specialising in condition monitoring:

*“We have a contract with *** to do condition monitoring on the compressors. There is a monthly meeting with them where they provide detailed feedback on vibrations, temperatures, the coolers and everything.”* (Participant 6)

3.3.3.4 Breakdowns

One participant indicated that despite efforts to put condition monitoring in place, the PGM mining industry still does a great deal of unplanned maintenance due to breakdowns:

“To date, 90% breakdown maintenance is being done.” (Participant 7)

The location of a compressor experiencing a breakdown determines the priority of attending to the breakdown. The highest priority is given to shafts that ‘import’ compressed air:

*“The frequency of the breakdowns is the not the biggest problem. Sometimes it is just where the breakdown occurs that is the problem. Consider *** Shaft where their consumption went up considerably over the past few months. They require 80 000 to 90 000 cubes on average per hour; they only have two compressors at the shaft which give only 60 000 cubes. The rest of their demand needs to be imported from other shafts, either *** Shaft or *** Shaft, which are the adjacent shafts”.* (Participant 2)

3.3.3.5 Standardisation

Standardisation is a proven strategy for reducing maintenance costs (Poling, 2019:1). Two participants confirmed that a lack of standardisation on the electric motors that power

the compressors is a problematic aspect. The problem originates from the fact that shaft engineers have always had the freedom to decide which brand of electric motor to use.

*“Yes, our big thing is the electrical part, it is like a liquorice allsorts; I mean every engineer who was involved with the project at the time decided, if he liked ABB, he put in ABB motors. This engineer liked Toshiba, then he put in Toshiba motors. Even your spare motors are not compatible with all the compressors. There are certain motors, that can only be used at certain places. Like a new shaft, for instance, *** Shaft, they put in three VK50s, instead of buying motors for which we have spares available, they converted old water-cooled motors. Now, *** Shaft is one shaft that has unique compressor motors. They have bought a spare motor, but that spare can only be used at *** Shaft.” (Participant 1)*

Another reason for a lack of standardisation on compressors is because every PGM mining company has its own standards. Should a PGM mineshaft be sold to a new owner, the chances are good that the standards of the new owner will differ from the standards of the previous owner:

“Yes, and you know at the time, [PGM A] belonged to [PGM B]. [PGM B] standards were applied at [PGM A]. And [PGM C] and [PGM D] belonged to [PGM E], so they had their own views. And I also think every mine had its own resident engineer who had his way of doing things. I believe this is the case in every industry.” (Participant 9)

3.3.3.6 Summary

A summary of the main findings of the ‘Maintenance Challenges’ theme is provided below:

- Routine maintenance procedures should be executed correctly.
- The industry is concerned about the dwindling quality of maintenance personnel.
- The age of electric motors powering compressors affects reliability significantly.
- The maintenance strategy followed by PGM mining operations is a compromise between cost and functionality.
- All PGM operations included follow a time-based routine maintenance schedule.
- All PGM operations included employ condition monitoring on their compressors.

3.3.4 Demand-side challenges

The network diagram for the 'Demand-side Challenges' theme is shown in Figure 3-10. The subthemes and categories of this theme are:

- Toxic leadership
- Ventilation
- Wastage
 - Discipline
 - Negligence
 - Carelessness
- Large mine footprint
- Awareness

3.3.4.1 Toxic leadership

Toxic leadership plays a role in the wastage of compressed air on shafts. Production is the number one priority on a PGM mineshaft and saving energy is an afterthought. Participant 3 said that decisions are often made to increase production, but that the negative consequences in terms of compressed air consumption are disregarded. Participant 3 gave an example by explaining that shaft management decides to mine in an area with inadequate ventilation. However, ventilation personnel is too afraid to point out that it would not be feasible due to inadequate ventilation. In such a situation, chances are good that compressed air would be used to compensate for the lack of ventilation:

“On a mine, the guys who shouts the hardest gets what he wants ... if the GM [general manager] tells a ventilation guy that it is not going to work like that, he is going to mine in a certain area, then the GM is going to mine there. The ventilation guy is supposed to stand up to the GM and tell him that it cannot work like that, I am a professional ventilation practitioner and I am telling you that we need to close off that area.”

(Participant 3)

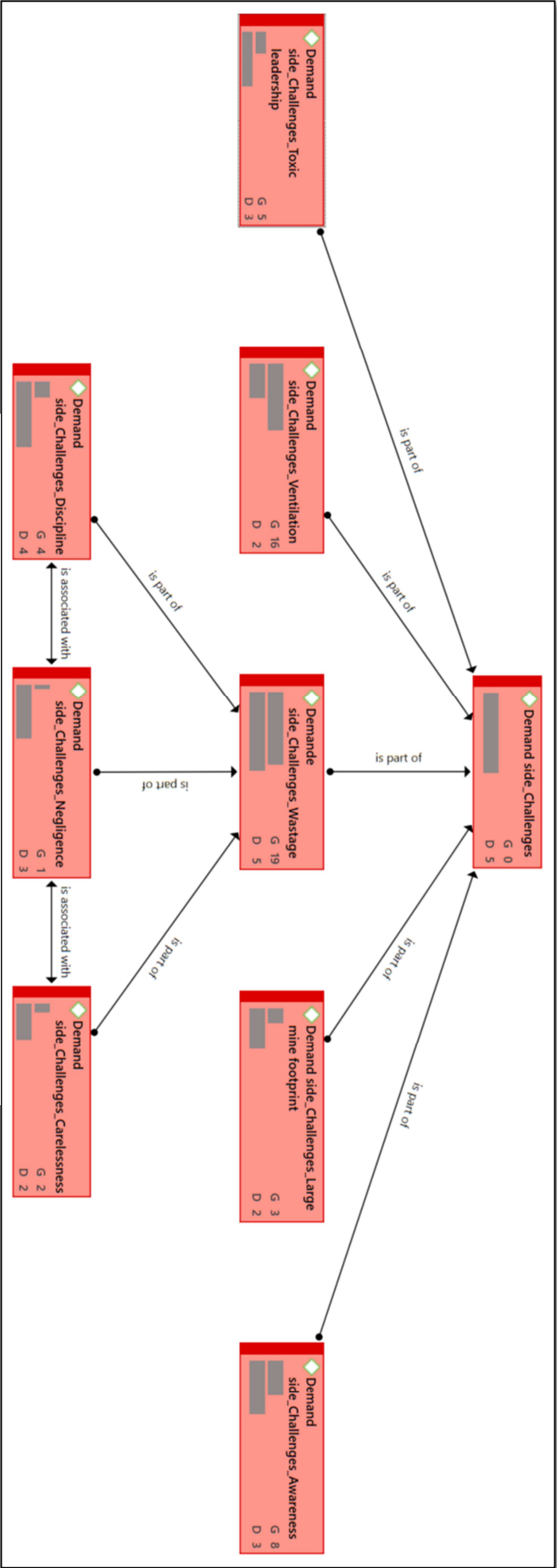


Figure 3-10: Network diagram: Demand-side challenges

3.3.4.2 Ventilation

Ventilation with compressed air is a problem on all the PGM operations included in this study. The underlying problem is that PGM mines are inherently hot. The ventilation of the mine is often inadequate, which results in workers using compressed air for ventilation.

“Your typical problems will be where there is poor ventilation ... guys will ventilate with compressed air.” (Participant 4)

“... you know what stops a guy to open ventilation pipes to cool down? And it costs us a lot of money. And if it is necessary to cool down, then it is fine, but the ventilation doors and the ventilation fans must also be operated in an effective manner.” (Participant 8)

*“The working environment where those people work is of such a nature that the worker does not necessarily have any other choice than to use compressed air for ventilation. My opinion is that at places such as *** Shaft where there is not a significant difference between the baseload and the peak consumption, I know for a fact that the guys use the compressed air outside of the drilling shift for purposes for which it is not intended to be used. My assumption is that it is ventilation. The problem goes further back and that is that the guys ventilate the working areas with compressed air because it is warm. It is warm because the ventilation is inadequate.” (Participant 3)*

3.3.4.3 Wastage

All the interviewees agreed that the biggest wastage of compressed air occurs at the shafts:

“Wastage. This is the only issue if you ask me. We can supply air, but the people waste it and they do not realise the impact of that wastage in terms of rands and cents.”
(Participant 2)

“Well, the baseloads of the shafts are too high. This stands like a pole above water. And the reason why the baseloads are so high is because compressed air is for purposes that it is not supposed to be used for ...” (Participant 3)

“This is a big problem, the leaks and those things. The result of all of this is that you end up with a huge baseload, you know a baseload of 70 to 80% of your peak demand is a ridiculous.” (Participant 6)

Discipline

A lack of discipline among mineworkers is a major cause of compressed air wastage underground:

“The discipline comes in where you have a guy going into a refuge bay, opening the valve, and leaving it open when he goes out of the refuge bay. He does not close the valve when he walks out, this is discipline.” (Participant 2)

“That is another thing, poor discipline, I mean I spoke about the ones where they are leaving the valve open, but there is also poor discipline on the stopes as well. When a guy is finished drilling, instead of closing the valve, he just decided to leave it because they have this tendency that they believe that when they leave it open, when they come in the next morning their area will be cool ...” (Participant 4)

Negligence

Negligence also plays a role in the wastage of compressed air underground:

“Mining people have this tendency when there a leaking compressed air pipe or a leaking water pipe, they do not attend to it immediately. It will be left until ...” (Participant 4)

Carelessness

Production is the first priority on a PGM mineshaft. Initiatives to save compressed air are lower on the priority list.

“... one of the biggest things is the mining, the mining guys, and I understand you know where it comes from, they, they as in Afrikaans, they say “boor en blaas” you know that is all they really think about you know.” (Participant 5)

“... you know the focus of the people is not always, it is not always their core business ...” (Participant 6)

3.3.4.4 Large mine footprint

Participant 2 pointed out that older mines have a very big footprint. The result is a large and intricate compressed air network, spanning over multiple underground mining levels, which is difficult to manage and maintain:

“The other part is the challenges with a very big footprint, it is big and complex, making it difficult to keep fingers on the pulse.” (Participant 2)

3.3.4.5 Awareness

The average mineworker is not aware of how expensive compressed air is. Raising awareness among miners about the high cost of wasting compressed air is an important step towards reducing demand.

