Using simulation to prioritise implementation of platinum mine compressed air efficiency solutions

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering* *in* *Mechanical Engineering* at the North-West University

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Graduation: June 2021

Student number: 26046318

ABSTRACT

Title: Using simulation to prioritise implementation of platinum mine compressed air efficiency solutions

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Degree: Master of Engineering (Mechanical)

Keywords: Compressed air, simulations, energy efficiency, mining, energy savings

Platinum mines are facing several challenges and a higher-than-inflation increase in electricity costs is amongst the most significant. Compressed air accounts for up to 38% of a platinum mine’s energy consumption. To improve the efficiency of compressed air systems, several energy efficiency solutions have been developed and proven to be successful. Unfortunately, mines do not have clarity regarding the most beneficial order for implementing energy efficiency solutions. This is further worsened by the capital expenditure required to implement these energy efficiency solutions, whilst uncertainty remains how feasible they may be. This motivates the need for this study, namely developing a methodology that prioritises the implementation order of mine compressed air efficiency solutions.

Recent software advances have made it possible to use simulations to investigate the feasibility of energy efficiency solutions. A new methodology was created that uses simulation models to evaluate and prioritise the implementation order of energy efficiency solutions on deep-level platinum mines according to annual savings, payback periods, level of automation and implementation time. The methodology entailed analysing the system, creating simulation models, verifying simulation models and, finally, determining the implementation priority of the energy efficiency solutions. This methodology was applied to two case studies to determine the implementation priority of the energy efficiency solutions. The best projects were implemented first and unfeasible projects were avoided, which led to significant savings of R35.1 million per annum. Moreover, the methodology enabled the savings to be obtained in the shortest possible time with the smallest payback period. When the savings were extrapolated to the South African platinum mining industry, potential annual savings of R342 million were predicted.

This implementation methodology contributes by ensuring that future energy efficiency projects are prioritised and implemented correctly to ensure that maximum savings are achieved at the lowest cost and in the shortest possible time. Furthermore, labour and investigations required for unfeasible energy efficiency solutions will be avoided.

ACKNOWLEDGEMENTS

Above all, I wish to give thanks to Jesus Christ, my Lord and Saviour. Without Your unfailing love and guidance, this would not have been possible. It is my sincere hope that the way I have approached this dissertation is even a small testament to Your unmerited goodness in my life.

I would like to thank my wonderful parents, Henco and Heidi de Jager. Your tireless support, love and prayer mean more to me than words can say. Thank you for instilling a passion for learning from a young age; this greatly aided me throughout this dissertation. To my brother, Jonathan, thank you for your support. Your perseverance and the way you approach challenges have inspired me during the course of this study.

To my mentor, Dr Handré Groenewald, thank you for your scrupulousness, open-door policy and the many hours you have sacrificed to refine this dissertation. You have been a tireless source of positivity and guidance, which leaves me greatly indebted.

I would like to thank my study leader, Dr Hendrik Brand, for asking the challenging questions and helping me balance the detail with the big picture, so as to not miss the forest for the trees. I am grateful to Prof. Marius Kleingeld for all his help at the start of the study in refining the storyline for this dissertation.

I would like to thank Prof. Edward Mathews and George Mathews Snr. for affording me the wonderful opportunity to complete this dissertation whilst growing as an engineer. I am convinced that the skills I have acquired throughout this study will hold me in good stead in any future endeavour. I would also like thank ETA Operations (Pty) Ltd and its sister companies for the financial support to complete this study.

To my colleagues, it has been an immense privilege working with you. Thank you for inspiring me to always give my best. I would like to especially thank Pierro Schoeman for continuously challenging the way I think and reminding me of how work fits into the bigger picture.

To my proofreader, Marike van Rensburg, thank you for your expert inputs and for answering my numerous questions throughout the year.

Lastly, I would like to thank all my friends for their support and motivation throughout this dissertation. Thank you for not only providing ample opportunities for clearing my head, but also for understanding when I had to decline an adventure or had to cut it short. I look forward to the memories to come.

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ADDITIONAL INDICES

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List of Abbreviations

Abbreviation	Description
CPI	Consumer Price Index
DSM	Demand Side Management
GDP	Gross Domestic Product
MAE	Mean Average Error
MRD	Mean Residual Difference
PBP	Payback Period
PGM	Platinum Group Metal
PI	Proportional Integral
PLC	Programmable Logic Controller
PTB®	Process Toolbox
REMS®	Real-time Energy Management System
SCADA	Supervisory Control and Data Acquisition
TOU	Time-of-Use

Glossary

"Baseline"	A reference data set used for comparing other data sets
"Blasting shift"	The period during which explosives are used to release ore from underground rock bodies
"Cleaning shift"	The period during which blasted rock is collected
"Compressor house"	A building that houses compressors
"Drilling shift"	The period during which holes are drilled into underground rock bodies
"Life-of-mine"	The projected date when all of a mine's ore reserves are expected to be extracted
"Load shedding"	The intentional shutdown of electricity to prevent the failure of the electricity supply system in its entirety
"Potable water"	Water that is suitable for consumption
"Pressure ratio"	The ratio between a compressor's discharge pressure and its inlet pressure
"Transient system"	A system that does not remain constant but changes over time
"Validation"	The process used to ascertain whether the problem statement is addressed by the results that were obtained
"Verification"	The process used to ensure whether the solution strategy that was developed is accurate and suitable for use

List of symbols

Symbol	**Description**	**Unit**
$Error\%$	Percentage error	%
$\dot{m}_c$	Corrected flow	kg/s/bar/K
P	Pressure	kPa
$\mathbb{P}$	Power	kW
PR	Pressure ratio	–
Q	Volumetric airflow	m^3/s
R	Universal gas constant	kJ/kg·K
r^2	Coefficient of determination	–
T	Temperature	K
t	Time	s
UA	Overall heat transfer coefficient	kW/°C

Nomenclature

–	Dimensionless
/	Division (per)
%	Percentage
bar	Pressure in bar
c	Cent
GWh	Gigawatt-hour
K	Kelvin
kg	Kilogram
kPa	Kilopascal
kW	Kilowatt
MW	Megawatt
MWh	Megawatt-hours
Nm^3	Nominal cubes
oz	Ounces
R	South African Rand
s	Second

CHAPTER 1 – INTRODUCTION

1.1 The South African platinum mining industry

1.1.1 Industry overview

The mining industry is an important contributor to the South African economy [1]. Mining contributed R360.9 billion to the country's gross domestic product (GDP) in 2019 [2]. This amounted to 7.9% of the country's GDP [3]. Figure 1-1 shows the percentage of South Africa's GDP from 2010 up until 2019 that was attributed to mining. Although mining contributed 9.6% of the GDP in 2011, the contribution declined steadily and reached 7.9% in 2019.

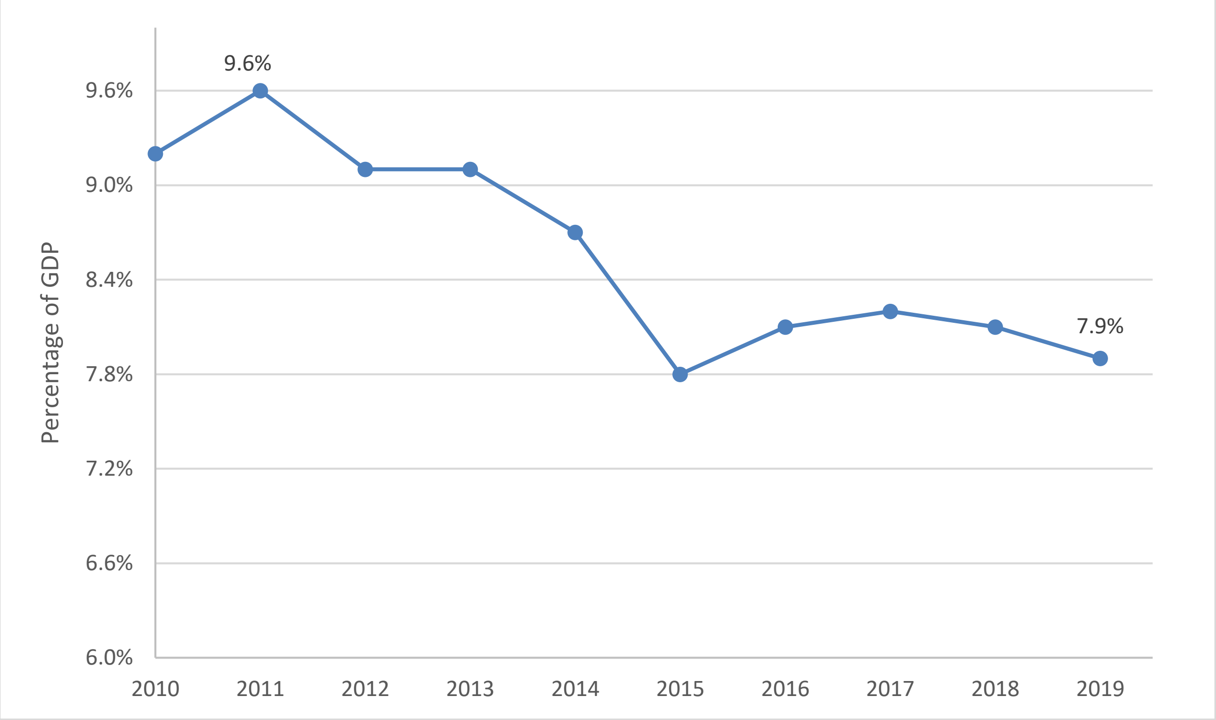

Figure 1-1: Mining percentage of total GDP (adapted from [3])

The mining industry is one of South Africa's largest consumers of electricity and it accounted for 13.9% of the total electricity consumption in 2019 [4]. South Africa's largest mining sector is the platinum group metal (PGM) sector [3], [5]. It is further a large contributor to the country's economy [6]. Approximately 90% of the world's known remaining PGM resources are in South Africa [7]. PGMs consist of platinum, rhodium, palladium, osmium, iridium and ruthenium, which are some of the rarest metals on earth [8]. The three most significant PGMs in economic terms are platinum, rhodium and palladium [9]. In 2019, 54% of globally produced platinum and palladium was produced in South Africa [7].

Unfortunately, the PGM industry (henceforth referred to as the platinum industry) is facing several challenges with a prominent challenge being that operational costs are increasing [10]. Since mines are becoming deeper, more electricity is used to sustain operations [6], [11]. In other words, for the same amount of platinum to be produced, more expenses are incurred [9], [12]. Electricity tariffs increasing significantly above inflation also contributes significantly to the rising cost of operations [3]. Furthermore, the demand for platinum is decreasing and the production of platinum is stagnating [11].

1.1.2 Increasing electricity costs

As noted above, a significant challenge facing the platinum mining industry is the rising cost of operations [10]. According to the South African Mineral Council, the mining sector’s input cost inflation for 2019 was 7.6%. Contrarily, the national average production inflation rate was 4.7% [2]. A large contributor to these increasing operational costs has been the increase in electricity tariffs [6]. It is predicted that due to the tariff increase, 15 000 jobs could be lost in the platinum sector by 2022 [6].

Eskom, the country’s state-owned electricity supplier, is responsible for supplying 90% of South Africa’s electricity demand and approximately 40% of Africa’s electricity demand [4]. The South African power grid is under severe strain due to financial mismanagement, inadequate planning, a crisis of governance and corruption in Eskom [4], [13], [14]. Eskom is trying to address the shortage by commissioning new power stations; however, this initiative, coupled with the aforementioned corruption and mismanagement, resulted in high electricity tariffs increases [13].

Figure 1-2 compares Eskom’s average standard electricity tariffs and South Africa’s inflation measured in terms of the consumer price index (CPI), which have both been normalised to a value of 100 in 2010. It is clear that Eskom’s tariffs (as given in blue) increase at a much faster rate than inflation (given in red). From 2010 to 2019, Eskom’s average standard tariff increased by 129% [15]. This is in stark contrast with inflation during the same period, which increased by 59% [16].

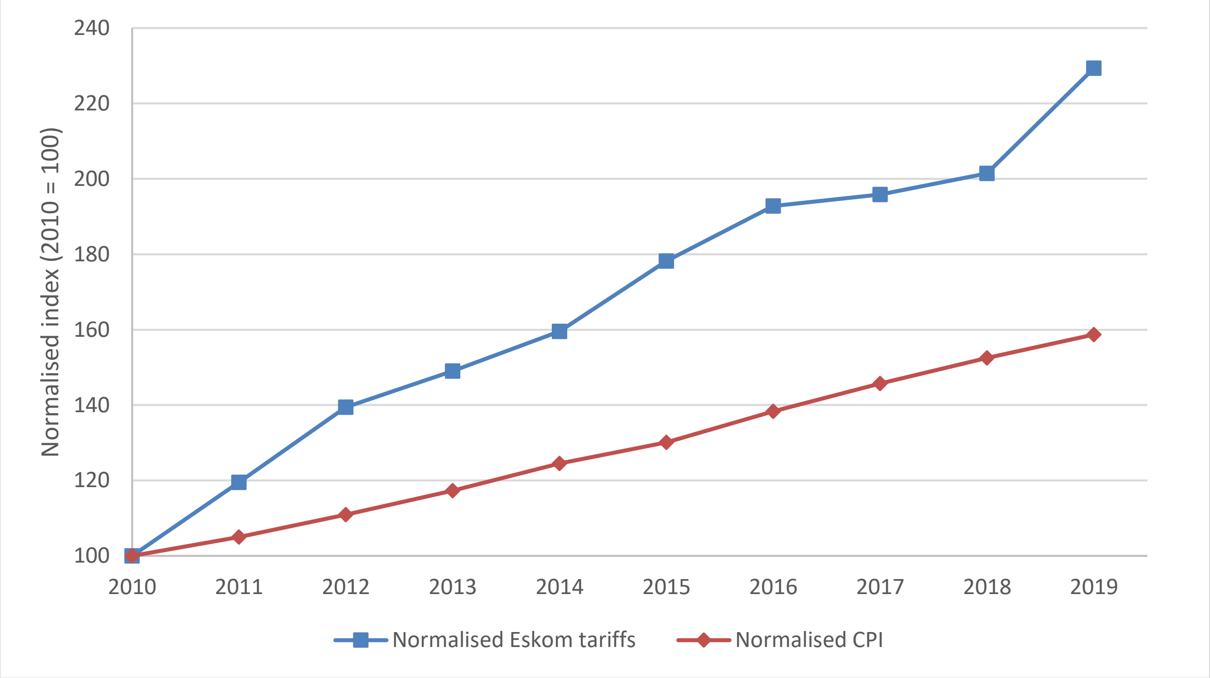

Figure 1-2: Eskom electricity tariffs compared with CPI (adapted from [15-18])

Since 2008, Eskom has been unable to constantly supply the electricity demand and had to resort to load shedding [4]. In 2019, this mismatch between supply and demand was the largest yet, which resulted in the energy supplier having to purchase more than 10 000 GWh from independent power producers to match the grid's demand [4].