“So why is it important? People take it for granted. The general guy in the mine knows there is compressed air available in a mine, but he thinks it is like the air that that he breathes, there is an endless supply. He misses it when it is not available, if it is not enough, but he does not really have a feel for what it entails.” (Participant 2)

“And that is where the challenges lie, to swing those guys’ mentalities that they really start to focus on this and understand what the compressed air costs. That sense of realising you need to close your valve at the end of the shift. I would say that is the biggest challenge we have; it is something we have not really solved yet. It is like sweeping water uphill with a broom, the moment you stop, the water just flows goes back to where you started.” (Participant 6)

3.3.4.6 Summary

To summarise, the main findings of the ‘Demand-side Challenges’ theme are:

- Toxic leadership that prioritises production above saving compressed plays a role in the wastage of compressed air on shafts.

- A PGM mine is inherently a hot environment. Ventilation is often inadequate in certain areas of a mine, resulting in compressed air being misused to compensate for the lack of ventilation.
- Most compressed air wastage occurs on the demand side at the PGM mineshafts.
- A lack of discipline, negligence and carelessness drive compressed air wastage on the shafts.
- The older a shaft, the larger and more intricate its compressed air network is, which makes it difficult to manage and maintain.
- The average mineworker is not aware of the significant cost of wasting compressed air. It is therefore important to raise awareness in this regard.

3.3.5 Efficiency

The 'Efficiency' theme shown in Figure 3-11 consists of the two subthemes, with the 'Best Practices' subtheme consisting of five categories:

- Best practices
 - Specialisation
 - Outsourcing
 - Insourcing
 - Teamwork
 - Reporting
- Priority

3.3.5.1 Best Practices

Since the interviewees all managed compressed air on PGM operations, they were well aware of best practices in terms of compressed air management, albeit on a high level:

"You must get your consumption vs reduction efficiency right. Your compressed air cubes per tonne needs to be right. If you get it right the mine makes money. It is as simple as that." (Participant 3)

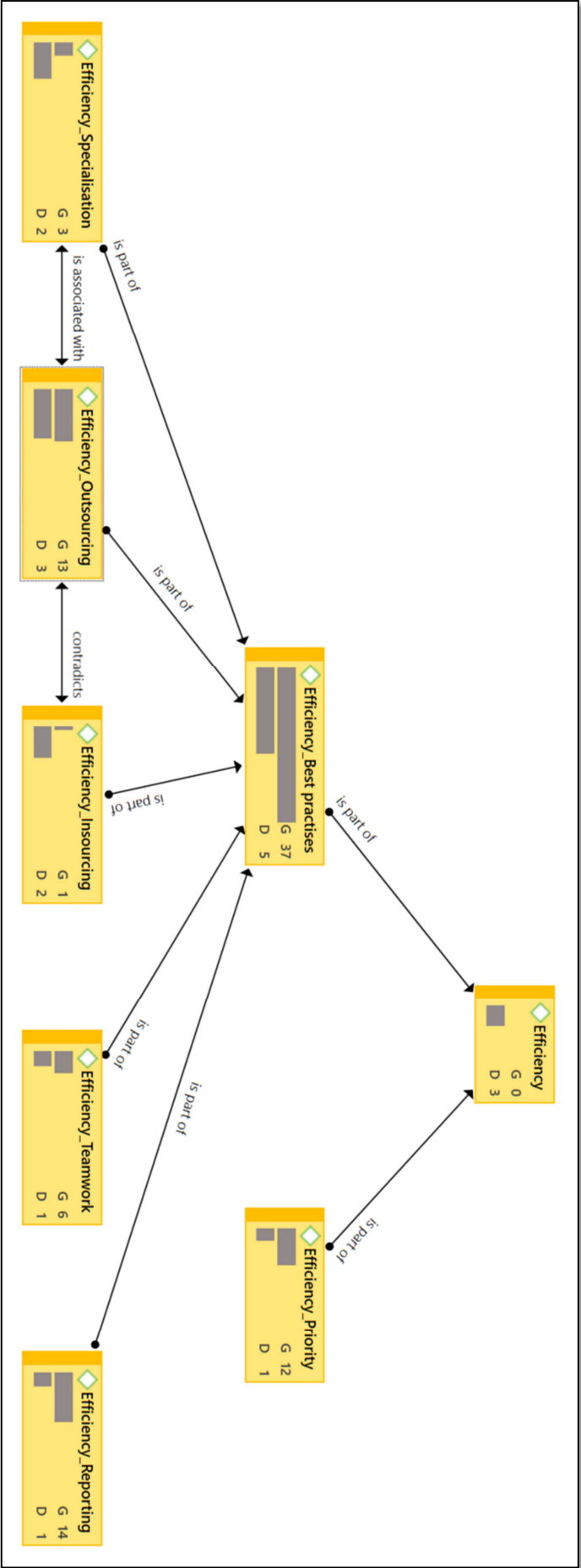


Figure 3-11 : Network diagram: Efficiency

“Well, we try to save. We pay x cents per kWh. The idea is to run as few units as possible. That is why we constantly look at it with the control room, we look at the pressures, the pressure profiles per shaft and we try to keep the pressure as low as possible, while still allowing the miners to do their jobs. By doing this, you will find that you can stop certain units during certain periods of the day, especially in off-peak periods such as afternoons and evenings. During the drill shift ... then we must give the pressure, then we run the necessary compressors. But it's more in the off-peak times that we try to save by stopping compressors.” (Participant 6)

“Ja, well look we've got ... we have installed certain valves as well. I am talking about on the levels as such, you know with the drilling session from about 08:00 to 12:00 is usually the drilling period. You know that time we don't touch anything, but you know later on in the evenings as well you know it is much better to rather close off the air to certain areas where we know it just gets wasted. That is a very big saving as well. And then of course the set points also make a difference as well of the compressors you know how you load it, how you unload it to a certain extent. But then of course you know you can only unload to, as I say, a certain extent then you have to rather stop it. Because then it is not feasible in running it.” (Participant 5)

Specialisation

The consensus among the interviewees was that specialisation is a best practice.

“What I like about the whole arrangement is that the guys who are there, they are actually subject experts. When it was still with the shafts, ... the guy's attention is divided, he was having compressors, he was having fridge plants, he was having winders, he was having the shaft, so his attention was not entirely on the compressors. He was not a specialist. Now we took that, and we booked it under a specialist. And that is how it is going to stay ...” (Participant 4)

Outsourcing versus insourcing

Eight of the nine interviewees agreed that specialist tasks such as energy management on compressed air systems and condition monitoring on compressors should ideally be outsourced to third-party specialists:

“I think there is value to you guys. Firstly, because you are specialists, because you work on different mines, you know you guys come here with a lot more knowledge than a guy who just works here. Also, you know in my job, I do not have time to go into such detail. Unfortunately, this is the problem we have. If I had a lot of resources, then we could have done it ourselves, but we just do not have the resources. The foremen are stretched, the engineers who work here, they have so many other things that keep them busy all day, from meetings with unions to all kinds of HR issues. They just do not have time to focus on the detail of energy management. You offer that expertise and you offer systems. I see value in that.” (Participant 6)

“I think the mine has the knowledge to do it ourselves, but we don’t have the capacity to do it ourselves. My personal feeling is, yes there is a place for third-party guys. Because you come with a different perspective. We are here to drill and blast. My main function is to supply compressed air to the miners.” (Participant 9)

*“Well I think ... the condition monitoring I believe is too specialised for the mine to do. I do not really believe that the mine can do it. Also, the time that it takes, and the guys of *** knows exactly what to look at because they are the experts. And the same applies to you guys, I do not think we are really compressed air energy savings experts. So, I do not think it is bad thing to outsource certain things.”* (Participant 1)

Participant 5 was the only interviewee who believed that PGM operations should build the capacity to do everything by themselves and not use third-party service providers. His motivation was that third-party service providers often overcharge for their services.

“Ja, I think the mine should build the capacity themselves hey. You know, not to be funny, those guys take us to the cleaners hey. You know we are talking about compressed air, but there are a lot of other things that I look after like variable speed drives and things like that.” (Participant 5)

Teamwork

It was found that teamwork is essential to the success of compressed air management initiatives, especially if an initiative is rolled out simultaneously at the different shafts of a PGM mining operation:

*“... there has been a lot of thought on this subject, it has just never been correctly implemented and managed. But one guy like me cannot run it on a mine like ***. It is way too big. You need leaders at every shaft to do it.” (Participant 7)*

“One thing that I would actually change is how compressed air is seen, and obviously the repairs of leakages, the data analysis in terms of checking where we are using a lot of compressed air and that is also important. For me it is more all about having the buy-in from all stakeholders. And when I am talking about that, I am talking about the services as well, I am talking about the Rock Engineering Department, I am talking about the Ventilation Department, I am talking about the Mining Department. If all of us could actually have buy-in ...” (Participant 4)

Reporting

Reporting on compressed air intensities, in terms of compressed air consumption [indicated in cubic metres (m³) per tonne], is a prevalent practice on all PGM operations included in this study. This reporting usually takes place on a weekly or monthly basis.

*“Depending on what the shafts want to see, but yes, the guys are aware of their intensities. They know where the problem areas are, and I also think that management are starting to monitor it in this way. And this is where demand control plays a role, because shafts such as *** or *** that are running at over 400 cubes per tonne is simply not acceptable. Those graphs point it out.” (Participant 6)*

3.3.5.2 Priority

The interviewees were all acutely aware of the high cost of generating compressed air and the resulting importance of saving compressed air.

“Yes ... we have come a long way with compressed air. You know in earlier years people did not really care about compressed air. We made such good money with the good platinum prices years ago. It was not really an issue. Now with the lower metal prices that have fallen so drastically, you know, we started looking at the large costs and we know for a fact that compressed air is an expensive commodity. With compressed air it is a big saving because compressed air costs a lot of money.”
(Participant 5)

The problem lies with the demand side, the shafts, where production is priority and saving electricity is an afterthought:

“When the engineer goes to the shaft and tells the GM that they are unproductive in terms of compressed air consumption per tonnes, the GMs often say that is negligible and that they are willing to pay that premium if the shaft keeps on producing the tonnes ...” (Participant 3)

3.3.5.3 Summary

The main findings of the ‘Efficiency’ theme are:

- Managers of compressed air systems on PGM mining operation are aware of the high-level best practices concerning the management of compressed air.
- Specialisation is a best practice that should be applied in the management of compressed air on PGM mining operations.
- Outsourcing of certain compressed air management tasks to third-party specialist service providers is recommended.
- Teamwork is imperative to the success of compressed air management initiatives, especially when such initiatives are being rolled out to multiple shafts.
- Reporting on compressed air intensities per shaft is a best practice that is widely used in the PGM mining industry.
- The low priority given to saving compressed air on PGM mineshafts is problematic.

3.3.6 Information

The network diagram for the ‘Information’ theme is shown in Figure 3-12. The theme consists of the following subthemes:

- Lack of information
- Information overload
- Adequate information

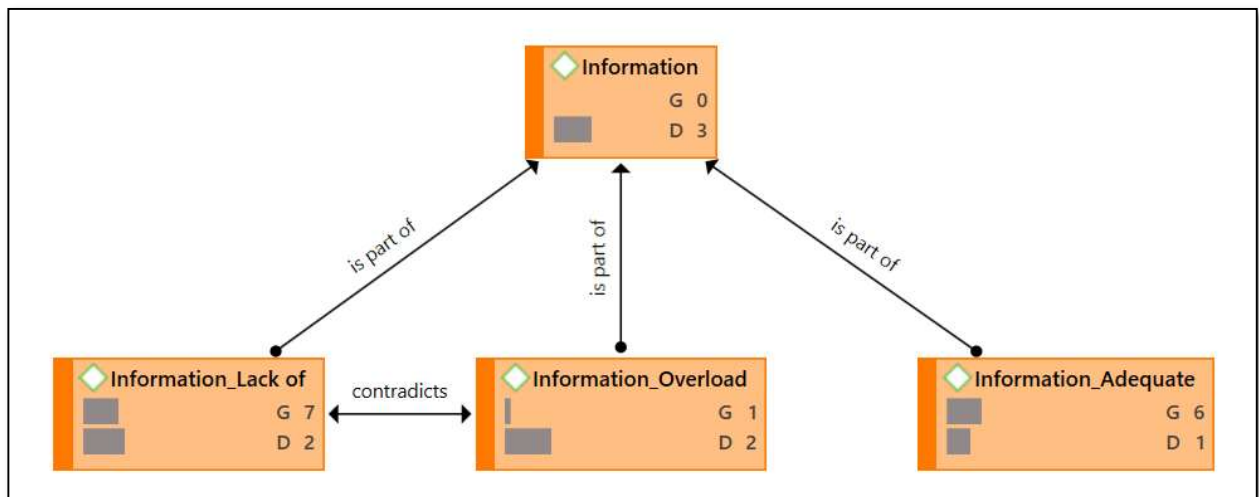


Figure 3-12: Network diagram: Information

3.3.6.1 Lack of information

Two interviewees indicated that a lack of information makes it difficult to manage the compressed air consumption of the shafts. Although the flow of compressed air to the shafts is measured accurately, the problem is that not enough flow meters are installed underground to measure the compressed air consumption of the mining levels. Some mining levels have flow meters installed, but these do not always give accurate readings due to a lack of calibration and maintenance:

“The moment the air goes down the shaft, it is limited information. This is where our shortcoming is. I cannot really say I know what happens with the compressed air underground. This is my shortcoming; I would really like to know what the compressed air consumption of every underground working area is. If I could know this for every minute of the day, then it would be the ideal. Then I could pinpoint exactly what is going on and where the problem areas are. Currently, we do not know this. We have very limited information after the compressed air goes down the shaft. On certain shafts, we have the consumption per level and in most cases that consumption measurements are also inaccurate. It is indicative, but not accurate.” (Participant 2)

Participant 4 pointed out that he would like to verify the readings that he receives from the surface flow meters with underground flow meters on the levels:

“... the shortcomings on my side, which I see, is that I do not have anything underground to compare what I am seeing on surface. In most cases what I am seeing on the graphs, is what is recorded on my bank. So, I am saying that, even though it might be a problem with what I am getting from the bank, I would not know. It is something that I am even questioning now. I would like to have a means that I can compare underground as well ...” (Participant 4)

3.3.6.2 Information overload

This category is a contradiction of the previous category. Only one interviewee indicated that he receives an overload of information:

“I spend my first hour and a half every morning to go through reports. And this is something that I do not think people always realise. An hour and a half of my time is spent every day on going through this wealth of information to find out if there is anything important.” (Participant 1)

3.3.6.3 Adequate information

Five interviewees felt that they receive adequate information that supports them in the management of the compressors:

“I get information, I get water temperatures, I receive all the information I need ... I really get a lot of information that helps me. I do not think we are lacking in that area.”
(Participant 1)

“There is almost nothing on our machines that I do not monitor. If there is anything we want to know, that we got a bug on, then I get my technician to trend the data.”
(Participant 8)

3.3.6.4 Summary

The main findings of the ‘Information’ theme are:

- Compressed air infrastructure underground is not instrumented adequately. For example, the compressed air consumption per mining level is seldomly measured.

The lack of underground instrumentation could be attributed to it being more difficult to install and maintain instrumentation underground than on surface.

- Compressed air infrastructure on surface is adequately instrumented. For example, each shaft's compressed air consumption is measured accurately with a flow meter installed on surface.
- It is important to use the available information to manage compressed air infrastructure on a PGM mine effectively. Care must be taken to prevent counter-productive situations in which employees are overwhelmed with information.

3.4 Results of the Quantitative Study

3.4.1 Introduction

The quantitative results indicate the impact of various initiatives to reduce compressed air consumption at the PGM operations included in this study. The results are provided in the form of 24-hour profiles, indicating either power consumption (measured in kW) or compressed air consumption (measured in m³/h).

The quantitative data originate from electric power and flow meters installed at the PGM mines included in this study. Each graph shows a baseline profile and an actual profile. The baseline profile represents the power or flow profile before the implementation of the initiative, while the actual profile represents the power or flow profile after the implementation of the initiative. The difference between the baseline and the actual profile indicates the impact of the initiative. If the actual profile is lower than the baseline, it indicates that a saving was achieved.

The resulting electricity cost savings of each initiative were calculated by using the 2019/2020 Eskom Megaflex electricity tariffs (Eskom, 2019b:17). The specific tariffs apply to consumers supplied directly by Eskom and that are located in the < 300 km transmission zone with a supply voltage ranging between 500 V and 66 kV.

3.4.2 Supply-side control

Figure 3-13 shows the impact of supply-side control on the power consumption profile of a compressed air ring supplying multiple PGM shafts. The supply-side control consisted of lowering the supply pressures to the shafts outside the drilling shift. This explains the small difference between the two profiles in the period from 08:00 to 13:00.

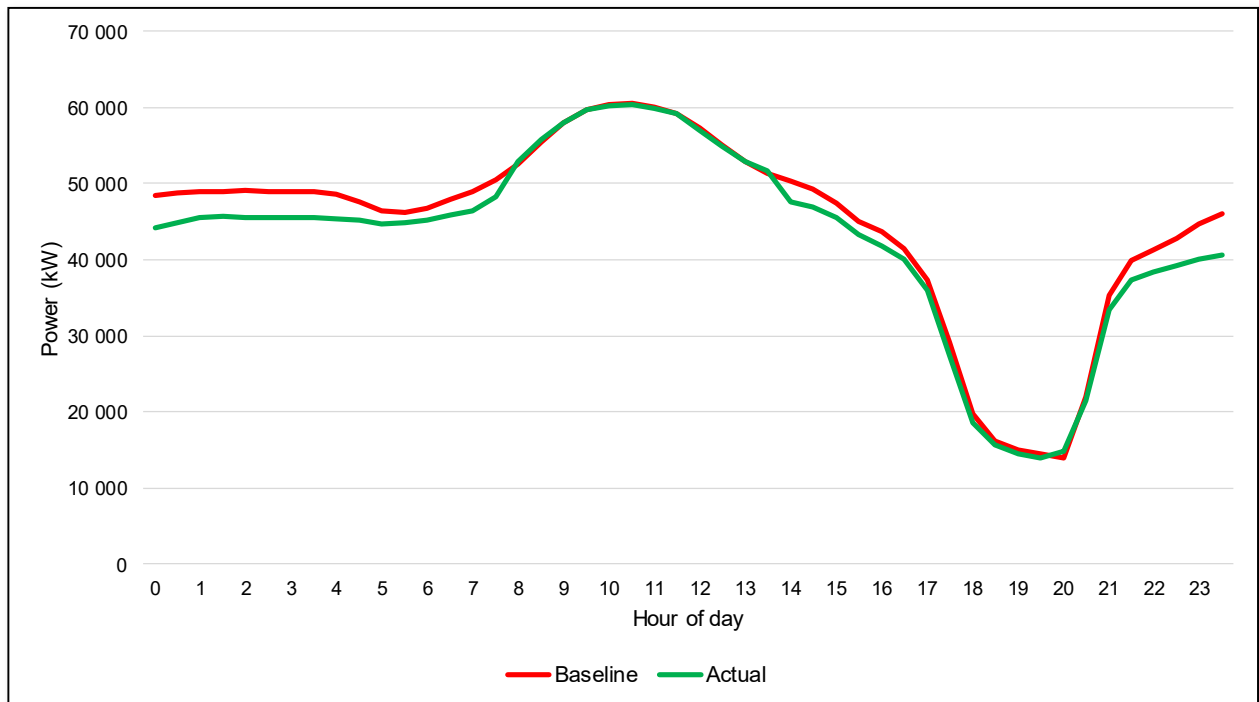


Figure 3-13: Impact of supply-side control

This supply-side control was achieved by training the control room operators to use the minimum number of compressors in combination with lower compressor output set points to prevent the oversupply of compressed air to the shafts. The supply-side control shown in Figure 3-13 represents an annual electricity cost saving of R12 million. The results shown in Figure 3-13 confirm the applicability and effectiveness of the compressed air supply-side savings measures discussed in Section 2.5.1.