New power stations

To address the mismatch between the supply and demand, Eskom commissioned two new power stations, namely Medupi and Kusile [4], which were expected to be completed by 2015. Unfortunately, the power stations are significantly over budget and behind schedule. Medupi is expected to be completely operational by the end of 2020 once design defects on all the units have been addressed [19]. In October 2020, Kusile's second unit (of six) achieved full commercial operation [20] and it is expected to be completely operational by 2023 [21].

The significant additional expenses of the over-budget power stations have placed Eskom under severe financial strain. This incited Eskom to further increase its tariffs [22]. The increase in electricity tariffs coupled with rotational load shedding not only have debilitating effects on South Africa's economy, but also on its industries [6].

1.1.3 Other industry challenges

Along with the ever-increasing electricity tariffs, the industry also faces challenges in a decreasing demand for platinum and stagnating production. This section elaborates on each challenge individually, starting with the decreasing platinum demand. Two further challenges, which are not discussed at length, are the move to ore-bearing reefs with a lower grade of PGMs (from the Merensky reefs to Platreef and UG2 reefs) and the additional costs to ensure utmost safety [11].

Decreasing platinum demand

The global platinum demand has increased annually by 5% for nearly 30 years before the 2008 global economic crisis [6]. The economic crisis incited structural changes in the market. This meant that the platinum demand stagnated, which was further worsened by palladium replacing platinum in catalytic converters and the gasoline sector [6]. However, it is important to note that because palladium substituted platinum, the prices of palladium could spike due to the increased demand, resulting in users reverting to platinum [11].

Figure 1-3 shows the demand for the platinum market sectors in 2019 [23]. Autocatalysis was responsible for 34% of the global demand, the industrial sector for 28%, the jewellery industry for 25%, and investment for 13%.

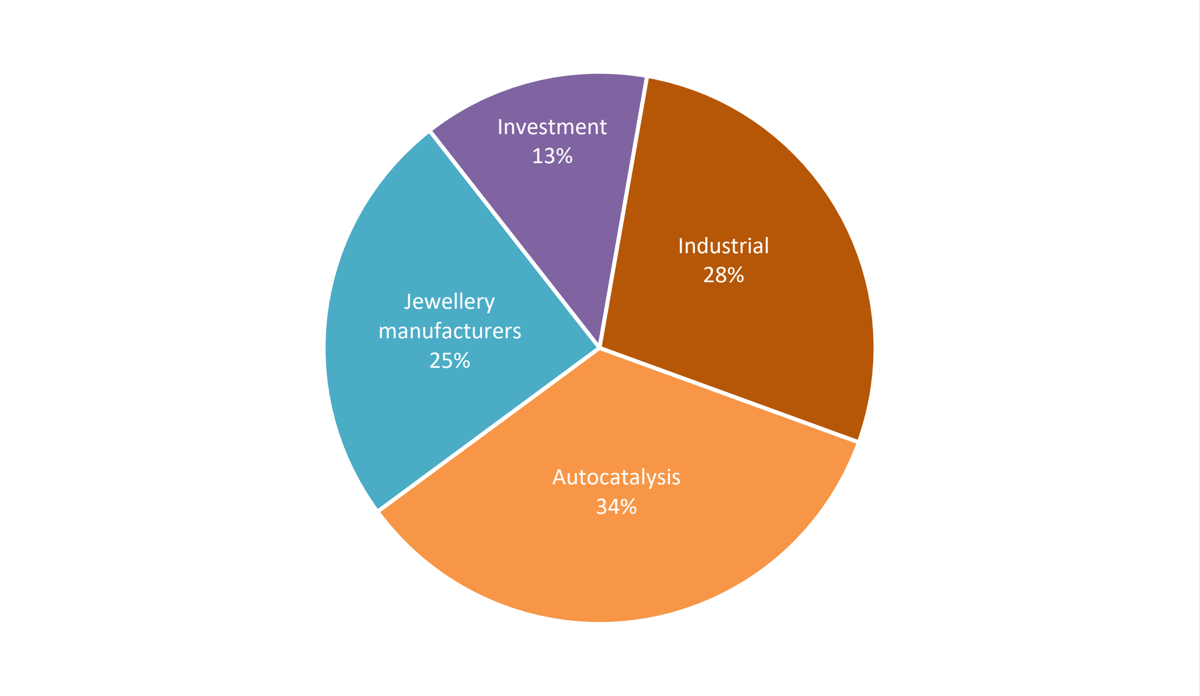

Figure 1-3: Platinum market sectors (adapted from [23])

There are two different streams to the supply of platinum, palladium and rhodium. The mining industry functions as the primary supply. The secondary supply comes from the recycling of electronic equipment, jewellery and autocatalysis convertors from out-of-order vehicles [8].

Figure 1-4 shows the demand for platinum and the recycling of platinum between 2015 and 2019. The net demand is the total demand minus the total recycling. In other words, the net demand is the amount demanded from the mining industry. It is apparent that the total amount of recycling in the industry is experiencing an upward trend, whilst the total net demand has not exceeded the amount reached in 2015 again. Figure 1-4 shows that in 2015, the total amount of platinum recycling amounted to 1 739 000 oz, which was 21% of the total gross demand. This increased to 2 261 000 oz in 2019, accounting for 27% of the total gross demand. Due to the increasing amount of recycling, less primary supply was required from the mining industry [6].

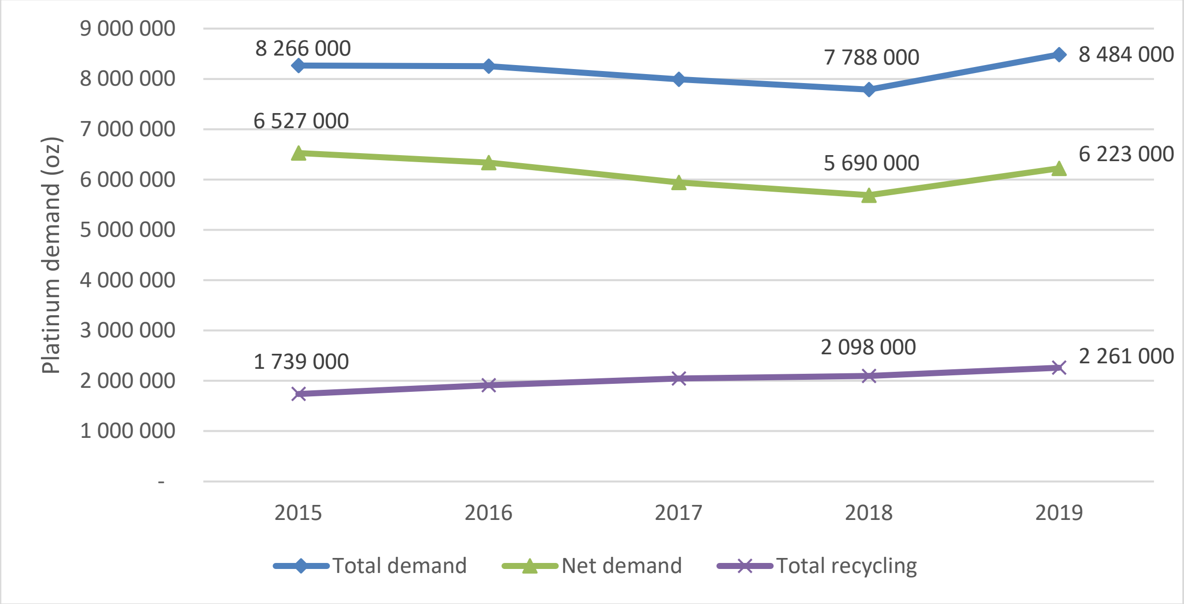

Figure 1-4: Platinum demand (adapted from [23])

Stagnant production

In 2009, South Africa’s platinum production stood at 4 603 000 oz and remained fairly constant until 2011, during which 4 740 000 oz were produced [23]. Since 2012, however, the production of South African platinum mines has stagnated [11]. This can be seen in Figure 1-5, which shows the production of platinum mines in South Africa from 2009 to 2019.

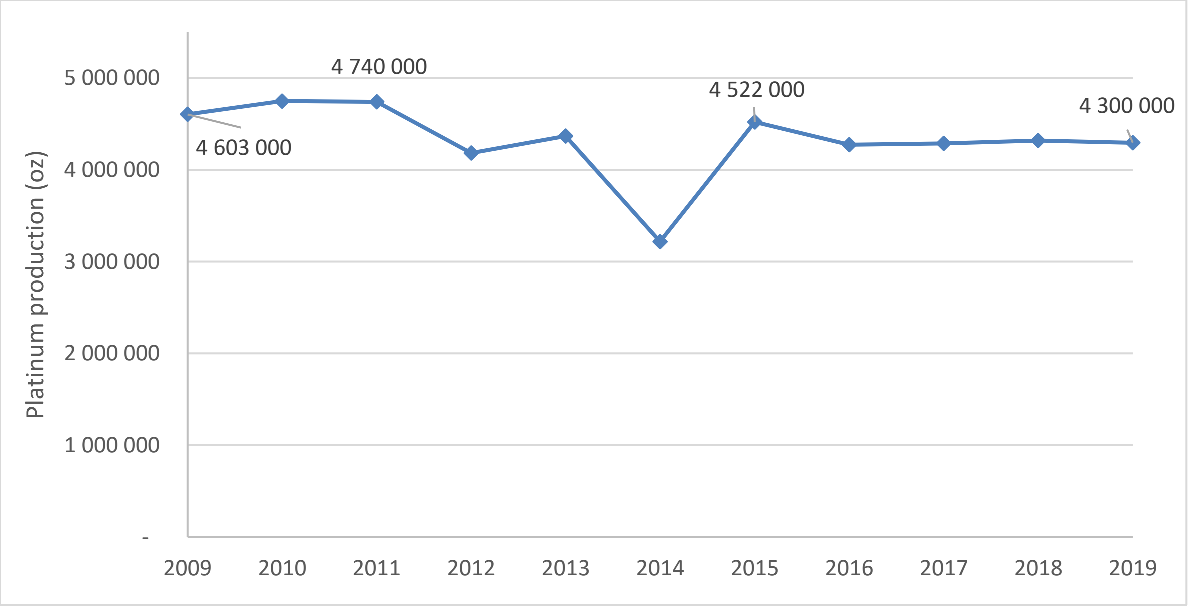

Figure 1-5: South African platinum production (adapted from [23])

The significant drop that can be observed in 2014 was due to a five-month strike, which affected production severely [3]. Production recovered to 4 522 000 oz in 2015, but thereafter the stagnant trend ensued. In 2019, approximately 4 300 000 oz were produced [23]. There are several reasons for the stagnating production, which include electricity supply challenges, logistical challenges, such as rail capacity, and industrial action [2]. Furthermore, the South African mining industry's productivity has decreased by 0.3% per annum between 2013 and 2017. This is in stark contrast with the mining sectors in Asia, North America and Australia, where productivity improved by 5% year-on-year in the same period [24].

1.1.4 Cost breakdown

As discussed, the platinum industry is facing several challenges. For the industry to remain profitable, it must reduce costs significantly [6]. Figure 1-6 gives a breakdown of the platinum industry's costs [9]. The most significant cost is labour, which amounts to 41% of the total costs, followed by financial costs at 16%, equipment costs at 15%, and electricity costs at 10%. Other costs summate to 18% of the total.

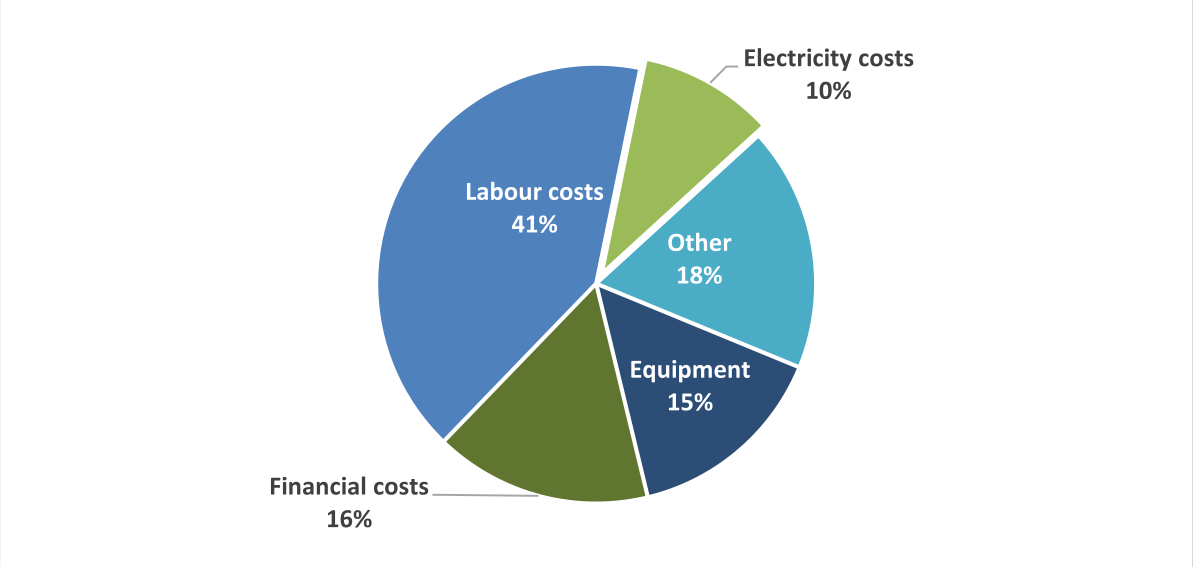

Figure 1-6: Typical platinum mining costs (adapted from [9])

If the expenditure on some of these expenses is decreased, it will have adverse effects on the industry [25]. For instance, decreasing labour expenses will impair production due to fewer personnel being available. Electricity expenditure, however, can be decreased without having negative effects on production or profitability.