3.4.3 Demand-side control

Figure 3-14 shows the impact that isolating the supply of compressed air to an inactive working area has on the compressed air consumption of a mining level. A comparison of the consumption of all the mining levels of a particular PGM mineshaft with the production

figures of each level indicated one mining level that consumed an abnormally high amount of compressed air. A portable air flow meter was used to do an underground audit of the level to measure the amount of compressed air flowing into the different working areas. A line supplying compressed air to an inactive working area was discovered. The line was isolated and the compressed air consumption on the level reduced significantly by about 50%, representing an electricity cost saving of more than R6 million per year. This confirms the qualitative results presented in Section 3.3.4, which indicated that compressed air is wasted regularly on the demand side.

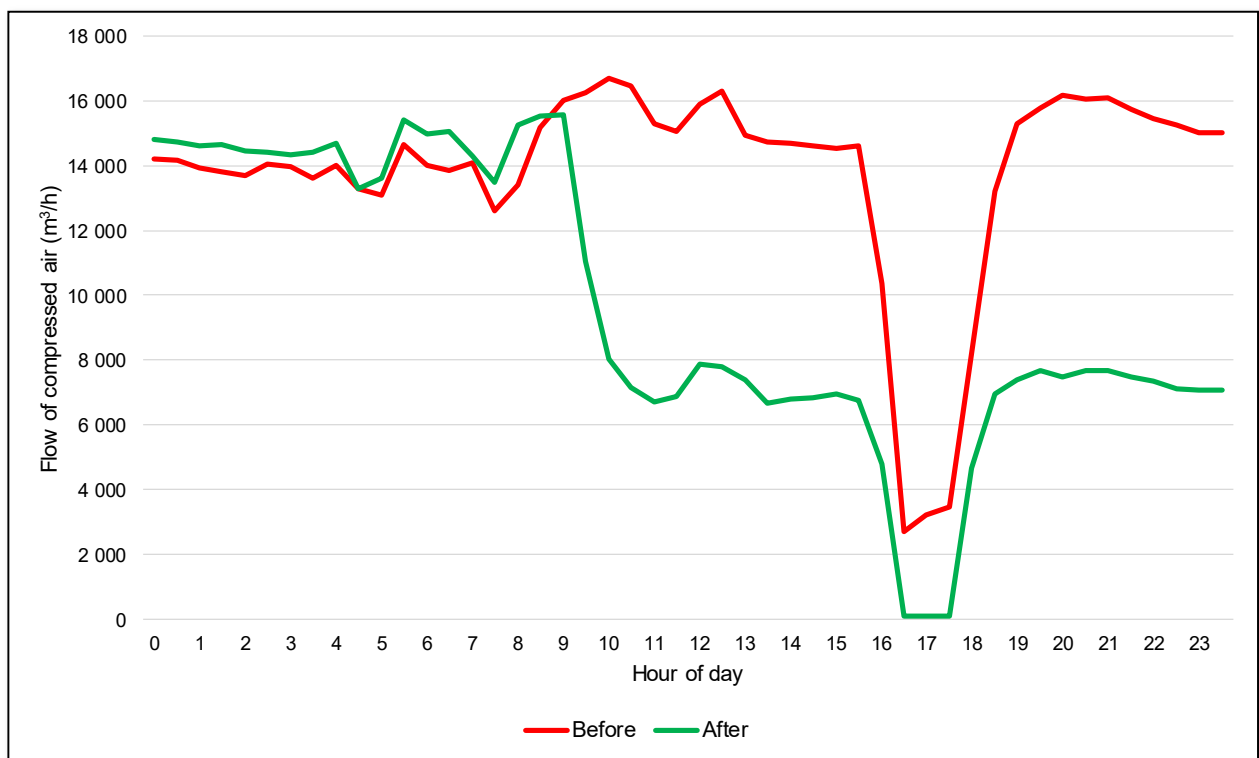


Figure 3-14: Impact of closing off compressed air at an inactive working area

Figure 3-15 shows the result of optimising the control philosophy of a surface valve that is installed in the main compressed air line that supplies a PGM shaft.

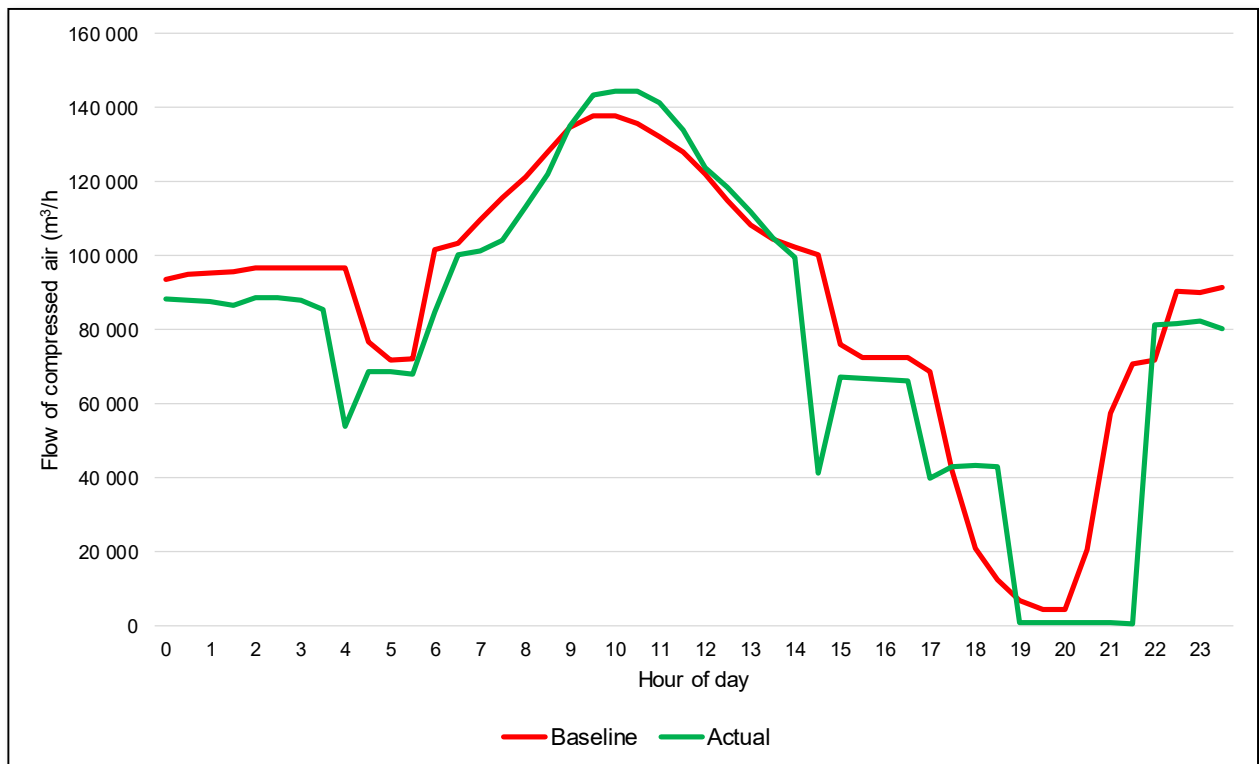


Figure 3-15: Impact of optimising the control of a shaft valve

The baseline profile represents the flow profile before optimisation. The actual profile represents the flow profile after optimisation. The optimised flow profile was achieved by gradually reducing the downstream pressure set point of the automated surface control valve. The reduced pressure set points did not have any adverse effects on production since the reduced compressed air pressures supplied were still adequate to support the production processes. The resulting annual electricity cost saving from applying the optimised control philosophy is about R4 million.

3.4.4 Combination of supply- and demand-side control

Figure 3-16 shows the impact of applying a combination of supply-side and demand-side control on the power profile of the same compressed air ring shown in Figure 3-13.

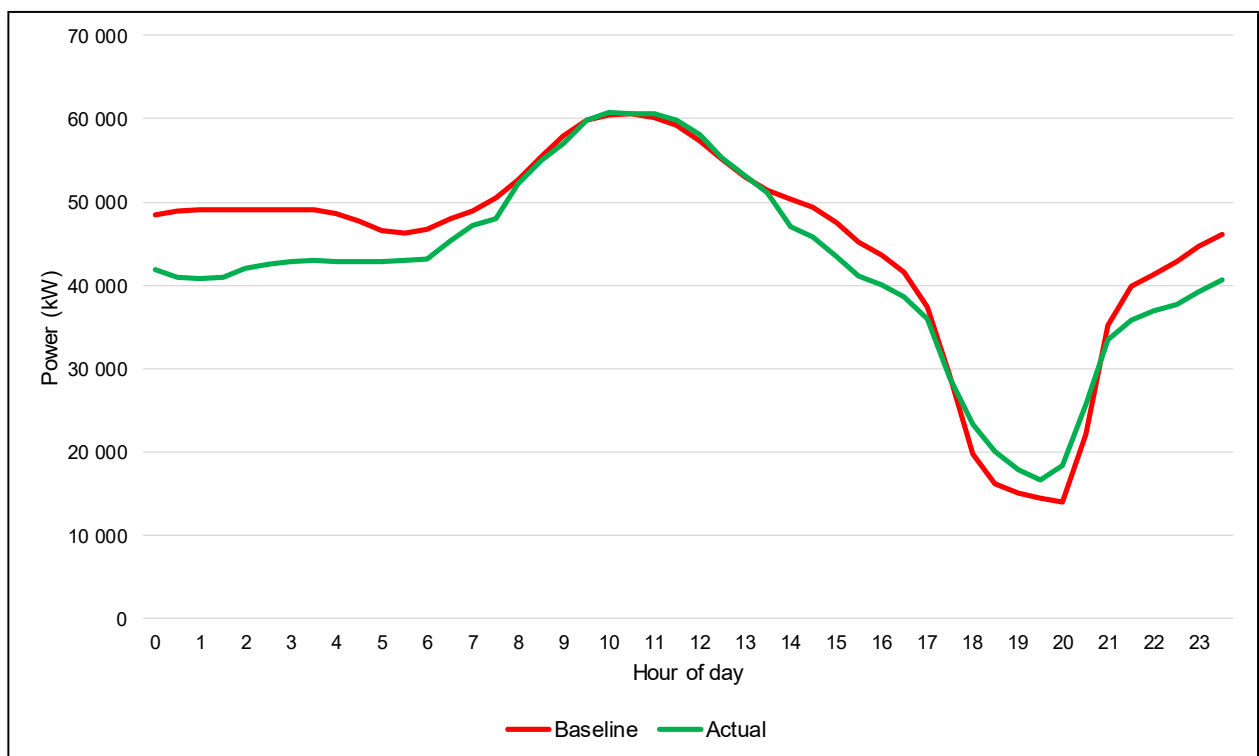


Figure 3-16: Impact of a combination of supply-side and demand-side control

While the supply-side control resulted in an annual electricity cost saving of R12 million, the combination of supply-side and demand-side control measures yielded an annual electricity cost saving exceeding R14 million. Thus, demand-side and supply-side initiatives should not be done in isolation. A combination of supply-side and demand-side initiatives to reduce compressed air consumption yields the best results.

3.4.5 Summary

The results of applying supply-side initiatives, demand-side initiatives and a combination of supply-side and demand-side initiatives were provided. Interestingly, these results were achieved in a relatively short period of only 8 months while using only existing infrastructure on a single compressed air ring. Further electricity cost savings could be obtained, especially if the PGM operation is willing to spend capital on infrastructure such as control valves and flow meters on mining levels.

If the results achieved over the period of 8 months are extrapolated to all the shafts of the PGM operation, the expected electricity cost saving is conservatively calculated as R66 million per year. This is 15% of the current annual compressed air cost of R438 million per year. The expected time frame for achieving this cost saving is 24 months. The 15% reduction equates to an average hourly electricity demand reduction of 13.5 MW. This is a significant demand reduction from Eskom's perspective because it is equal to the average yearly electricity consumption of 13 500 South African households.

3.5 Conclusion

The results of the qualitative study were presented in this chapter. Six themes were identified in the quantitative data. Each theme focused on an aspect of managing compressed air in the PGM mining industry. Valuable information on the practical aspects and challenges of each theme was obtained from the interviewees. The qualitative study was supported by a quantitative study on the impact of various initiatives to reduce compressed air consumption in the PGM mining industry. The findings of the qualitative and quantitative studies correspond with the literature study on compressed air consumption on the compressor savings measures introduced in Chapter 2. Although compressed air is the highest electricity consumer on a PGM operation, there are numerous opportunities for improving the efficiency of compressed air consumption in the PGM mining industry.

3.6 Chapter Summary

This chapter started by presenting an overview of the qualitative research process followed in this study. Aspects such as data gathering, sample size and thematic analysis were discussed. Information on the demographic profile of the interviewees, consisting of experienced senior managers who manage compressed air at PGM mining operations, was provided. The results of the qualitative study were presented in the form of a thematic analysis, comprising six themes consisting of various subthemes and categories. Quantitative results were also presented to show the impact of measures to reduce compressed air consumption.

CHAPTER 4 – CONCLUSION AND RECOMMENDATIONS

4.1 Introduction

Chapter 4 presents a framework for managing compressed air in the PGM mining industry. The framework is developed on the basis of the qualitative and quantitative results presented in Chapter 3. This is followed by a section that describes the additional benefits of applying the framework. A summary of the entire study is provided, whereafter the chapter concludes with recommendations for future work.

4.2 Framework for Managing Compressed Air in the PGM Mining Industry

4.2.1 Introduction

The primary objective of this study is to develop a framework for managing compressed air in the PGM mining industry. The framework was developed on the basis of both the qualitative and quantitative results presented in Sections 3.3 and 3.4.

The framework is divided into two parts, namely supply-side (applies to the generation of compressed air) and demand-side management (applies to the consumption of compressed air on the shafts). The framework consists of focus areas, which are divided into priorities. Each priority consists of one or more actions steps.

4.2.2 Supply-side measures

The supply-side part of the framework is presented in Table 4-1. More detailed information about the focus areas, priorities and actions are provided below.

Table 4-1: Supply side of framework for managing compressed air on PGM mining operations

	Focus area	Priority	Action
Supply side	Compressor management	Positioning	1. Use simulations to determine optimal positioning of compressors. 2. Use cost-benefit analysis to determine feasibility of compressor relocation.
		Redundancy and capacity	1. Monitor compressors continuously to determine potential shortcomings before there production is affected negatively.
	Maintenance	Continuous improvement of maintenance procedures	1. Monitor efficiency and quality of routine maintenance procedures. 2. Monitor efficiency and quality of condition-monitoring procedures. 3. Implement improvements to routine maintenance and condition-monitoring procedures.
		Access to information	1. Implement automated reports to monitor the key performance indicators of compressor maintenance on a daily basis. 2. Use different levels of data abstraction in the automated reports to prevent an overload of information.
		Specialisation	1. Ensure that compressor maintenance is conducted by specialists. Outsource maintenance if necessary to ensure specialisation.
		Standardisation	1. Ensure that new equipment such as electric motors and compressors adhere to the same standard.
	Efficient supply of compressed air	Match supply with demand	1. Switch off compressors when not needed. 2. Use inlet guide vane control to reduce the output pressures of compressors in periods when less compressed air is required.

4.2.2.1 Compressor management

Positioning

To minimise transmission losses, compressors must be positioned as close as possible to the shafts being supplied with compressed air. Fluid modelling software should be used to simulate the compressed air networks. These simulations could be used to determine the effect of relocating compressors in terms of the pressure and volume of compressed air supplied to PGM mineshafts. This enables business cases for compressor relocation to be developed through cost-benefit analyses.

Redundancy and capacity

The redundancy and capacity of compressors should be monitored continuously to identify shortcomings before production is affected adversely. Redundancy and capacity should be addressed by ensuring, firstly, that enough compressed air is available to meet demand and, secondly, that enough spare compressors are available during breakdown events to prevent production interruptions. Another way of addressing redundancy and the capacity of compressors is by lowering the demand for compressed air.

4.2.2.2 Maintenance

Continuous improvement of maintenance procedures

Routine maintenance and condition-monitoring procedures are worthless if they are not performed correctly. Continuous monitoring and improvement of both routine maintenance procedures and condition-monitoring procedures are important for ensuring that compressors are maintained adequately.

Access to information

On all the PGM operations included in this study, the compressors are well-instrumented and, resultingly, a wealth of data is available for each compressor. It is important to transform this data into information and use it to enhance the maintenance management process. Importantly, data should not overload maintenance personnel with information. This could be achieved by developing compressor maintenance reports that provide different levels of abstraction. Reports should be set up in such a way that high-level

information is provided first, with detailed information only presented later in the report. This ensures that the reader is not bombarded with a wealth of detailed information. Instead, the information is available at different levels of detail.

Excerpts from a compressor maintenance report that employs the abstraction principle are provided in Appendix F. The report starts with high-level information regarding the occurrence of surge warnings, compressor trips and blow-off before providing more detailed information about individual compressors. This enables the reader to get a high-level overview of problem areas first before drilling deeper into the detailed information concerning the identified problem areas.

Specialisation

Work specialisation of maintenance personnel should be an important priority where the maintenance of production critical equipment such as compressors is concerned. Specialisation will result in higher quality work as well as productivity in the execution of maintenance tasks and procedures. Specialisation could also be achieved by outsourcing compressor maintenance tasks to third-party service providers.

Standardisation

Standardisation is a priority that is relevant to any maintenance procedure. It makes sense that standardising equipment reduces maintenance costs since fewer spare parts need to be kept in stock and maintenance procedures are simplified.

4.2.2.3 Efficient supply of compressed air

Matching the supply of compressed air with the demand is important from a supply-side perspective. As shown in Section 2.5.1, the demand of a typical PGM mineshaft varies over the different working hours of a day since the different production processes have different demands for compressed air. At all the PGM operations included in this study, there is a tendency to oversupply the mineshafts with compressed air outside the drilling shift. Measures to reduce the pressure of compressed air supplied to the shafts should be implemented to reduce consumption. The supply pressure of the compressed air to the shafts should be lowered gradually until complaints of inadequate supply pressure are received. This could be done by reducing the compressor output pressure set points.

4.2.3 Demand-side measures

Table 4-2 presents the framework's demand side. 'Efficient Use of Compressed Air' is the only focus area. More information about the priorities and actions are provided below.

Table 4-2: Demand side of framework for managing compressed air on PGM mining operations

	Focus area	Priority	Action
Demand side	Efficient use of compressed air	Reduce wastage	1. Use control valves to reduce supply pressure to shafts or levels in periods with lower demand for compressed air. 2. Manage leaks. 3. Blank off compressed air flow to inactive working areas. 4. Monitor the efficiency of ventilation in working areas to prevent the misuse of compressed air to make up for inadequate ventilation.
		Access to information	1. Install instrumentation such as flow meters on mining levels to allow the detailed monitoring of compressed air consumption. 2. Benchmark underground working areas in terms of compressed air consumption versus production to determine problem areas. 3. Implement automated daily compressed air efficiency reports. 4. Use different levels of data abstraction in the automated reports to prevent an overload of information. 5. Motivate mining personnel to report wastage of compressed air underground. 6. Do frequent inspections in underground working areas to find leaks and other compressed air inefficiencies.
		Awareness of the cost of compressed air wastage	1. Put up posters that indicate the cost and/or potential impact of wasting compressed air.
		Teamwork	1. Implement bonus scheme for all employees linked to compressed air efficiency on shaft level.
		Specialisation	1. Ensure that efficiency improvement initiatives are implemented by specialists. Outsource if necessary.

4.2.3.1 Reduce wastage

Control valves

As shown in Section 3.4.3, using a control valve installed in the main compressed air supply line of a shaft is a proven way of reducing consumption. Such a control valve could be programmed to reduce the supply of compressed air to the shaft automatically based on predetermined flow or pressure set points that vary according to the varying compressed air demand of the shaft. The same principle could be applied to control valves installed in the compressed air supply lines on the mining levels.

Leak management

Leakage on compressed air pipes underground is a common phenomenon. Leak detection and repair should be prioritised to reduce the wastage of compressed air. A complicating factor is that the network of pipes supplying compressed air to different mining areas could be quite large and intricate, especially in older shafts.