Figure 1-7 gives a breakdown of the electricity expenditure of a typical platinum mineshaft, which shows that compressed air generation accounts for the largest part of the expenditure [26]. It is responsible for 38% of the total electricity cost. Mining accounts for 32% of the total cost, followed by ventilation at 17%, and refrigeration at 13%.

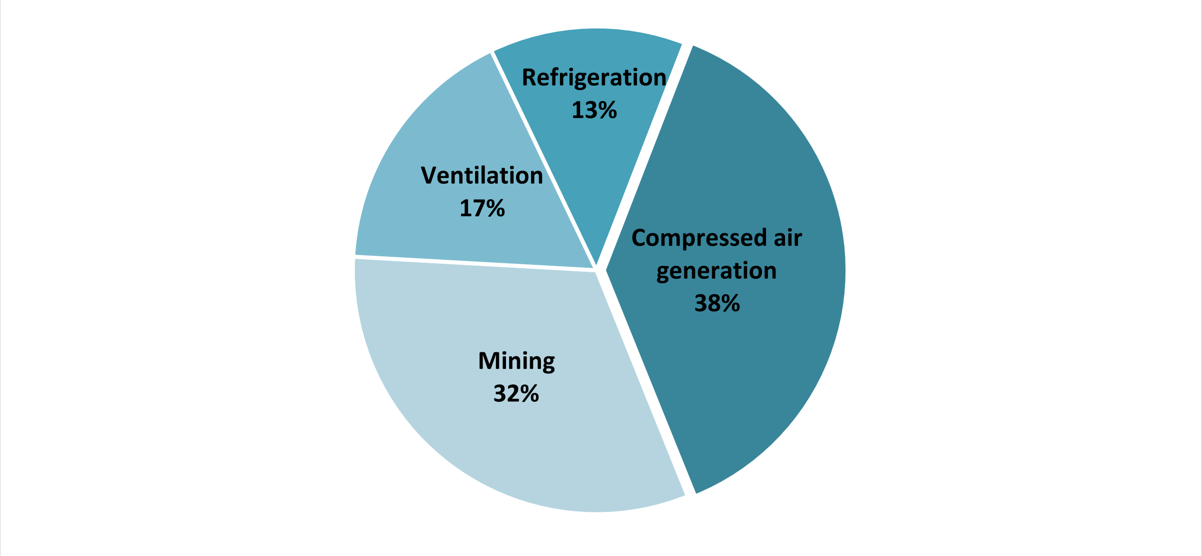

Figure 1-7: Platinum mineshaft electricity breakdown (adapted from [26])

Since compressed air generation amounts to such a large percentage of the electricity costs, it is a large expense on mines. The monthly expenditure on compressed air generation exceeds R5 million for a typical platinum mineshaft during Eskom's low-demand season (September to May) [26]. In the high-demand season (June to August), the expenditure is even more due to the higher tariffs (this is discussed in Section 2.5.2) [26].

1.1.5 Summary

This section discussed the various challenges the platinum mining industry is facing. Not only are the electricity tariffs increasing rapidly, but the demand for platinum is also decreasing. For the platinum mining industry to remain profitable, it must reduce costs. Compressed air is the largest electricity expense on platinum mineshafts. The next section discusses the components of platinum mine compressed air systems and how these systems work.

1.2 Compressed air systems in platinum mining

1.2.1 Background

Platinum mining operations consist of two distinct categories, namely production and utilities [27]. Production is divided into drilling, blasting, cleaning and hoisting, whilst utilities consist of all the systems on a mine that support production, including refrigeration, ventilation, pumping and compressed air systems [28].

Compressed air is a vital component on platinum mines [28]. Albeit inefficient, compressed air is used as an energy carrier for various processes [29]. Table 1-1 compares the overall efficiency of different energy carriers for powering pneumatic rock drills. The overall efficiency is the amount of energy that the pneumatic drill can provide divided by the energy that is generated to power the drill.

Table 1-1: Overall efficiency of energy carriers (adapted from [29])

Energy carrier	Overall efficiency
Electric drill	32%
Hydropower gravity	24%
Oil electrohydraulic	23%
Hydropower pumped	20%
Compressed air	2%

Table 1-1 shows that compressed air has the lowest energy efficiency by far at 2%. The other energy carriers have overall efficiencies of 20% or more. Despite its low overall efficiency, compressed air is used as an energy carrier because safety is paramount in the mining industry, and compressed air is safer than other energy carriers [29]. Furthermore, pneumatic equipment are used rather than electric equipment because electric equipment carry the risk of igniting methane gas, which is prevalent underground [30].

Compressed air systems are made up of compressed air demand in the form of end users, which use the compressed air, and compressed air supply from compressors [31]. Several compressors, working concurrently and supplying the same piping network, are known as a compressor house [32]. The compressor houses, or compressors, are connected to the end users through compressed air pipes in a network [31]. The end users, or consumers, of compressed air are predominantly mineshafts and processing plants [26].

This section describes how compressed air networks on a mine work and how compressed air is supplied to these networks. Furthermore, the section discusses the different compressed air users on a mine and how compressed air is consumed for various purposes throughout the day.

1.2.2 Compressed air networks

The piping networks that connect the mineshafts and processing plants to the compressed air supply are either stand-alone systems or ring-feed systems [33], [34]. In a stand-alone system, a compressor or a compressor house is connected directly to the compressed air users. Figure 1-8 shows a stand-alone system where a single compressor house feeds a processing plant and a shaft.

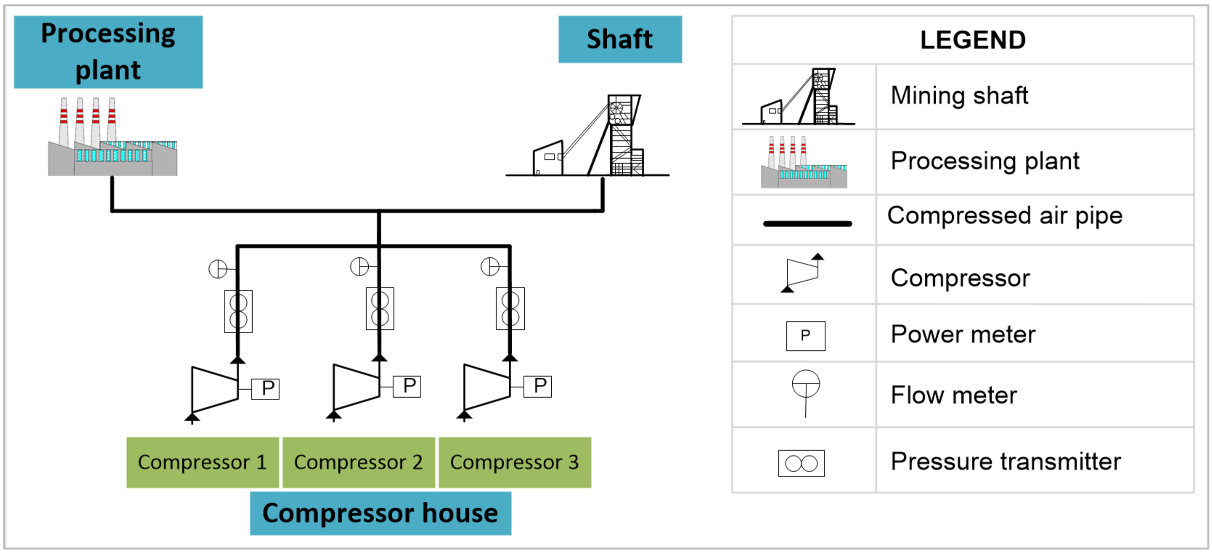

Figure 1-8: Stand-alone compressed air system[1]

A ring-feed system is more complex than a stand-alone system because multiple compressor houses are connected to multiple end users. Figure 1-9 gives an example of a ring-feed compressed air system, where three compressor houses (housing seven compressors in total) feed four mineshafts and a processing plant.

Due to the intricacy of ring-feed compressed air systems, they require more piping. This not only means that ring-feed systems are significantly more expensive, but also that they are more prone to inefficiencies [34]. Furthermore, because several users are connected to the same network, end users that consume excessive compressed air affect other end users adversely [33]. Nevertheless, there are several benefits to a ring-feed system. Due to the shared supply of several compressor houses, the system is not affected detrimentally when a compressor either trips or requires maintenance. Moreover, if an end user uses less compressed air, other end users benefit from the surplus of compressed air [34]. Compressed air end users can, however, be isolated from the network by using compressed air valves [35].

On large mines, the total length of compressed air piping networks can be over 40 km [32]. Due to their significant size, the networks are inefficient and substantial energy losses occur [32]. Considering all the systems in the mining industry, compressed air systems are the least efficient [36]. The largest cause of energy losses is compressed air leakage, which can contribute to 35% of the energy losses [37]. Piping characteristics (such as friction), piping components (such as reducers, bends and junctions), faulty valves and inefficient compressors also contribute to the energy losses.

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[1] Researcher’s own compilation.

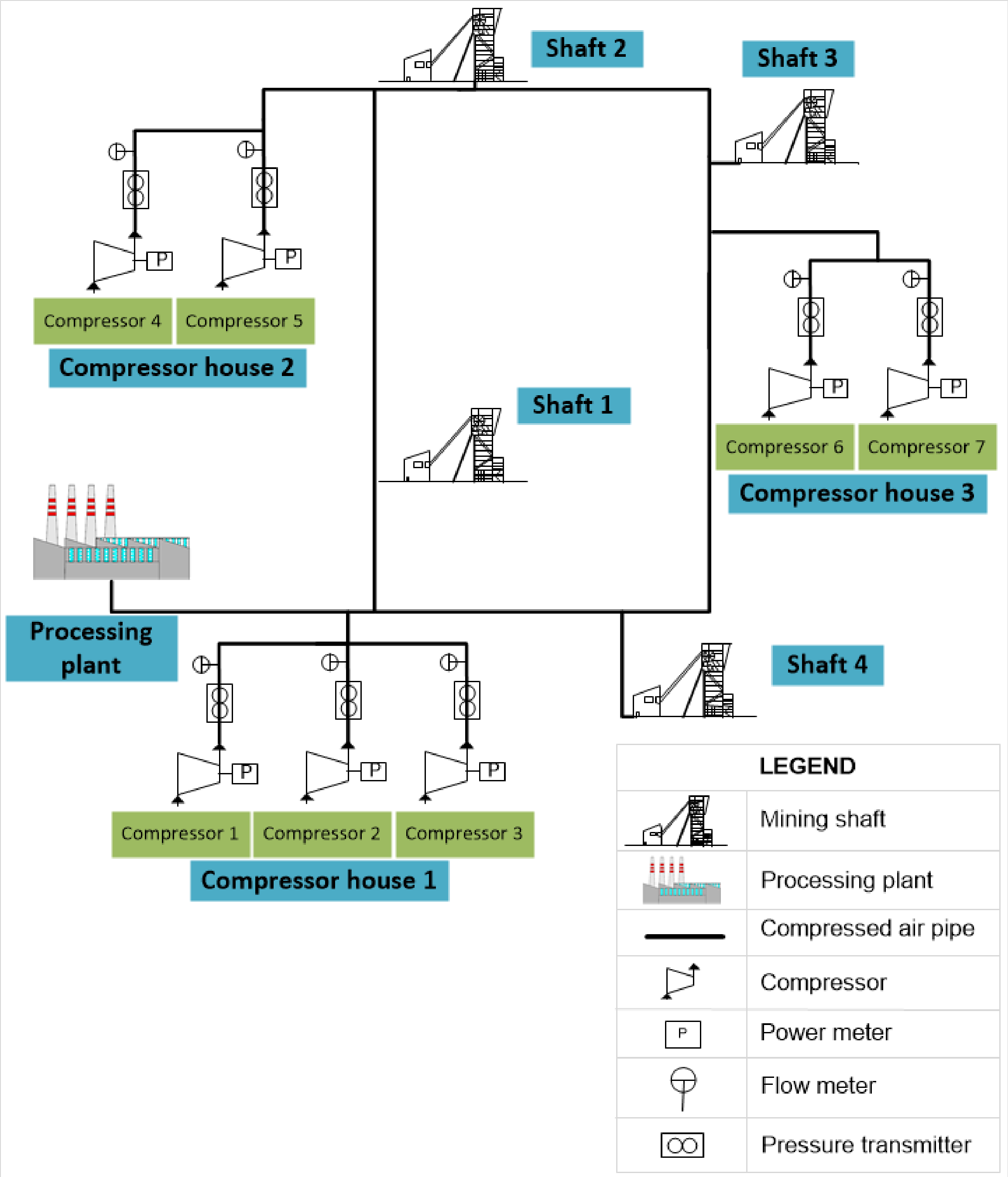

Figure 1-9: Ring-feed compressed air system[2]

To make compressed air systems more cost-efficient, mineshafts can share compressed air with production plants [32]. However, the pressure requirements of processing plants differ from mineshafts. Consequently, compressed air optimisation and supply can often be challenging [38].

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[2] Researcher’s own compilation.