Inactive mining areas

Due to the intricate nature of underground compressed air networks, it often happens that the compressed air supply pipes to underground working areas are not blanked off. Therefore, sporadic checks must be done to make sure that there are not compressed air flowing in pipes that supply inactive working areas.

Monitoring of ventilation efficiency

As indicated in Section 3.3.4, inadequate ventilation is one of the most common reasons for compressed air wastage. In mining areas with inadequate ventilation, compressed air is used to compensate for the lack of ventilation. This can be prevented by monitoring the ventilation efficiency in active mining areas and implementing measures to improve ventilation efficiency where necessary.

4.2.3.2 Access to information

Instrumentation

It is important to install instrumentation to quantify compressed air consumption. The ideal solution is to have a flow meter installed in the main compressed air supply line on each mining level. This enables compressed air consumption to be measured per mining level and the changes in consumption patterns to be detected. For example, if the compressed air consumption of a mining level shows a drastic increase and there is no justification for the increased consumption, it is evident that there are leaks or other inefficiencies on that mining level.

Benchmarking of the compressed air consumption of underground working areas

The installation of flow meters further allows the mining levels to be benchmarked in terms of actual versus expected compressed air consumption. The expected compressed air consumption is calculated by auditing all the equipment on the level that uses compressed air. A significant difference between the actual and expected consumption of compressed air indicates leaks or other inefficiencies.

Daily compressed air efficiency reports

An automated report that compares the compressed air consumption of an entire shaft with the baseline is a useful tool for monitoring consumption on a daily basis. To ensure that inefficiencies are addressed promptly, it is important to monitor compressed air consumption daily rather than weekly or monthly.

The baseline is determined by:

- Using the historical consumption of the shaft.
- Using a benchmark based on the production of the shaft.
- Using a benchmark based on best practices for compressed air consumption.

Appendix E provides an example of a daily compressed air efficiency report. For the daily compressed air report, it is also necessary to employ data abstraction principles: the report starts with high-level information of the compressed air consumption of the entire

shaft before it provides more detailed information about compressed air consumption per mining level.

Reporting of compressed air wastages and inefficiencies

Managing and maintaining an underground compressed air network is difficult because the network is often extensive and intricate. It is therefore recommended that mineworkers should be motivated to report leaks and other inefficiencies that they notice while working underground.

Underground inspections

Underground inspections of compressed air infrastructure are necessary, especially in known problem areas where many inefficiencies exist. For verification purposes, it is necessary to do follow-up inspections after repairing compressed air network infrastructure or addressing inefficiencies.

4.2.3.3 Awareness on the cost of compressed air wastage

At all the PGM operations included in this study, there is a lack of awareness regarding the cost of wasting compressed air, especially among the mining personnel working on the shafts. Measures to increase awareness regarding the cost of compressed air should be implemented. One such a measure is displaying posters in the shafts that focus on the cost of compressed air. An example of such a poster is provided in Appendix G.

4.2.3.4 Teamwork

The qualitative results indicated that the average mineworker on a PGM shaft is not concerned with the cost of compressed air. Compressed air is merely a resource used to achieve production, which is a mineshaft's top priority. Saving compressed air is regarded at the shaft engineer's problem. One measure of changing this mindset is to implement a bonus scheme for all shaft employees. The bonus scheme should be linked to the overall efficiency of compressed air consumption of the shaft in terms of the volume of compressed air (measured in m³) consumed per tonne. This will motivate all employees of a shaft to do their part in saving compressed air.

4.2.3.5 Specialisation

Specialisation should also be an important priority when implementing measures to improve the efficiency of compressed air usage on PGM mineshafts. This can be achieved by outsourcing the implementation of compressed air savings initiatives to third-party service providers.

4.3 Additional Benefits of Applying the Framework

The immediate benefit of implementing initiatives to reduce compressed air consumption is electricity costs savings. There are also other benefits, which are briefly discussed below:

- **Reduced potable water consumption:** The compressors used at the PGM operations consume large amounts of potable water for cooling purposes. Reducing compressed air consumption results in less running time of compressors, which implies reduced volumes of potable water being consumed for cooling purposes.
- **Reduced maintenance costs:** Reduced running time of compressors results in reduced wear of electric motors and other compressor components.
- **More compressed air available for its intended purpose:** Reducing the wastage of compressed air on the demand side results in more compressed air being available for its intended purposes. This is a significant advantage, since PGM shafts that waste compressed air often experience problems with inadequate compressed air pressure, which affects production negatively.
- **Reduced electricity demand from Eskom:** Lower demand for compressed air implies a reduction in the electricity required to power compressors. This assists Eskom to meet South Africa's electricity needs.

4.4 Summary of the Study

Chapter 1 commenced by introducing the PGM mining industry. South Africa possesses an estimated 91% of the known remaining PGM resources in the world. The country is also the largest PGM producer in the world, with the PGM mining sector being a major

contributor to the South African economy. Unfortunately, the sustainability of the PGM mining sector in South Africa is under threat due to aspects such as rapidly increasing costs of labour and electricity. Eskom's electricity tariffs have increased four times faster than inflation over the past 12 years. Apart from the large tariff increases, Eskom is experiencing problems in terms of generating enough electricity to meet South Africa's demand.

With the majority of PGM mining operations in South Africa (65%) being marginal or loss-making, the industry is forced to implement measures such as improving energy efficiency to counter the effect of rising costs. It was shown that the electricity cost spent on generating compressed air is a significant expense for PGM mining groups. On shaft level, compressed air consumption accounts for about 38% of the total electricity cost. This motivates why compressed air should be the primary target for improving energy efficiency in the PGM mining sector.

Energy consumption represents about 80% of the total running cost of a compressor, with the remaining 20% being spent on maintenance. There is a direct correlation between the availability of compressors and energy efficiency. The higher the availability of compressors, the better the energy efficiency. It therefore makes sense that a framework for managing compressed air in the PGM mining sector should consider both energy and maintenance. This motivated the research objectives that were set in Chapter 1:

1. Primary objective: Developing a framework for managing compressed air in the PGM mining sector. The intended outcome of applying the framework is to reduce the operational costs of a compressed air network.
2. Secondary objectives:
 - a. Developing a strategic guideline for improving and maintaining energy efficiency on compressed air networks in the PGM sector.
 - b. Developing a strategic guideline for monitoring and preventing the occurrence of events that result in increased maintenance costs of compressors used in the PGM mining sector.

The remainder of Chapter 1 provided information on the research method. For this study, the primary research method consisted of qualitative data collected through semi-structured interviews. The primary research method was supported by quantitative data collected from power and flow meters installed on PGM operations. The population targeted for the qualitative research was senior personnel responsible for managing compressed air at three different PGM operations located on the western limb of the BIC.

Chapter 2 started with more detailed information on the PGM industry in South Africa, with the purpose of providing insight into the current state of the industry. The major PGM mining companies were introduced. The 2018 production figures indicated the dominance of South African companies when considering the six largest producers of platinum, palladium and rhodium.

An overview of the historical prices of platinum, palladium and rhodium was provided. Platinum prices have remained relatively low over the past four years. Fortunately, the prices of palladium and rhodium have increased steadily over the past two years and made a significant positive impact on the balance sheet of PGM mining companies. Supply and demand figures for platinum, palladium and rhodium were provided. The high surplus of platinum explains the current low price of the metal, while the small rhodium surplus and palladium deficit explain their high prices.

Chapter 2 provided information on compressed air generation and consumption in the PGM mining industry. It started by explaining basic compressor operating principles after which the focus shifted to the centrifugal compressor, which is the most common compressor used on PGM mining operations. Technical details about inlet guide vane control and surging were provided as these two factors play an important role in energy efficiency and compressor maintenance.

Compressed air networks were introduced and information on the uses of compressed air in the PGM sector was presented. The major consumer of compressed air is pneumatic drills, which play a key role in the production process. Compressed air also plays an important part in underground safety since it provides a positive air pressure inside refuge bays, which prevents smoke and toxic gases from seeping in during emergency situations.

An overview of energy savings measures on compressed air networks was given. Both supply-side and demand-side measures were discussed. This was followed by a discussion on compressor maintenance that introduced the concepts of breakdown maintenance, time-based maintenance and condition monitoring. Chapter 2 concluded with a literature review of previous studies on energy savings projects implemented on mine compressed air networks.

The purpose of Chapter 3 was to present the results of the empirical study. The chapter commenced by discussing information on the procedure and scope of qualitative research. The data gathering process, sample group and sample size were discussed. The data gathering process consisted of nine semi-structured, face-to-face interviews that were conducted and transcribed by the researcher. A brief overview of thematic analysis was provided. Thematic analysis was used to identify, analyse and describe the qualitative data. The thematic analysis was conducted using ATLAS.ti software.

Demographic information on the interviewees was provided. It indicated that the interviewees were not only very experienced about PGM mining in general, but also in compressed air management on PGM mines. The results of the qualitative study were presented in the form of six themes. For each theme, a network diagram showing the relationships between the theme, subthemes and categories was provided.

Quantitative results in the form of 24-hour profiles of power consumption and compressed air consumption were provided. The quantitative results indicated the impact of various supply-side and demand-side initiatives to reduce compressed air consumption on the PGM operations that formed part of the study. These results were obtained over a period of only 8 months. When the results are extrapolated to all shafts of a PGM operation, the expected electricity cost saving is R66 million per year. This represents a 15% saving on the total annual electricity cost spent by the operation on the generation of compressed air.

Chapter 4 started by discussing the framework for managing compressed air in the PGM mining industry, which was developed based on the quantitative and qualitative results of the study. The framework consisted of separate supply-side and demand-side parts. For the supply side, three focus areas were identified, namely, 'Compressor Management', 'Maintenance' and 'Efficient Supply of Compressed air'. For each of the focus areas,

different priorities were identified and action steps were provided. There was only one focus area for the demand side, namely, 'Efficient Use of Compressed Air'. Five priorities were identified for the focus area, with practical action steps that focused on each of the five priorities.