1.2.3 Compressed air supply

Compressed air is predominantly supplied by centrifugal dynamic compressors on platinum mines [26]. This is not only due to their good reliability, but also their ease of maintenance [25]. Another benefit to using these compressors is their ability to reduce their electricity consumption by reducing their generated airflow [25]. This is done by means of guide-vane control, which is discussed later in this section.

Within these compressors, an electric motor drives the rotating impellers or blades on a shaft. Air continuously flows through the compressor. The centrifugal force of the rotating impellers increases the air’s velocity [32]. As a result, the air is compressed. Figure 1-10 visualises a cutout of a multi-stage centrifugal compressor. Air enters the compressor via the air inlet. The shaft drives the impellers, which are used to compress the air. Thereafter, the compressed air exits the compressor via the outlet.

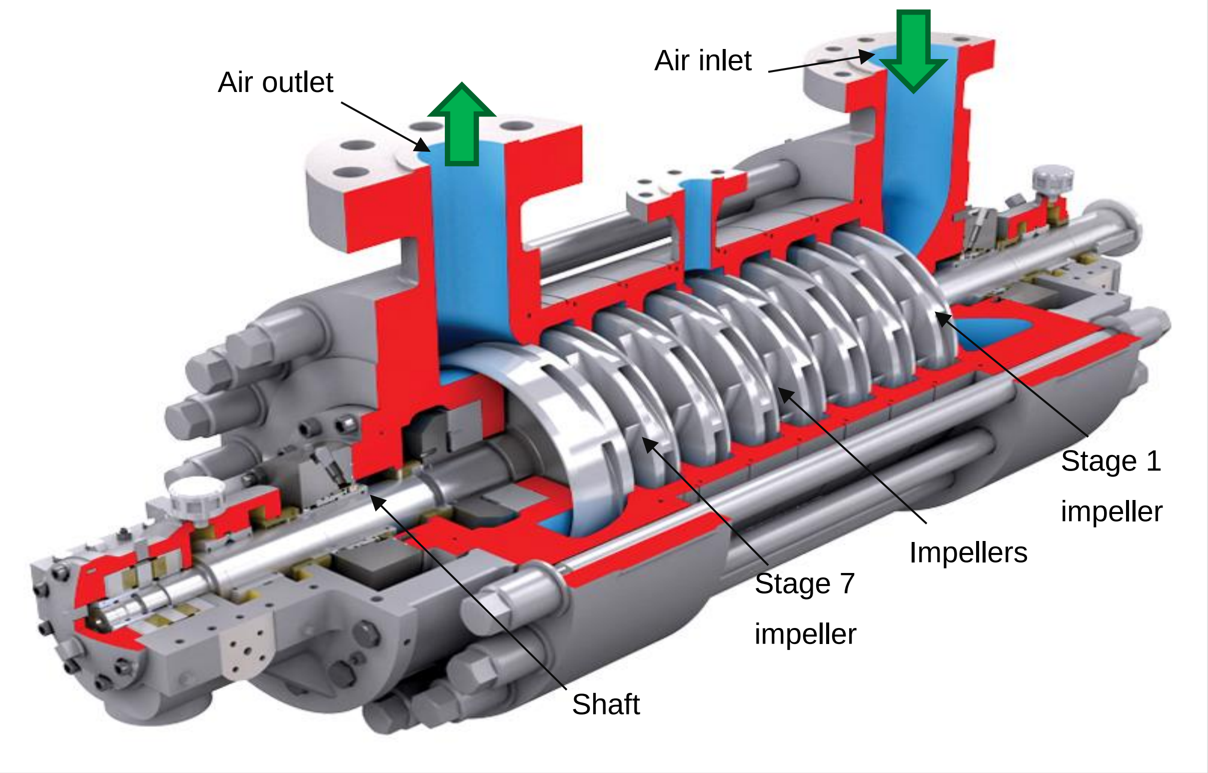

Figure 1-10: Multi-stage centrifugal compressor (adapted from [39])

Some centrifugal compressors have a single impeller, whilst multi-stage compressors have multiple stages of impellers. The compressor shown in Figure 1-10 is a multi-stage compressor, as evident from its seven impeller stages. These multiple impeller stages result in higher pressure ratios, which mean larger compressor discharge pressures [40]. Once the air is discharged from the compressor, it flows through an aftercooler. This reduces the temperature of the compressed air and subsequently reduces the moisture content. The reduced heat and reduced moisture mean that the equipment and the pipelines are protected [41].

Compressor guide-vanes

Guide-vanes are situated at the inlet of the compressor. The guide-vanes are used to control the flow of air at the intake and, subsequently, the compressor's discharge flow. When not operational, the guide-vanes are fully open and parallel to the line of flow, as to not obstruct the flow. When in use, however, the guide-vanes rotate their orientation to be at an angle (up to and including perpendicular) to the direction of flow. As a result, the mass flow of the compressor is reduced. This is known as 'cutting back' and is used when the compressed air demand is less than what is generated by the compressor [40]. Guide-vanes can further be used to control the discharge pressure of a compressor. Pressure set points are specified and the guide-vanes adjust accordingly to ensure that the discharge pressure matches the pressure set points.

Compressor surge

Surging occurs when the pressure of a network that is supplied by a compressor is higher than the compressor's discharge pressure. This results in flow being pushed back into the compressor, which harms the compressor's internal parts [37]. Compressor surge must be avoided at all costs because it is detrimental to the compressor.

Compressor blow-off

Blow-off valves, also known as anti-surge valves, are used to help prevent the surging of compressors [26]. When the network pressure is greater than the compressor's discharge pressure (when surge occurs), these valves open to isolate the compressor from the network and to release the compressor's excess air. Surge is thereby prevented since the air from the network does not flow back into the compressor, but is rather released into the atmosphere.

1.2.4 Compressed air demand

Compressed air is predominantly used underground in mineshafts where it has multiple uses. The purpose of platinum mineshafts is to extract ore from the PGM-bearing reefs and to transport it to surface. Compressed air is used as an energy carrier for various utilities, such as pneumatic drills, loading boxes, refuge chambers and agitation [42]. Fraser indicated that for every tonne of ore extracted, between 12 kg and 24 kg of compressed air is required across the various utilities [43]. Some of the largest users of compressed air are discussed below.

Pneumatic rock drills

To extract ore from a mine, the ore must be removed from the reef [44]. Pneumatic rock drills are used to drill holes into the face of the rock in the production areas, which are also known as stopes. Figure 1-11 shows pneumatic rock drills being used to drill holes in a rockface.

Figure 1-11: Pneumatic rock drill [3]

Pneumatic rock breakers

After drilling has taken place, explosives are placed in the drilled holes. The explosives are detonated to break up the rock [32]. The rocks are broken into smaller rocks with pneumatic rock breakers, which makes the rock easier to transport and easier to process [42].

Pneumatic loaders

Once the rock has been broken into smaller pieces, it must be moved to rail-bound material-handling equipment [32]. A pneumatic loader is used to lift the broken rock into its hull using a front loader. Hereafter it is transferred to transporting equipment, such as hoppers (also known as train carts), and subsequently moved to loading boxes via rail [45]. A pneumatic loader, as well as its hopper, is shown in Figure 1-12.

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[3] Adapted from Mining Technology. Available: https://www.mining-technology.com/contractors/drilling/canun/attachment/canun6 [Accessed: 03-May-2020].

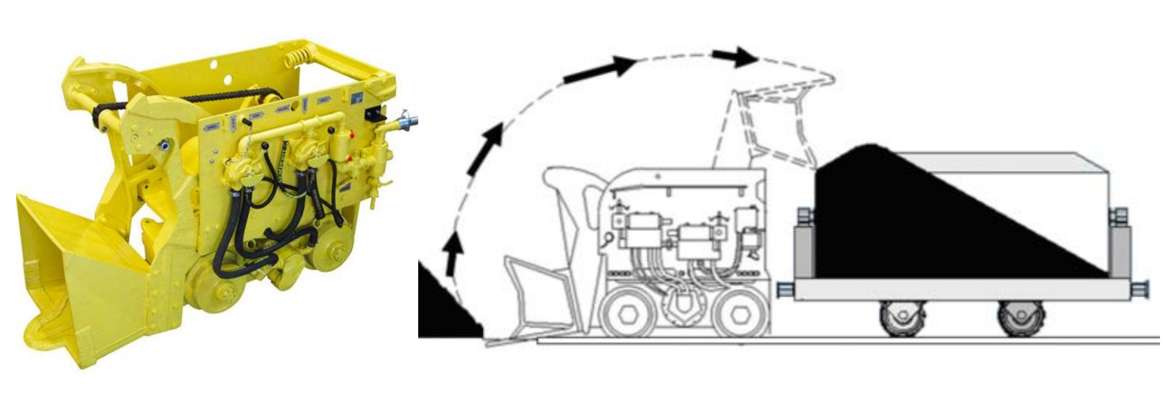

Figure 1-12: Pneumatic loader and hopper (adapted from [46])

Loading boxes

Once hoppers are full, the ore is tipped into loading boxes. Mined ore accumulates at the bottom of the mineshaft in loading boxes. The ore is transferred to skips that are hoisted to the surface with a winder [32].

Pneumatic cylinders

Pneumatic cylinders are used to open the loading boxes mechanically [32].

Pneumatic actuators

The supply of compressed air is controlled by using valves. These valves are set remotely to regulate the compressed air to specified parameters. To regulate and open or close the control valves, pneumatic or electric actuators are used. Should the actuator fail due to unforeseen circumstances, a manual override is used to open or close the valve [45].

Agitators

Water, which is used for cooling and mining operations underground, is stored in underground dams. Compressed air is released into these dams to agitate particles, such as mud, to ensure that the particles do not settle at the bottom of the dams [47].

Refuge chambers

To provide safety to underground miners during emergencies, refuge chambers are installed underground. The Mine Health and Safety Act (Act no. 29 of 1996) stipulates that refuge chambers require a constant supply of fresh air [48]. Compressed air is used to provide fresh air to refuge chambers and to prevent toxic gases and smoke from entering [49]. Along with emergency supplies (such as potable water), refuge chambers are equipped with a telephone, a stretcher, a fire extinguisher, benches and a compressed air line [48].

The refuge chambers require compressed air at a fairly low pressure of 200–300 kPa, with 5 m^3/h per person required [49]. Mining personnel use a manual valve in the refuge chamber to control the airflow. Workers often misuse the valve to provide cool air to the refuge chamber, even when it is left unattended [50]. Figure 1-13 shows a typical underground refuge chamber as well as the compressed air pipe feeding the refuge chamber.

Figure 1-13: Underground refuge chamber[4]

Table 1-2 summarises the compressed air requirements of the aforementioned compressed air consumers in terms of pressure and flow requirements [27], [42], [44], [47].

Table 1-2: Pneumatic equipment and their compressed air requirements (adapted from [27], [42], [44], [47])

Equipment	**Pressure requirement**	**Flow requirement**
Pneumatic rock drill	400–620 kPa	210–1 500 Nm³/h
Pneumatic rock breaker	450 kPa	1 000 Nm³/h
Pneumatic loader	450 kPa	1 000 Nm³/h
Loading box	350–600 kPa	20–500 Nm³/h
Pneumatic cylinder	350–600 kPa	1.7–400 Nm³/h
Pneumatic actuator	350–600 kPa	~0 Nm³/h
Agitator	400 kPa	1 300 Nm³/h
Refuge chamber	200–300 kPa	5 m³/h per person

Surface compressed air users

After the ore has been mined at the mineshafts and transported to the surface, processing plants are used to extract valuable metals from the ore. Here, compressed air is used for agitation, this time during the processing of ore, where it facilitates the recovery of the platinum

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[4] Photos taken by ETA-Operations personnel.

[44]. Pneumatic cylinders are used on the surface in ore-moving systems and pneumatic actuators are used on surface compressed air valves.

1.2.5 Typical schedule

Due to the variety of compressed air equipment being used, all with different requirements, it is important to understand the operational schedule of a compressed air network. There are three main shifts during the typical daily mine underground operation:

- **Drilling shift:** During the drilling shift, rock drills are used to drill holes into the rockface that is mined [42]. Maximum flow is required during this time because this is the peak production shift.
- **Blasting shift:** After the drilling shift, workers place explosives in the holes that were drilled into the rockface. Once explosives have been placed into the holes, the explosives are charged and the areas are evacuated. Hereafter, the explosives are detonated and the ore is released [42]. This shift requires minimal compressed air since the refuge chambers are the only end users that should be using compressed air.
- **Cleaning shift:** During the cleaning shift, the ore, which was blasted during the blasting shift, is gathered using the rock loaders and transported to surface. This shift requires a lower amount of compressed air than the drilling shift, but still more than blasting shift. This is due to equipment such as rock breakers, loaders and loading boxes being operational.

After each shift, there is a shift change during which workers are taken back to surface with an elevator. The workers for the subsequent shift are then taken underground. Figure 1-14 shows a typical daily flow profile of a PGM mineshaft with the three main shifts and the auxiliary periods superimposed thereon. During the drilling shift (shown in yellow in Figure 1-14), the maximum amount of compressed air is used. The cleaning shift (shown in green) and blasting shift (shown in red) are periods of lower demands for compressed air. The cleaning shift uses less compressed air than the drilling shift, whereas the blasting shift is the least compressed air intensive shift of all the shifts. The auxiliary periods are indicated in grey.

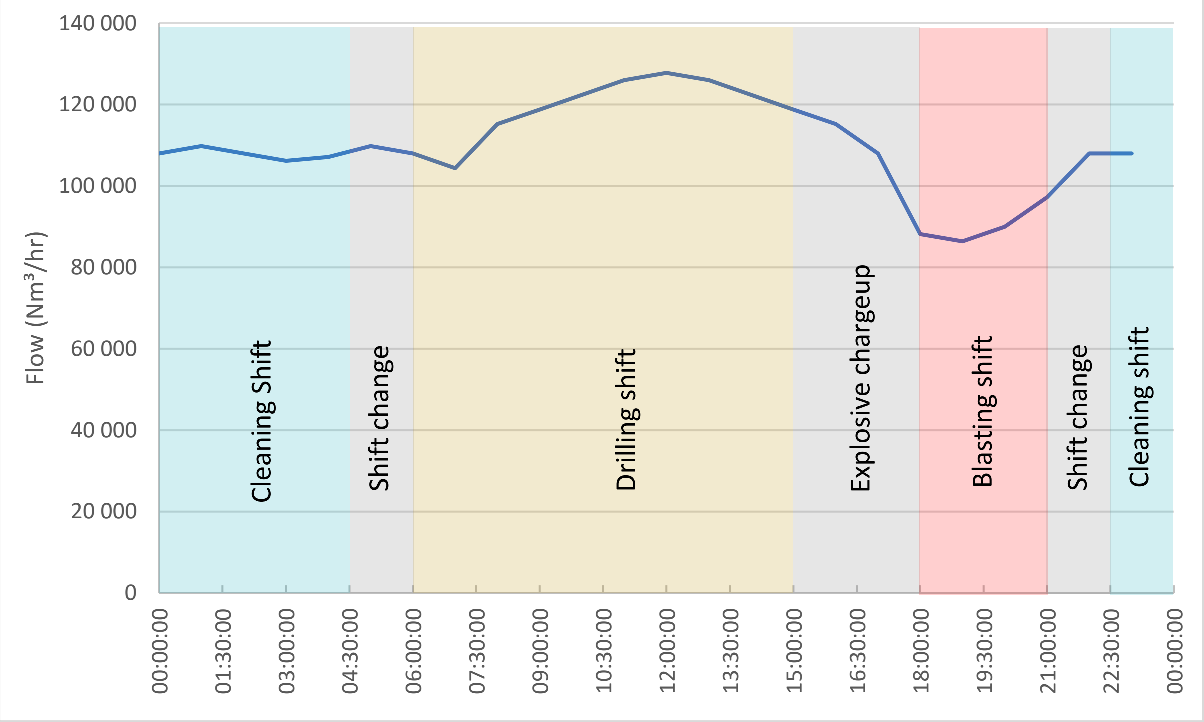


Figure 1-14: Typical PGM mineshaft flow profile (Adapted from [73])

The compressed air requirements of equipment must be met continuously, especially during the drilling shift. If this is not the case, the entire mine's production could be affected since there is no ore to process [35]. During the low-demand periods (outside of the drilling shift), compressed air networks are often oversupplied [35], [51]. This oversupply of compressed air results in energy wastage and should be avoided if possible [26], [52].

As a result of their significant electricity usage and the low efficiency of compressed air systems, these systems are ideal candidates for implementing energy efficiency solutions [50]. Marais stated that improvements to the energy efficiency of these systems can result in energy savings of over 30% [32]. The next section investigates energy efficiency solutions that are available to use in compressed air systems.

1.3 Literature review on energy efficiency solutions

1.3.1 Preamble

Mining compressed air systems are responsible for a significant amount of energy usage, as discussed in Chapter 1.2.2. Moreover, these systems are often inefficient and several energy efficiency solutions exist to address this [53], [54]. When these solutions are implemented, however, the mine's production must be left unaffected. This is done by ensuring that the compressed air supply constantly matches the demand [35].

The solutions that can improve the efficiency of compressed air systems are divided into two distinct categories [55]. The first category is demand-side management (DSM), which pertains to managing the air requirements of the compressed air networks and the compressed air users. The second category is supply-side management, which includes solutions that focus on saving energy on the supply side of compressed air networks [55].

This section reviews previous studies that implemented efficiency solutions from both categories. First, solutions that improve compressed air demand are discussed, followed by solutions that improve the supply side. For each study, the section discusses the study's purpose, benefits and results that were obtained. For the studies where the monetary savings were noted, the savings are given according to 2020/2021 Eskom tariffs. Furthermore, drawbacks in using the energy efficiency solutions are discussed.

1.3.2 Improving compressed air demand

Several solutions exist for improving compressed air systems on the demand side (at the end users). This section discusses two possible solutions, namely using control valves and repairing leaks.

Control valve utilisation

Compressed air networks use control valves on the surface or underground. The purpose of control valves is to control the pressure, which subsequently restricts airflow. The valves are fitted with actuators, which control the position of the valve. An actuator is controlled with a programmable logic controller (PLC) that is connected to a supervisory control and data acquisition (SCADA) system. The SCADA system is used for monitoring the data of various parameters in real time [45].

The valves reduce the pressure to ensure that compressed air users only get the required pressure and are not oversupplied, especially during low-demand periods. With the resultant reduction in airflow, system losses, such as leaks and friction, are also reduced [50].

Due to the lower demand for compressed air, compressors can be switched off or guide-vanes on compressors supplying the network can be used. As discussed in Section 1.2.3, using guide-vanes reduces a compressor's intake airflow and, consequently, its power consumption.

Marais and Kleingeld considered using valve control on several mining levels [55]. It was found that conservative energy savings of between 10% and 20% could be achieved on shafts that already had valve control. By contrast, conservative savings of 20% could be achieved on shafts without valve control.

In 2015, Deysel, Kleingeld and Kriel [28] considered a control strategy featuring eight control valves at end users coupled with compressor control at five compressors. The purpose of combining these energy efficiency solutions was to allow for a more effective compressed air control to realise cost savings. This resulted in overall savings of R3.3 million per annum, with an estimated payback period of 25 months.

Pascoe, Groenewald and Kleingeld [25] considered using compressed air control valves during low-demand periods in 2017. A large valve was installed that could close the main pipeline, whilst a smaller valve was installed on a bypass pipeline. The smaller valve could be controlled to not only ensure that the pressure and flow requirements were met, but also that the user was not oversupplied. This resulted in annual savings of R1.9 million per annum. The study only focused on matching the compressed air demand with the supply for low-demand periods. The authors recommended that a dynamic compressor selection system be used to ensure that the supply of the compressors matched the demand throughout the day and not only in certain periods.

In 2019, Shaw *et al.* [54] considered valve control amongst other energy efficiency solutions. The authors created a method that characterised the compressed air system to identify areas where energy efficiency solutions can improve the system’s efficiency. The projects were combined to holistically reduce the consumption of compressed air. Annual savings of R4.8 million were projected. The authors noted the importance of strict valve scheduling on the ability of valve control to be impactful.

A drawback to using control valves is that they can be expensive [38]. Conversely, one of the biggest advantages of using control valves to improve the energy efficiency of compressed air systems is that savings can be realised as soon as the valves are installed [55]. Thus, more valves can be installed incrementally as the savings accumulate, leading to more savings.

Leak repair

Compressed air pipelines are regularly in operation for extended periods – often from when the network is constructed up until the life-of-mine is reached. As time progresses, leaks can appear on the compressed air pipelines in the form of open pipes or breaks. Corrosion is a significant contributor to leaks occurring on these pipes [56]. Furthermore, due to the substantial size of the compressed air networks, leaks are often difficult to find or occur in places that are difficult to reach or are visited infrequently.

Figure 1-15 visualises the annual financial impact of compressed air leaks with various hole diameters. It is clear that as the hole diameter of a leak increases, the cost of the leak increases significantly. For instance, there is a R100 000 difference between a leak of 5 mm and a leak of 10 mm. When comparing a 50 mm leak with a 100 mm leak, the financial impact differs by almost R10 million per annum.

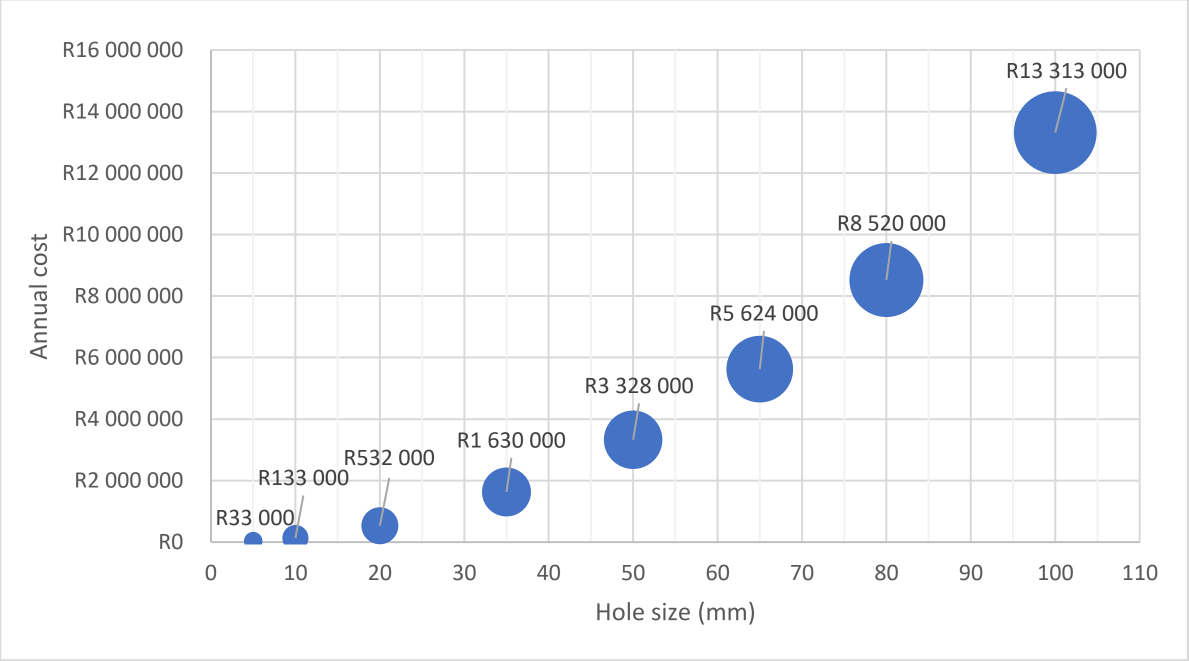


Figure 1-15: Annual cost of compressed air leaks (adapted from [57])

Saidur, Rahim and Hasanuzzaman found that leaks in compressed air systems contribute to between 20% and 30% of a system’s compressed air demand [58]. Identifying and repairing these leaks is an effective way of improving the efficiency of compressed air systems [57]. Several methods are available to identify leaks [57], [59]:

- Pipeline audits.
- Theoretical calculations.
- Soap water.
- Dye additives.
- Ultrasonic detectors.
- Automated acoustic wave detectors.

The benefits and drawbacks of using these leak identification methods are summarised in Table 1-3 [57], [59], [60].

Table 1-3: Benefits and drawbacks of leak identification methods (adapted from [57], [59], [60])

Method	Benefit	Drawback
Pipeline audits	• Inexpensive • No equipment required	• Time-consuming • Small leaks are difficult to find
Theoretical calculations	• Can quantify the magnitude of leaks	• Cannot pinpoint the location of leaks
Soap water	• Inexpensive • Production unaffected	• Not feasible on large compressed air networks
Dye additives	• Inexpensive	• Only works in dark areas
Ultrasonic detectors	• Can detect inaudible leaks • Has a specific frequency range for detecting leaks	• Time-consuming
Automated acoustic wave detectors	• Can pinpoint the location of leaks on large networks	• Requires expensive equipment

In 2016, Fouché [61] developed a method which mitigates the impact of leaks by combining leak repairs with valve control during changeover periods. The author identified levels with pressures that were much lower than expected to help identify possible leaks. This guided underground audits. When the leaks were fixed, the control valves could be used more aggressively whilst leaving underground pressures unaffected. The author was able to achieve a total energy efficiency saving of 877 kW, which amounted to annual savings of R6.3 million.

Saidur *et al.* found that leaks are only repaired if they affect a system’s operation adversely [58]. Furthermore, repairing compressed air leaks can lead to downtimes on compressed air networks and be time-consuming. Marais and Kleingeld stated that as a consequence of the ever-lengthening compressed air pipelines, fixing leaks is a time-intensive and possibly never-ending task [62]. Instead of fixing leaks to reduce the effects of leaks, they proposed isolating certain sections of the network during non-production times by using isolation valves. Because compressed air is required continuously, albeit different amounts at different times of the day, it is not necessarily feasible to isolate sections completely. However, the amount of compressed air lost through leaks increases as the pressure in a vessel increases [42]. Therefore, it is beneficial to reduce the impact of leaks by using control valves to restrict the downstream pressure (the pressure after the valve) [62].

1.3.3 Improving compressed air supply

There are numerous energy efficiency solutions that improve compressed air systems on the supply side. This section expands on four supply-side energy efficiency solutions with regard to what they entail and how they were used in previous studies. The energy efficiency solutions are schedule optimisation, guide-vane control, network reconfiguration, and the utilisation of smaller compressors.

Compressor schedule optimisation

To save energy by avoiding the wasteful practice of oversupplying compressed air networks, the compressed air supply must be only that which the demand necessitates. This is done through schedule optimisation by selecting the compressors most suited for the instantaneous demand. Compressor schedule optimisation as an energy efficiency solution dictates that compressed air supply continuously matches the network’s demand by using the most suitable compressors. One highly efficient compressor, for instance, can better meet the network’s requirements than two compressors of moderate efficiencies [55]. Furthermore, compressors that are not necessary and result in an oversupply must be switched off.

De Coning considered a control strategy which, amongst other initiatives, considered the schedule optimisation of compressors [63]. The control strategy entailed switching off compressors during the peak Eskom time-of-use (TOU) periods when electricity was most expensive. These periods coincide with the blasting shift on mines. During these times, the surface valves of shafts should be closed and compressed air demand should be at a minimum. After the blasting shift has taken place, compressors are started to ensure that the subsequent shift gets the required compressed air. The control strategy proposed by De Coning is a feasible solution for mines that do not switch off compressors during blasting shifts. The strategy, however, can be expanded to include other non-production time frames, such as the cleaning shift. Hence, barring the drilling shift, compressors can be selected to ensure that the supply continuously matches the demand whilst not oversupplying the network.

In 2017, Jonker *et al*. [65] developed a dynamic compressor selector. The purpose thereof was to match the compressed air supply with the demand by optimising the scheduling of compressors. By predicting the flow and pressure profiles that will be required, they were able to accurately schedule the compressors. With this method, a demand reduction of 3.3 MW was obtained during the evening peak Eskom periods, amounting to annual savings of R3.8 million.