The primary objective of this study was reached by presenting the framework for managing compressed air in the PGM mining industry at the start of Chapter 4. The first secondary objective, namely, 'Developing a strategy for improving and maintaining energy efficiency on compressed air networks in the PGM sector' was achieved through the 'Efficient Supply of Compressed Air' focus area on the supply side of the framework and the 'Efficient Use of Compressed Air' focus area on the demand side of the framework.

The second secondary objective, namely, 'Developing a strategy for monitoring and preventing the occurrence of events that result in increased maintenance costs of compressors in the PGM sector' was reached through the 'Compressor Management' and 'Maintenance' focus areas of the supply side of the framework.

4.5 Methodological Conclusions

The qualitative research method employed in this study entailed interviews conducted with experienced senior managers involved in the management of compressed air systems on South African PGM operations. Thematic analysis of the interviews, conducted with the ATLAS.ti software, resulted in the identification of six themes that had to be addressed in order to achieve the primary objective of the study, i.e. the development of a framework for managing compressed air in the PGM mining industry in SA.

The thematic analysis of the interviews also served the purpose of gaining an in-depth understanding of the importance and scope of the problematic aspects of managing compressed air in the PGM mining industry in South Africa. Interestingly, the problematic aspects were not all of a technical nature, various other management challenges were identified. Examples include the prevalence of toxic leadership, poor discipline among mining personnel when using compressed air and a lack of awareness regarding the impact and cost of wasting compressed air.

4.6 Recommendations for Future Work

The following opportunities for future work were identified during the development of the framework for managing compressed air in the PGM mining industry:

- Action steps were presented for each priority listed under the focus areas of the framework (see Section 4.2). The action steps provide high-level guidance towards achieving each of the priorities. More detailed information on achieving the objective of each priority can be provided.
- The framework is currently being implemented at one of the largest compressed air networks at a South African PGM operation. Follow-up research should be done to assess the success thereof and suggestions for improving the framework should be made.
- If proven successful, the framework should be adapted to other energy consumers on PGM mines such as ventilation and refrigeration.
- There are many similarities between PGM mines and gold mines in terms of the generation, distribution and consumption of compressed air. The framework could therefore be adapted for the South African gold mining industry.

4.7 Conclusion

The PGM mining industry in South Africa needs to adapt to survive in the current challenging economic conditions. New, innovative methods that focus on improving efficiencies should be developed and applied on a large scale to different sectors of the PGM mining industry. This ultimate goal should be to improve the long-term sustainability of the PGM mining industry in South Africa. The research contribution of this study, namely, the framework for managing compressed air in the PGM mining industry in South Africa, is a step towards this goal.

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Appendix A: Interview Questions

Demographic questions

1. What is your age, current position and how long have you been working in your current position?
2. In what manner are (or were) you involved in the management of compressed air on a PGM operation?

General challenges

1. What are the major challenges of managing compressed air at a PGM operation?

Energy efficiency (electricity costs)

1. How important is managing electricity costs for the sustainability of the PGM industry?
2. How are (or were) the costs of generating and using compressed air being managed on your operation?

Condition monitoring

1. What maintenance practices are (or were) conducted on compressed air infrastructure at your operation?
2. How are (or were) the operation of critical parts of the compressed air network monitored at your operation?

Conclusion

1. Is there value in outsourcing certain areas of compressed air management (e.g. energy management and condition monitoring) to specialist service providers?
2. How can the management of compressed air on PGM operations be improved?

Appendix B: Interview Protocol

Name of participant: _____

Mine or shaft: _____

Date/Time: _____

Location: _____

1. Introduction (5 minutes)

- a. Thank the participant for his/her willingness to partake in the study.
- b. Provide brief background information on the study and discuss the primary research objective, i.e. developing a framework to manage compressed air in the South African PGM mining industry.

2. Complete informed consent form (5 minutes)

- a. Go through the contents of the informed consent statement with the participant.
- b. Ask the participant to sign the informed consent statement, if he/she agrees with the contents.

3. Discuss the rules of the interview (3 minutes)

- a. The responses of the participant are important and will be respected.
- b. Candid answers are important.
- c. Any question may be deferred to answer at a later time.
- d. Ask if there are any last questions before the start of the interview.
- e. Ask for permission to record the interview.
- f. Start the recording.

4. Ask the interview questions (20 minutes) listed.

5. Conclusion (3 minutes).

- a. Inform the participant that he/she is welcome to contact the study leader if there are any questions or concerns regarding the study.
- b. Provide the contact details of the study leader:
Mr Johannes Coetzee
johannes.coetzee@nwu.ac.za
Tel: 018 299 4012
- c. Thank the participant for partaking in the study.
- d. Stop the recording.

Appendix C: Sample Informed Consent Statement



NWU Business School
North-West University
Potchefstroom Campus
Private Bag X6001
Potchefstroom
2520

INFORMED CONSENT STATEMENT

Researcher: Hendrik Johannes Groenewald
University number: 12301507
Contact: handregroen@gmail.com; 072 902 6159

Dear Interviewee

This **Informed Consent Statement** serves to confirm the following information as it relates to the MBA mini-dissertation on the Developing a framework for managing compressed air in the Platinum Group Metal Mining Industry in South Africa.

1. The sole purpose of this study is to obtain information from experts (such as yourself) employed and/or operating in the PGM mining industry in an attempt to determine the nature of your everyday experience related to the research topic.
2. The procedure to be followed is a qualitative research design, which includes structured, controlled and prescriptive questions but also open-ended questions. Basic background information related will be asked e.g. your name, academic qualifications and related experience to the topic.
3. The duration of the interview will take no longer than a maximum of 30 minutes.
4. If at any point during the interview you should feel uncomfortable, you will be provided with the opportunity to make your discomfort known or immediately have the option to end your participation.
5. This interview takes place on a voluntary basis.
6. The confidentiality of the interview data is guaranteed. Fictitious names will be utilised when quoting statements in the dissertation.
7. Any confidential information that prohibits the researcher to publish it in the final dissertation should be communicated during the interview.
8. A list of questions to be asked in the interview will be made available to the interviewee prior to the interview. This is done to ensure a mutual understanding of what will be asked to avoid confusion during the interview.
9. A summarised copy of the final dissertation will be made available to the interviewee upon request.
10. The data gathered from the interview will only be used for research purposes.

I, _____, hereby declare that I have read and understand the contents of the Informed Consent Statement, and give my full consent to HJ Groenewald to progress with the interview on _____ (date) and use the information communicated by myself to him in his MBA dissertation.

Name and designation	Signature	Date
Interviewee		
Student		

Appendix D: Letter From Employer



SOUTH AFRICAN OFFICES
REG NO 1992/002056/07
VAT NO 4390196550
P.O.BOX 11206
SILVERLAKES
0054
SOUTH AFRICA
TEL +27 (0)11 809 1076
FAX (012) 809 3842
E-MAIL: mkleingeld@rems2.com
5 August 2019

To Whom It May Concern

PERMISSION TO CONDUCT INTERVIEWS AND DISTRIBUTE QUESTIONNAIRES

This letter confirms that Hendrik Johannes Groenewald, student number 12301507, has been given permission to conduct interviews and distribute questionnaires among ETA Operations's clients and personnel who work in the platinum group metal (PGM) mining industry.

The confidentiality of the information gathered through the interviews and questionnaires is guaranteed. Participation in this study is done on a voluntary basis and each interviewee and respondent will sign an informed consent statement.

Best wishes

Dr. Marius Kleingeld
CEO

EXECUTIVE DIRECTORS: EH Mathews (Chairman), M Kleingeld (CEO), SM Jiyana (Projects support)
TML Seiloane (Marketing & Strategy)
INDEPENDENT NON EXECUTIVE DIRECTOR: KM Nossiep
DISTRIBUTOR: OSIMS and MTB



Appendix E: Daily Shaft Compressed Air Monitoring Report

Please note that the names of the shafts and operation are blanked out for confidentiality purposes.

1 Project information

Project name: [REDACTED]
Saving structure: Resource efficiency
Target: 84 000.00 m3
Project stage: Maintenance

2 Performance (Thursday 2019-10-24)

Performance of day:		Month-to-date performance:	
Resource saving:	118 256.36	Cumulative resource saving:	4 465 162.85
Resource usage:	35 653.48 m3/h	Average resource usage:	747 310.65 m3/h
Cost saving:	R 11 554	Cumulative cost saving:	R 436 246

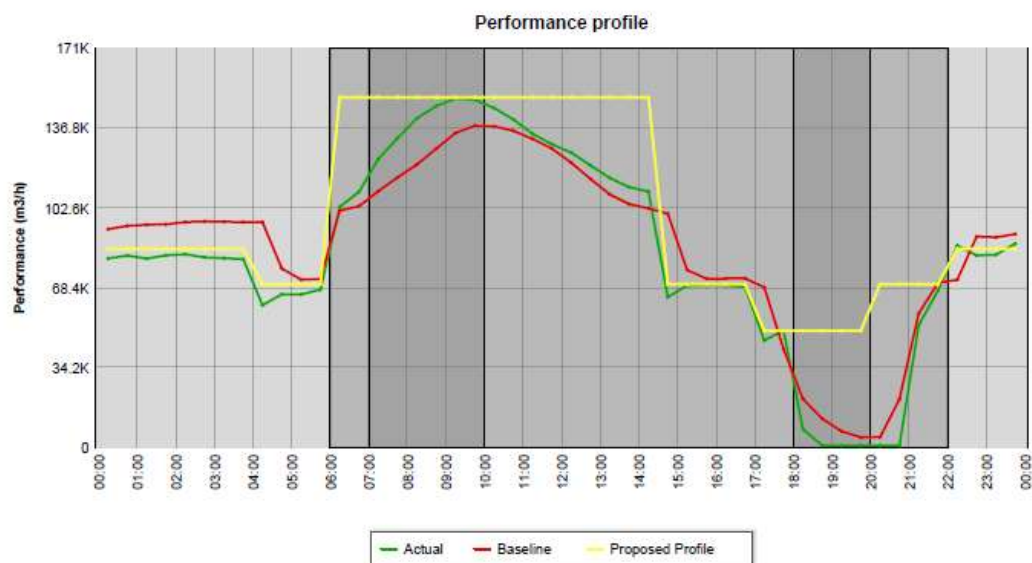


Figure 2.1: Performance profile for 24 October 2019

Appendix F: Daily Compressor Monitoring Report

Excerpts from the daily compressor monitoring report are shown below. This automated report enables the high-level monitoring of the following events:

- Surge warnings
- Machine trips
- Blow-off

More detailed information concerning the individual compressors are also provided in the report. The ensures that the reader of the report is first confronted with information on problem areas before delving into the detailed information. The names of the shafts and compressed air rings are blanked out for confidentiality purposes.