Marais [32] considered various energy efficiency solutions to curb the consumption of a compressed air network. One of the energy efficiency solutions considered was using the lowest number of compressors that was able to meet the network's demand. Furthermore, the compressed air demand was met by continuously selecting the most efficient compressors. In one of the case studies, optimisation of the compressor schedules resulted in a demand reduction of 2.45 MW, which equated to savings of R12.8 million per annum. A shortcoming of the study was that it omitted system inefficiencies, such as friction losses.

There is, however, a drawback to switching off compressors. Pascoe found that mining personnel are hesitant to switch off compressors because they claim that it has adverse effects on the lifetime of the compressors [59]. By contrast, one of the largest benefits of compressor schedule optimisation is that no additional capital expenditure is required if there are other compressors readily available.

Guide-vane control

As discussed in Section 1.2.3, guide-vanes reduce the airflow that a compressor provides, consequently reducing the compressor's power consumption. Guide-vane control is one of the most commonly used and effective supply-side management techniques [55]. The Moore controller is the most common controller used in guide-vane control [55]. The benefit thereof is that the requirements of the system can be specified in the form of a pressure profile. The controller will then control the guide-vanes accordingly to match the system's requirements. As discussed in Section 1.2.3, specific set points are used to control the discharge pressures of compressors.

Booysen, Kleingeld and Van Rensburg considered the optimisation of compressor control strategies [64]. Guide-vane control was used to lower the compressor output pressures during periods with low compressed air demand. This reduced compressor discharge pressure resulted in an energy consumption decrease of 17.3% and monetary savings of R6.8 million per annum.

In 2017, Vermeulen, Cilliers and Marais [52] developed a strategy which improves the compressor throttle control. This meant that the flow leaving the compressor can be reduced further when the demand was low. Average savings of 650 kWh were achieved for weekdays, amounting to annual savings of R4.3 million. The study noted the importance of ensuring that the surge margins of the compressors were updated and closely monitored.

Guide-vanes can further be used in conjunction with compressor schedule optimisation. Once the optimal number of compressors are running, guide-vanes can be utilised to ensure that the supply of compressed air closely matches the demand. This strategy is used in cases where the supply exceeds the demand slightly, but switching off any compressor will result in an unmet demand. As with compressor schedule optimisation, guide-vane control does not require capital expenditure, making it a low-risk cost-efficiency strategy.

However, guide-vane control often relies on human intervention. Mining personnel may be tasked with manually implementing the guide-vane control and using pressure set points if an automated system is not available. This can affect the savings achieved and the effectiveness of the energy efficiency solution. Furthermore, guide-vane control is restricted by the end user on the network with the highest pressure requirement. Since the ring pressure stabilises, it is challenging to supply compressed air at different pressures to different end users. This means that some end users, which operate at lower pressures, are supplied higher pressures. Consider, for instance, a compressed air ring with two shafts, namely Shaft X and Shaft Y. If Shaft X must operate at 450 kPa during the cleaning shift, whilst Shaft Y must operate at 500 kPa, the ring pressure must be kept at 500 kPa to ensure that Shaft Y has ample supply. To circumvent this, valve control must be used.

Network reconfiguration

As discussed in Section 1.2.2, compressed air rings are designed to ensure that all end users receive compressed air. They can also operate close to normality when there are unexpected changes to the system. For instance, if a compressor supplying the ring requires maintenance, it can be substituted by other compressors on a ring.

When a compressed air ring is built initially, it is designed for a specific set of compressor houses and end users. As time goes by, the compressed air need of end users could change or new end users appear. Furthermore, other end users could cease to exist and new compressors could be connected to the compressed air ring. The result is a compressed air ring, which was tailormade for a specific combination of end users, being used for a different combination of end users. Consequently, the compressed air ring becomes inefficient. To address this, the network can be reconfigured by means of using alternate pipelines that connect different parts of the compressed air ring or by closing existing pipelines. The reconfiguration helps optimise the current compressed air ring and ensures that compressed air is supplied as effectively as possible.

Bredenkamp considered the reconfiguration of compressed air networks to save energy [47]. The network was oversupplied during low-demand periods, thereby wasting energy used for compressed air generation. The author investigated the relocation of a compressor and the connection of two mineshafts' compressed air pipelines. Before the project's commencement, a simulation was constructed to ensure its feasibility. The strategy led to an average demand reduction of 1.7 MW, which was 24% of the total demand. With the repair of leaks, the average demand reduction increased by 0.3 MW. Bredenkamp concluded that reconfiguring compressed air networks could result in significant cost savings, with annual savings of R13.8 million predicted. A major drawback to this strategy is that it requires significant capital funding because it is expensive to reconfigure compressed air networks. It should therefore only be used when the resources are already available or when the benefit thereof far outweighs the cost.

Use of smaller compressors

As discussed above, the compressed air end users on a compressed air network can change as time progresses. The compressed air demand may increase as the underground mining operation of shafts expand or decrease as shafts are decommissioned at the end of their lifespans. Smaller compressors can be used to address the change in compressed air demand. Furthermore, several smaller compressors can be installed to match the capacity of a single larger compressor. This means that during periods of high demand, the smaller compressors can match the supply of a larger compressor. During periods of lower demands, rather than running the large compressor and oversupplying the demand, a few smaller compressors can be run.

In 2017, Pascoe *et al.* [25] considered using two smaller compressors to replace a larger compressor. The capital funding was not available to acquire two new compressors; thus, the project was limited to a theoretical analysis. A simulation was developed and verified to simulate the effect of using two 4 MW compressors instead of a large 15 MW compressor. Although the two smaller compressors were able to reduce the energy usage effectively, they were unable to match the network's demand during the drilling shift. This would have affected production adversely. To leave production unaffected would have necessitated the use of the 15 MW compressor during the drilling shift.

An alternative was to use the two smaller compressors during low-demand times, whilst using the larger compressor to ensure that the compressed air demand was met during periods of maximum demand. When considering the period during which the smaller compressors were able to match the network's demand (during shift changeovers and blasting shift), daily energy savings of roughly 50 MWh were obtained. This resulted in potential monetary savings of roughly R9.8 million per annum.

The potential drawback to using smaller compressors is that the solution is only beneficial when the compressors are already available. Substantial capital expenditure is required if smaller compressors are not available and must be acquired.

1.3.4 Summary

This section discussed the various methods for improving compressed air systems. First, it discussed the methods for managing the air requirements of compressed air users. Thereafter, the section discussed the methods for improving the efficiency of compressed air systems by improving the supply of compressed air. Table 1-4 summarises the compressed air energy savings methods.

Table 1-4: Summary of compressed air energy savings methods

Method	**Benefit**	**Limitation**
Leak repairs	• Can result in substantial savings	• Time-consuming [62]
Valve control	• Compressed air supply is controlled to ensure users are not oversupplied	• Capital funding is required • Can take long to implement
Schedule optimisation	• Compressors are used efficiently and not used needlessly	• Mining personnel might be hesitant to switch off compressors [59]
Guide-vane control	• Supply can closely match network's demand	• Reliant on human intervention • Pressures are dictated by highest pressure requirement in compressed air ring
Network reconfiguration	• Compressed air networks can be optimised	• Significant capital funding required • Implementation might be time-consuming • May result in some end users not receiving ample compressed air
Use of smaller compressors	• Ensures that most efficient compressors are used	• Requires significant capital if smaller compressors are not available

In this section, several energy efficiency solutions were investigated. Despite their individual drawbacks, these energy efficiency solutions can improve the efficiency of a compressed air network. However, with the large number of energy efficiency solutions available, uncertainty may arise regarding the most feasible energy efficiency solution and the implementation order.

From the studies considered, simulation was often used as a tool to quantify the impact of energy efficiency solutions on a compressed air system. The next section investigates the use of simulation for energy efficiency solutions by considering viable simulation software and how previous studies used simulation software for energy efficiency solutions.

1.4 Use of simulation for energy efficiency solutions

1.4.1 Preamble

Continuous advances in technology mean that computer hardware and software grow accordingly. This enables industries to put more powerful hardware and more intricate software to use in the form of simulations [66]. Simulation has been used in various industries, including, but not limited to the manufacturing, healthcare and defence industries [67]. Simulations are the best method for predicting the effect that changes in a system would have on the system's energy efficiency [68]. However, in the past, simulations did not lend well to the mining industry as they required input data that was difficult to obtain and could not be used for complex systems [32]. This necessitated the use of estimations.

For instance, Marais used a model to estimate how a compressed air network would react to various changes [32]. The model was a vessel that had a supply of compressed air and several leaks as compressed air demands. There are, however, several limitations to such an approach as numerous assumptions are made and the model can only be used to analyse simple situations [50]. Recent developments in simulation, however, allow simulation to also be used in the mining industry to identify and optimise opportunities for improvement [69]. This means that simulation can be used for various mining utilities, such as compressed air, water and ventilation [70].

This section discusses what must be considered when selecting simulation software, which is followed by an investigation on the simulation tools that are available for use on mine compressed air systems. Thereafter, previous studies where simulations were used on mine compressed air systems are discussed.

1.4.2 Simulation software

It can be challenging to select simulation software due to the large variety available in most industries [12]. This is also true of the mining industry since there are several software programmes available. There are several criteria, however, that simulation software must adhere to, to be feasible for use in mining operations. This can aid in selecting software. The criteria are as follows (adapted from [60], [70]):

- Criterion 1: The simulation software must be able to determine how the system will respond to various changes.
- Criterion 2: The simulation software must enable not only steady-state simulation, but also transient simulation (in transient systems, the process variables change over time).
- Criterion 3: The simulation software must be able to deliver its output for specific periods, which allows it to be compared with actual data.
- Criterion 4: The software must be intuitive and not time-consuming to use.
- Criterion 5: The software must be able to accommodate missing data inputs.

This section discusses feasible simulation software that can be used in mining operations, their benefits and drawbacks. Lastly, a simulation software is chosen for use in this study.

Simulation software

In 2018, Friedenstein, Cilliers and Van Rensburg identified the following simulation software that may meet the aforementioned criteria and can be used in mining industry simulations [50]:

- Flownex®.
- KYPipe GAS®.
- Real-time Energy Management System® (REMS).
- Process Toolbox® (PTB).

Van Tonder stated that both KYPipe and Flownex are simulation software commonly used for compressed air consultancy projects [60]. The drawbacks that the author found were that data must be entered manually for every scenario and that there is no interface for real-time system data to be accessed. Moreover, it was stated that these software packages are not feasible for use in the mining industry since they are time-consuming and require skill to be used. Watkins stated that although Flownex has the capability for the batch processing of data, the feature is time-consuming [71]. Hence, neither Flownex nor KYPipe are suitable for the simulation of compressed air networks as they do not adhere to Criterion 4.

Maré identified that a drawback of REMS is that it can only be used for steady-state simulations, hence it is unable to make predictions regarding system changes [70]. This statement was further substantiated by Van Niekerk [72]. REMS, therefore, is not adequate for the use of simulating compressed air networks since it does not adhere to Criterion 2.

PTB is designed to be intuitive and can be used for mining applications [70]. In 2018, Watkins noted that PTB can simulate complex compressed air networks accurately [71]. PTB has built-in functionalities for thermal-hydraulic systems, such as compressed air, water and ventilation.

Furthermore, it can simulate transient and steady-state conditions. PTB can be used to evaluate various scenarios and system changes. Of the available software packages, PTB is the best package to use for mining compressed air systems since it meets all the required criteria. Therefore, PTB was used for all simulation purposes within this study.

1.4.3 Simulation in compressed air systems

Simulations have been used to serve various purposes in compressed air systems. This section investigates compressed air simulations from previous studies. First, the purpose of the simulation and the methodology that was used to create the simulation are investigated. Furthermore, if the study resulted in monetary savings, the savings obtained are given according to the 2020/2021 Eskom tariffs. Lastly, the shortcomings of the studies are identified.

Methodology for developing a simulation for compressed air systems

In 2017, Maré, Bredenkamp and Marais formulated a methodology for developing simplified compressed air simulations [73]. The method focused on developing simulations that have reliable accuracy and can be used for energy efficiency and service delivery improvements of compressed air systems. Furthermore, the method was aimed at making the use of simulations more intuitive. The authors underlined the following elements that are necessary when considering the simulation of compressed air systems (adapted from [73]):

- Dynamic operation of mine.
- Layout and drawings of compressed air system.
- Constraints and operational conditions.
- Data availability and data accuracy.
- Compressor specification availability.
- Operational boundary conditions.
- Time frame used in simulation.

The method developed by the authors, which takes the elements above into consideration, is summarised as follows in Figure 1-16 (adapted from [73]):

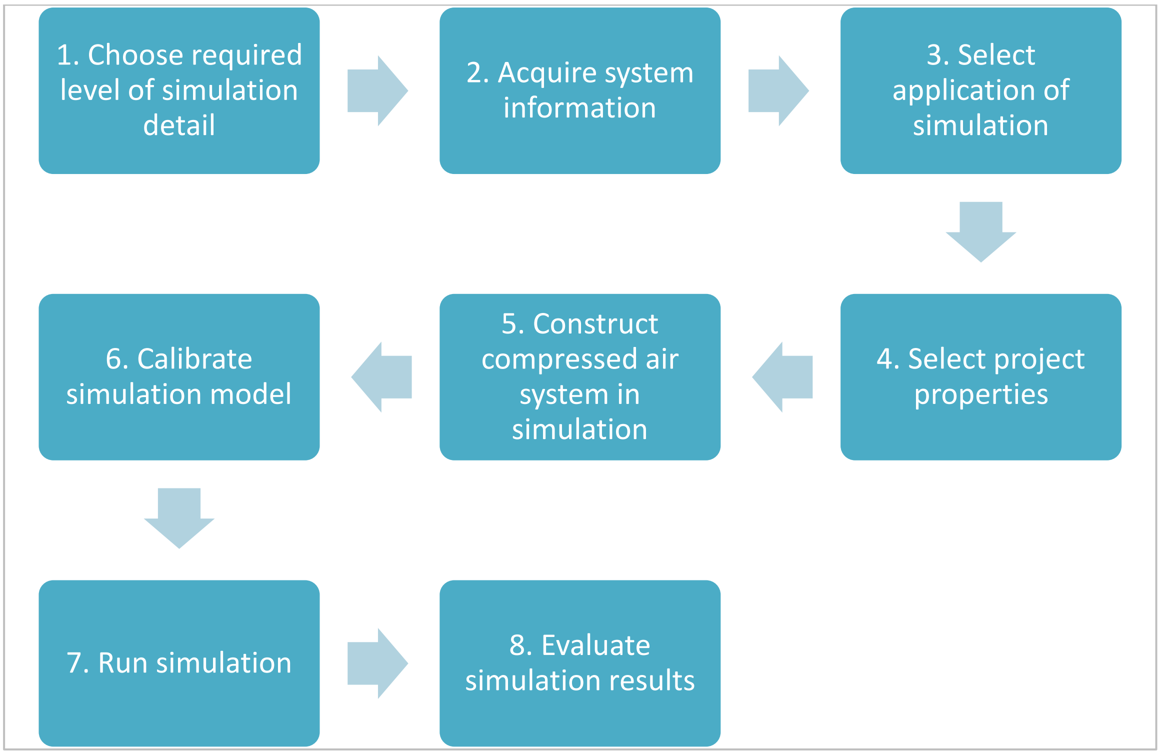


Figure 1-16: Developing simulation model for compressed air systems (adapted from [73])

By using the developed methodology, the authors were able to investigate the effect of several compressed air efficiency solutions. The most feasible energy efficiency solution could lead to an average demand reduction of 0.17 MW, resulting in annual cost savings of R1.8 million. The percentage of demand reduction or detailed figures from which it was calculated were not given.

A shortcoming of the study is that it did not prioritise the implementation order of the efficiency solutions. Although different energy efficiency solutions were compared, only the most feasible solution was implemented. The study did not detail how different energy efficiency solutions must be implemented and according to which priority.

Using simulations to identify compressed air efficiency solutions

In 2019, Mathews *et al.* [45] developed a methodology that focuses on the identification of compressed air energy efficiency solutions. The methodology focused on compressed air efficiency solutions as a whole and not on simulations specifically. The five-step methodology is summarised in Figure 1-17 (adapted from [45]).

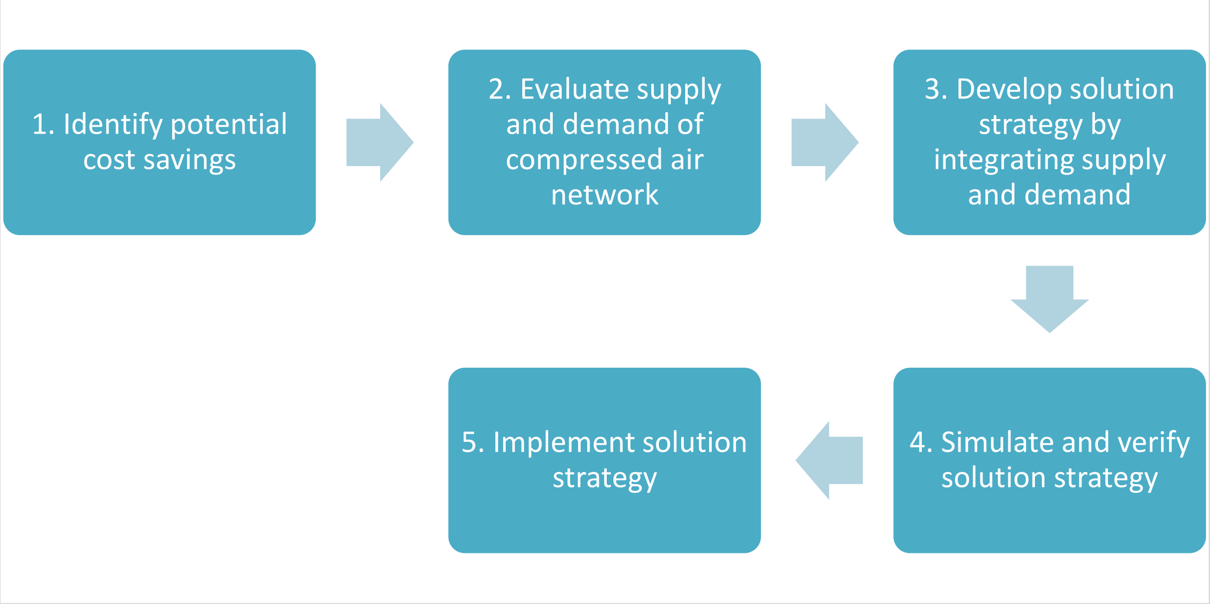


Figure 1-17: Identifying compressed air efficiency solutions using simulation (adapted from [45])

The methodology was implemented at a case study mine. Annual savings due to energy efficiency improvements of R1.1 million were obtained with no adverse effects on the mine's production. The demand reduction achieved was not provided.

As can be seen from the summary in Figure 1-17, a shortcoming is that the study did not detail a clear method on how the simulation must be developed and what its requirements are. Furthermore, the study did not prioritise which energy efficiency solutions should be implemented.

Using simulations to quantify cost savings of energy efficiency solutions

In 2017, Pascoe *et al.* considered the use of simulation to investigate the potential cost savings of two compressed air DSM projects [25]. The first project entailed using a control philosophy on a compressed air control valve during periods of low demand. The second project investigated the effect of replacing a large compressor with two smaller compressors. A simulation procedure was created that simulated, quantified and verified the possible effects of the DSM projects. The resulting simulation procedure is summarised in Figure 1-18 (adapted from [25]).

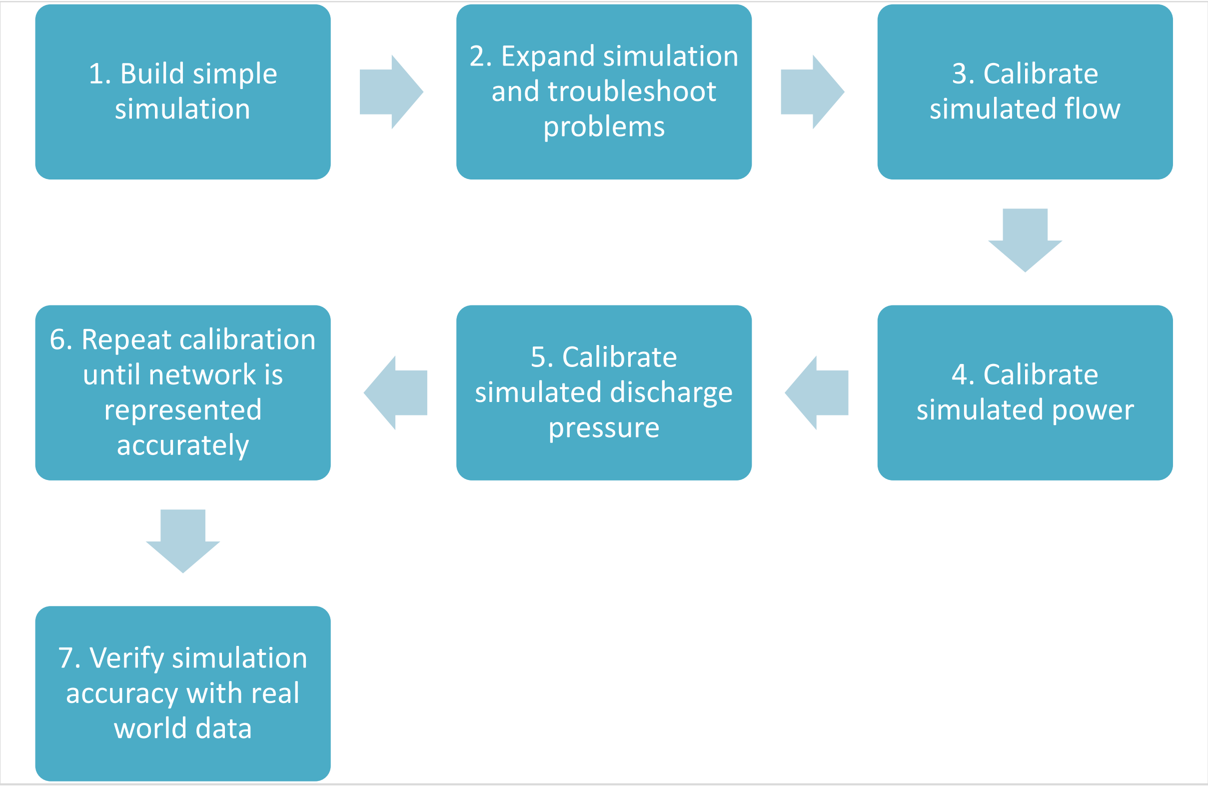


Figure 1-18: Quantifying cost savings of energy efficiency solutions using simulations (adapted from [25])

For the first initiative, the simulation model was able to predict a demand reduction of 3.1 MW during the blasting shift. This was a percentage reduction of 31%, which resulted in annual savings of R2.4 million. The second initiative was only conducted theoretically, but the simulation model predicted daily energy savings of 50 MWh, amounting to a saving of 30%. The method did not prioritise the implementation order of the energy efficiency solutions that were considered. In other words, thought was not given to the most beneficial order in which the energy efficiency solutions had to be implemented.

Friedenstein *et al.* created and implemented a simulation methodology to simulate detailed compressed air networks [50]. The simulation procedure is given in Figure 1-19 (adapted from [50]). The simulation methodology was applied to two case studies. In the first case study, the use of compressor set points was considered and implemented along with the use of underground pressure control by means of control valves. This resulted in a demand reduction of 1.46 MW during evening peak periods, which led to total annual savings of R1.5 million. The simulation results were verified by comparing the simulation's data with actual tests on the system.

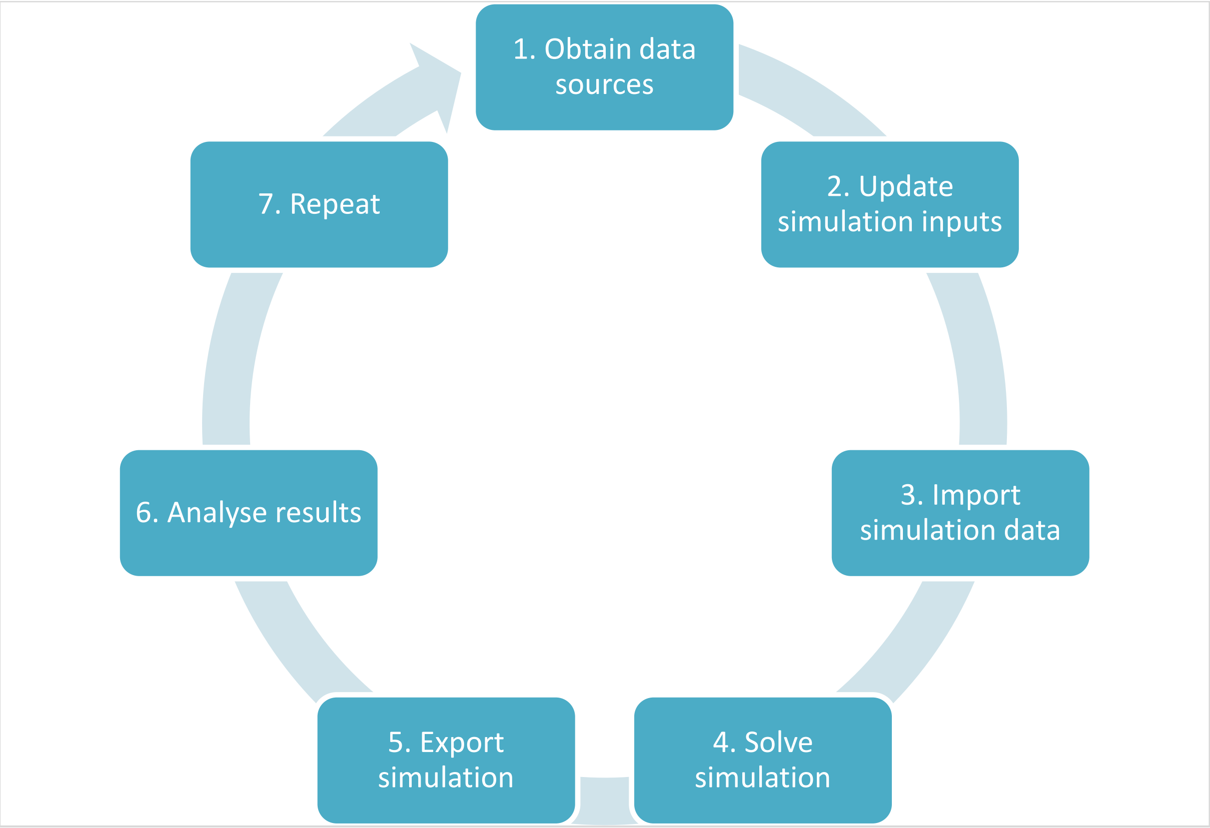


Figure 1-19: Simulating compressed air efficiency solutions (adapted from [50])

The authors' second case study, which only took place theoretically, considered reducing leaks in refuge chambers as well as optimising underground demand during the Eskom peak time. Reducing the refuge chamber leaks could result in a 0.92 MW demand reduction, which was 8% of the total demand. Optimising the underground demand could lead to a demand reduction of 2 MW during peak time, which was 22% of the total demand. The combined annual savings predicted by the simulation model were R7.8 million.

It was concluded that simulation is a helpful tool for improving compressed air systems. A key limiting factor of simulations, however, was underlined as the availability of reliable data, which influences the accuracy of simulations.