1 Summary (8 November 2019)

1.1 [REDACTED]

Table 1.1: [REDACTED] Surge Warning (Count)

Shaft Compressor	30/10	31/10	01/11	02/11	03/11	04/11	05/11	06/11	07/11	08/11
Central Compressor 1 (VK32)	0	0	0	0	0	0	0	0	0	0
Central Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
Central Compressor 3 (VK32)	0	0	0	0	0	0	0	0	0	0
Central Compressor 4 (VK50)	0	0	0	0	0	0	0	0	0	0
Compressor 1 (VK32)	–	–	–	–	–	–	–	–	–	–
Compressor 1 (VK32)	–	–	–	–	–	–	–	–	–	–
Compressor 2 (VK32)	0	1	2	1	1	1	1	0	1	0
Compressor 3 (VK32)	0	1	2	1	0	1	0	1	2	2
# Compressor 1 (VK32)	0	0	0	0	0	0	0	0	0	0
# Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
# Compressor 3 (VK32)	0	0	0	0	0	0	0	0	0	0
# Compressor 1 (VK32)	0	2	0	0	0	0	0	0	0	0
# Compressor 2 (VK32)	0	2	0	0	0	0	0	0	0	0
# Compressor 3 (VK50)	0	2	0	0	0	0	0	0	0	0
# Compressor 1 (VK50)	0	0	0	0	0	0	0	0	0	0
# Compressor 2 (VK50)	0	0	0	0	0	0	0	0	0	0
# Compressor 1 (VK32)	0	0	0	0	0	0	0	1	0	0
# Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
# Compressor 3 (VK32)	0	0	0	0	0	0	0	0	0	0

Legend

Unavailable	Warning

1.2 [REDACTED] Trip Indicator

Table 1.2: [REDACTED] Trip Indicator (Count)

Shaft Compressor	30/10	31/10	01/11	02/11	03/11	04/11	05/11	06/11	07/11	08/11
[REDACTED] Central Compressor 1 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] Central Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] Central Compressor 3 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] Central Compressor 4 (VK50)	0	0	0	0	0	0	0	0	0	0
[REDACTED] Compressor 1 (VK32)	–	–	–	–	–	–	–	–	–	–
[REDACTED] Compressor 1 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] Compressor 3 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 1 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 3 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 1 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 3 (VK50)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 1 (VK50)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 2 (VK50)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 1 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 2 (VK32)	0	0	0	0	0	0	0	0	0	0
[REDACTED] # Compressor 3 (VK32)	0	0	0	0	0	0	0	0	0	0

Legend

Unavailable	Warning

1.3 [REDACTED] Blow-off

Table 1.3: [REDACTED] *Blow-off Percentage In Terms Of Running Time*

Shaft Compressor	30/10	31/10	01/11	02/11	03/11	04/11	05/11	06/11	07/11	08/11
Central Compressor 1 (VK32)	6	4	7	3	1	1	4	6	0	0
Central Compressor 2 (VK32)	10	2	0	2	4	2	0	0	1	1
Central Compressor 3 (VK32)	2	2	1	2	1	2	2	4	2	1
Central Compressor 4 (VK50)	0	0	0	0	3	0	0	0	0	0
Compressor 1 (VK32)	–	–	–	–	–	–	–	–	–	–
Compressor 1 (VK32)	0	0	0	6	0	0	0	0	0	0
Compressor 2 (VK32)	0	0	0	6	0	0	0	0	0	0
Compressor 3 (VK32)	0	0	0	6	0	0	0	0	0	0
# Compressor 1 (VK32)	2	2	2	2	0	1	4	2	33	0
# Compressor 2 (VK32)	1	2	2	2	2	2	2	2	1	2
# Compressor 3 (VK32)	2	3	2	2	5	3	2	2	2	2
# Compressor 1 (VK32)	–	–	–	–	–	–	–	–	–	–
# Compressor 2 (VK32)	1	3	3	0	8	1	7	5	4	3
# Compressor 3 (VK50)	1	2	2	2	3	2	1	2	1	2
# Compressor 1 (VK50)	0	1	2	0	1	1	2	2	2	2
# Compressor 2 (VK50)	0	0	1	0	0	2	0	0	0	1
# Compressor 1 (VK32)	2	3	4	7	0	0	1	3	1	0
# Compressor 2 (VK32)	2	1	4	0	0	4	1	2	4	2
# Compressor 3 (VK32)	0	2	2	1	1	1	4	2	1	3

Legend

Unavailable	10% < Blow-Off < 50%	> 50%

3.6 Compressor 1 (VK32)

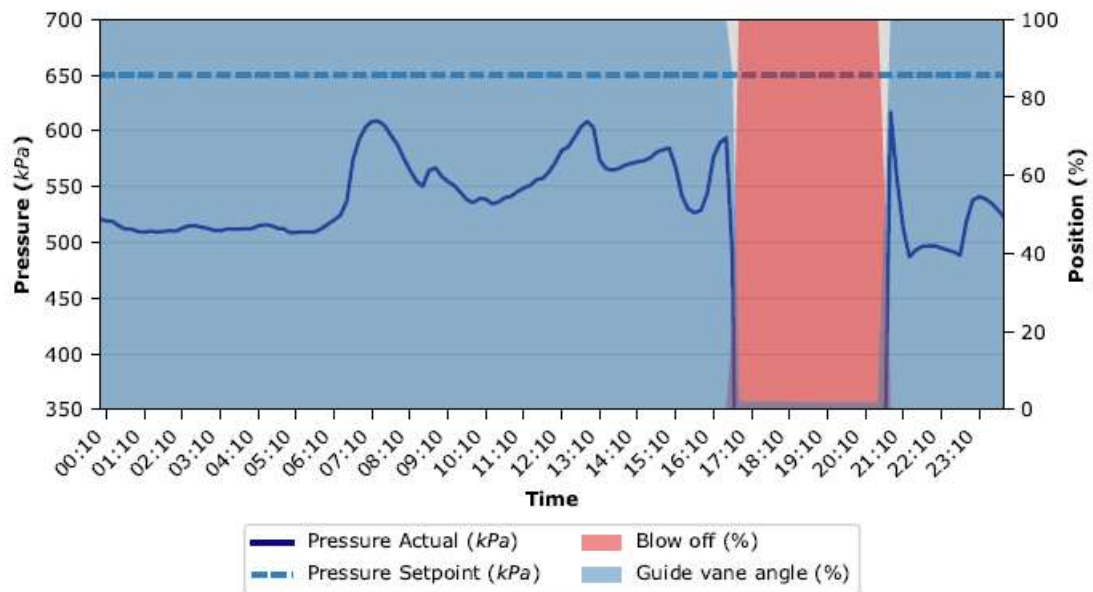


Figure 3.11: Pressure Profile

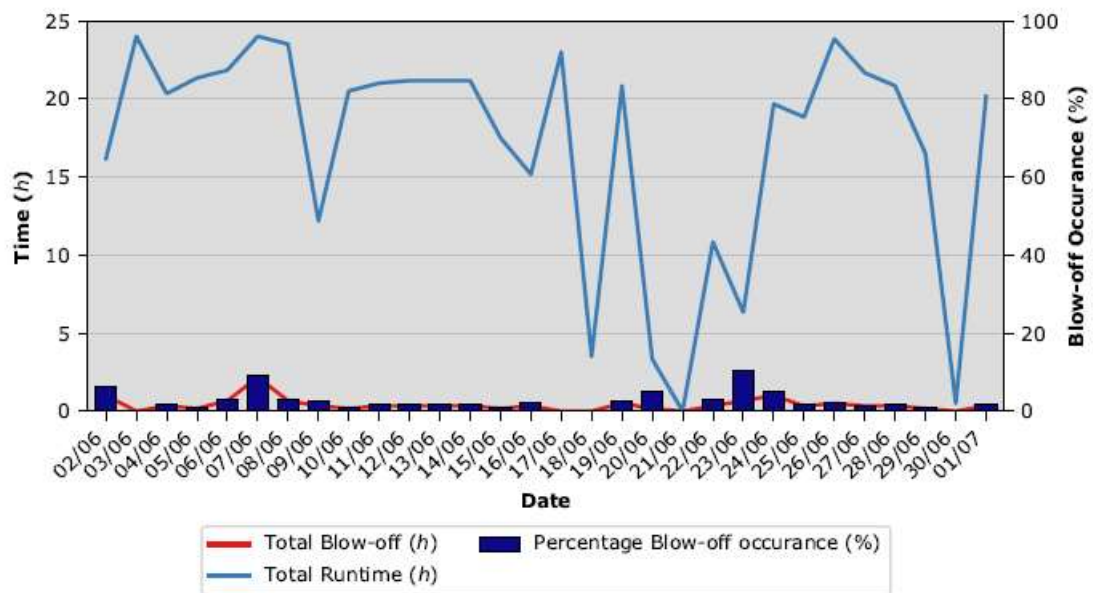


Figure 3.12: Daily Blow-off Feedback

Appendix G: Compressed Air Awareness Poster



Appendix H: Editing Certificate

In a Word

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22 November 2019

Editing certificate

This document serves to confirm that the following document has been edited:

Developing a framework for managing compressed air in the Platinum Group Metal Mining Industry in South Africa

The edit included:

- Checking spelling, grammar and punctuation.
- Checking consistency of terminology and style.
- Checking the style of references and citations (accuracy of source information remains the responsibility of the student).
- Identifying areas that require additional corrections.

The Microsoft Word® track changes functionality was used to make the student aware of changes. It is the student's prerogative to choose whether to accept or reject changes.

The document remains the original work of the student. The editor has not added any additional information, rewritten sections, or changed the structure of the document.

Sincerely,



Marike van Rensburg