Along with the studies of Mathews *et al.* [45] and Pascoe *et al.* [25], the methodology of Friedenstein *et al.* [50] did not prioritise the implementation order of energy efficiency solutions. Furthermore, it is found lacking in providing a method to achieve the simulation model. As can be seen in the methodology above, it does not detail how the simulation model must be created or verified.

Methodology to determine accuracy of compressed air simulations

Watkins developed a methodology for determining the accuracies of simulations with varying magnitudes of complexity [71]. This was done to represent mines with varying degrees of data availability. The author considered three simulation models, namely a simplified, standard and detailed model. The simplified simulation was a less complex version of the standard model, which in turn, was a simplification of the detailed model. The methodology the author followed is summarised as follows:

1. Analyse network.
2. Develop models.
3. Validate models.

Watkins concluded that the complexity of compressed air simulation models has little effect on their accuracy. This is apparent in the simulation results where the maximum error of the detailed model was 2.88%, the maximum error of the standard model was 4.5%, whilst the maximum error of the simplified was 4.87%. In other words, less complex simulation models that accommodate limited data availability are still able to simulate compressed air networks accurately [71].

The method developed by Watkins could successfully determine the expected accuracy of the three simulation types. A prominent shortcoming with Watkins' method, however, is that it only consisted of a simulation methodology and did not consider energy efficiency solutions. No energy efficiency solutions were therefore implemented.

1.4.4 Summary

This section discussed various studies that used compressed air simulations. These studies considered building compressed air simulations and using simulation to identify compressed air savings opportunities. Furthermore, the cost savings and/or demand reduction of energy efficiency solutions were given and the accuracy of compressed air simulations was determined.

A summary of the studies and their respective shortcomings are given in Table 1-5.

Table 1-5: Summary of compressed air simulations

Author	**Year**	**Use**	**Shortcoming**
Maré *et al.* [73]	2017	Develop compressed air system simulation	• Does not prioritise implementation order of solutions
Mathews *et al.* [45]	2019	Identify compressed air energy efficiency solutions	• Does not provide a clear method to create simulation • Does not prioritise implementation order of solutions
Pascoe *et al.* [25]	2017	Quantify cost savings of energy efficiency solutions	• Does not prioritise implementation order of solutions
Friedenstein *et al.* [50]	2017	Quantify cost savings of energy efficiency solutions	• Lacks detail of how simulation model must be developed and calibrated • Does not prioritise the implementation order of solutions
Watkins [71]	2018	Determine the accuracy of compressed air simulations	• Does not implement energy efficiency solutions

It is apparent that various studies have been done that considered compressed air energy efficiency solutions. However, there is a definite shortcoming in prioritising the implementation order of energy efficiency solutions since none of the studies considered this.

1.5 Problem statement and overview

1.5.1 Problem statement and objectives

Problem statement

One of the largest challenges facing the platinum industry is the above-inflation increase in costs, especially electricity costs. Since compressed air generation is a large expense on platinum mines and compressed air systems are used extensively and are inefficient, compressed air is a viable system to consider for energy efficiency solutions.

Research reveals solutions that can improve the efficiency of compressed air systems. Moreover, recent advances in simulation software allow for the accurate simulation of compressed air systems. Previous studies have used compressed air simulation for various purposes; most notably to quantify the potential effect of energy efficiency solutions.

There is, however, not a methodology that prioritises the implementation order of energy efficiency solutions. Therefore, mining personnel may be uncertain about the order with which energy efficiency solutions must be implemented. To address this problem, simulation can be used to prioritise the implementation order of these solutions.

A need, therefore, exists for a methodology that uses simulation software to prioritise the implementation order of energy efficiency solutions.

Research objectives

The primary objective of this study is to develop a methodology that uses simulation to evaluate and prioritise the implementation order of energy efficiency solutions. This is accomplished by achieving the following objectives:

- Develop and verify simulation models.
- Use simulation models to identify feasible energy efficiency solutions.
- Develop method to determine impact of energy efficiency solutions and to prioritise implementation order.

1.5.2 Dissertation overview

Chapter 1

This chapter introduced the dissertation by providing an overview of the South African platinum industry and its many challenges. An overview of compressed air systems in platinum mining and a review of compressed air efficiency solutions in the industry followed. Hereafter, the use of simulation in the mining industry was investigated.

By taking the use of compressed air efficiency solutions and simulations in the industry into account, a problem statement was provided. Finally, the research objectives of the dissertation were outlined.

Chapter 2

To address the problem statement formulated in Chapter 1, the chapter describes how a methodology was developed to create and verify simulation models of compressed air energy efficiency solutions. Furthermore, this chapter discusses how the methodology prioritises the implementation of energy efficiency solutions.

Chapter 3

This chapter presents the results for two case studies on which the methodology developed in Chapter 2 was implemented. Hereafter, the results obtained in this study are discussed and validated. Finally, the case study results are extrapolated to determine the potential impact of the methodology on the South African platinum mining industry as a whole.

Chapter 4

In Chapter 4, the study is summarised and concluded. The completion of the research objectives is discussed and the problem statement is addressed. Lastly, limitations that were present in the study are identified and recommendations for potential future studies are made.

CHAPTER 2 – DEVELOPMENT OF SOLUTION

2.1 Preamble

As discussed in the previous chapter, simulation has been used for various purposes in compressed air systems. However, there is a need for using simulation to prioritise the implementation order of compressed air energy efficiency solutions. In this chapter, a methodology is developed that uses simulation to prioritise the implementation order of energy efficiency solutions.

Insights obtained from previous studies discussed in Section 1.4.3 (which considered simulation for various purposes on compressed air systems) are considered during the development of this method. The methodology consists of the following four main steps, each with sub-steps:

1. Analyse system.
2. Create simulation models.
3. Verify models.
4. Determine implementation priority.

First, an analysis is conducted to ensure a thorough understanding of the system. Thereafter, a model is created in PTB and subsequently verified. Finally, a methodology is created that prioritises the implementation order of energy efficiency solutions.

2.2 Analyse system

2.2.1 Preamble

A thorough understanding of the system is required to create a simulation model that is representative of a complex compressed air system [50]. Not only must the system's requirements and its operating schedule be considered, but also all the components that are required in the model.

This section elaborates on the requirements for obtaining an adequate comprehension of the system. This is done by determining the system and data requirements, obtaining data and, finally, compiling the data.

2.2.2 Determine system and data requirements

Determine data requirements

It is vital to consider the entirety of a compressed air system’s operating schedule since the demand for compressed air changes throughout the day. There are different shifts in a typical day on a PGM mineshaft, as discussed in Section 1.2.5. Therefore, it is important to know what the requirements are during each shift, since each shift has specific requirements.

Most importantly, production must not be hindered during the drilling shift [38]. Therefore, unless the energy efficiency solution results in a service delivery improvement, it must not be implemented during the drilling shift. In other words, if it does not increase the pressure for the end users, it must only be implemented when the maximum amount of compressed air is not required. During the cleaning shift and blasting shift, however, understanding the compressed air requirements properly will aid in identifying compressed air efficiency solutions with the simulation model.

Therefore, the minimum required pressures during each shift must be established. This will ensure that all the components get the pressures they require. For instance, during the cleaning shift, underground loaders must receive compressed air at a specific pressure otherwise they will not be able to shovel ore properly. During the blasting shift, compressed air valves can be closed since no mining personnel are underground. Therefore, no compressed air is required for ventilation. During shift changes, compressed air is only used to feed refuge chambers since work is temporarily halted when the personnel change shifts.

Establish required data

For an accurate simulation model of the system to be created, it is vital to understand the simulation package and its requirements properly. As mentioned earlier, PTB allows the modelling of thermohydraulic systems. In PTB, a plethora of air, water, steam and auxiliary components are available, but the following are the key components used to create compressed air simulations [70], [74]:

- Air demands.
- Air nodes.
- Atmospheric pressure boundaries.
- Dynamic compressors.
- Pipes.

Each of these components requires specific data for the simulation model. This data ensures that once the component is calibrated properly, it is representative of its real-life counterpart. A summary of the required data for each component is given in Table 2-1.

Table 2-1: Required data for PTB components (adapted from [70], [74])

Component	**Required data**
Air nodes	Atmospheric pressure Atmospheric temperature Pressure in pipe Relative humidity
Air demands	Shaft pressure Shaft flow
Atmospheric pressure boundaries	Atmospheric pressure Atmospheric temperature
Compressors	Compressor efficiency Characteristic curve Discharge pressure Discharge temperature Post after-cooler temperature
Proportional integral (PI) controller	Compressor running status
Pipes	Valve fraction Hydraulic diameter Flow area Pipe length Surface roughness

Knowing what data is required makes it possible to obtain data efficiently and from the correct sources. Furthermore, this ensures that time is not wasted on obtaining unnecessary data.

2.2.3 Obtain data

There are various potential sources of data, including databases, physical drawings and mining personnel. It is a priority to establish communication channels with the relevant personnel on the mine, such as engineers, technicians and instrumentation superintendents. They should be able to provide access to data storage systems, documentation and instrumentation. This will allow the required data to be obtained and provide clarity regarding what the normal operation on the mine entails.

Mine database

Mine databases log the process parameters, such as pressure flow and power data [45]. This makes them ideal for obtaining the required data for the simulation model. The process parameters are further used to establish a period that represents the typical operation on the mine as well as the corresponding profile. This will serve as a baseline period, which is discussed later in Section 2.2.5.

System layouts

It is critical to obtain accurate system layouts that show the reticulation of the compressed air network (how compressed air pipelines distribute air through the network). The system layouts provide insight into how the system functions and where the critical components, such as compressor houses and shafts, are situated. Furthermore, important information such as pipe diameters, pipe lengths and the location of instrumentation should be included. Although this information can be obtained via satellite images and manual measurements, the focus should be on obtaining up-to-date layouts of the compressed air network. Satellite images can be used to verify the pipe lengths and pipe diameters can be verified by manual measurements.

Weather databases

Online weather databases can be used to access parameters that are not measured in the mine databases. These parameters include weather information such as atmospheric pressure, relative humidity and ambient temperature.

Data sources

Table 2-2 provides potential data sources for the required data listed in Table 2-1.

Table 2-2: Data sources for required data

Required data	Data source	Unit
Atmospheric temperature	Weather databases	°C
Atmospheric pressure	Mine database/ weather databases	kPa
Pressure in pipe	Mine database	kPa
Relative humidity	Weather database	%
Shaft pressure	Mine database	kPa
Shaft flow	Mine database	Nm^3/h

Required data	**Data source**	**Unit**
Compressor efficiency	Determined empirically	%
Compressor characteristic curve	Determined empirically	N/A
Compressor discharge pressure	Mine database	kPa
Compressor discharge temperature	Mine database	°C
Compressor post-aftercooler temperature	Mine database	°C
Compressor running status	Mine database	–
Pipe valve fractions	Mine database	%
Pipe hydraulic diameters	System layouts, manual measurements	mm
Pipe flow areas	System layouts	m^2
Pipe lengths	System layouts	m

When data is unavailable, manual data measurement methods are used. The main measurements that must be obtained are flow, power and pressure [45]. Table 2-3 summarises manual measurement devices for supplementing missing flow, power and pressure data, as well as other critical missing data.

Table 2-3: Supplementary measurement devices

Required data	**Manual measurement device**	**Unit**
Flow	Portable flow meter	Nm^3/h
Compressor power	Portable power logger	kW
Temperature	Portable pressure logger	°C
Pipe length	Satellite images	m
Pipe diameter	Measuring tape	mm

2.2.4 Compile data

Once all the data has been obtained, the quality of the data must be determined. The simulation model can only be representative of the actual system if quality data is used [74]. Therefore, it is vital to ensure that all the data obtained is accurate and that there are no discrepancies. Furthermore, issues in the data must be identified and rectified.

Mining systems are often in operation for long periods of time. Although most process parameters are monitored and recorded actively, some equipment may be outdated. This results in critical data for the model, such as flow, pressure or power data, being missing or erroneous. Therefore, data verification is required to ensure that the data is of high quality and that no faulty data exists. This can be done by determining the quality of the data and by rectifying erroneous data.

Data quality

To determine the quality of data, several checks are applied to the data [50]. Should a check not be passed, the data must be corrected or an explanation must be provided on why the check was not passed. The checks are as follows (adapted from [76]):

- Is the data complete?
- Do related parameters follow similar trends? For instance, the pressure in the system should be directly proportionate to the flow supply when the flow demand remains constant.
- Is the data free of outliers?
- Does the data remain constant only when it is expected to?
- Do the values accord with what is expected? For instance, the discharge pressure of a specific compressor should be between 500 kPa and 600 kPa when it is fully operational. If the values do not fall within this range when the compressor is fully operational, the data may be faulty.
- Do the measured values of the same process parameter correlate between different measuring devices? For instance, the readings of a compressor’s discharge pressure on the pressure meter should correlate with manual measurements.

Rectify faulty data

After the checks have been done, faulty data must be rectified. If possible, manual inspections and measurements should be conducted to rectify erroneous data. However, this is not always possible, which means that estimations must be made. For instance, if data for a compressor’s discharge flowrate is missing, its power can be used to estimate what the flow would be. If it is unclear when compressors were active due to missing running statuses, flow or power data can be used since non-zero values will show when the compressor was operational.

2.2.5 Establish baseline for simulation

After all data issues have been rectified, a baseline representing the typical operation on the mine is established. The baseline is used to calibrate the simulation model, which ensures that the model is representative of the actual system. The calibrated model will be used as a simulated baseline. Scenarios that have been tested on the simulation model will be compared with the simulated baseline.

In other words, the simulation model must first correspond with the baseline to ensure that it is an accurate representation of the system. Once this is completed, changes are made to the simulation model, which should then indicate how these changes should affect normal operation. This is because the simulated baseline is representative of the actual system.

A single day of normal operation must be chosen, since using the average of multiple days to represent a single day may even be detrimental to a simulation's accuracy. For instance, a compressor can be started and stopped at different times on different days. Consequently, the time frames where the compressor was running on a certain day might be negated by times it was not running on other days.

After the system has been analysed, data obtained, erroneous data has been rectified and a baseline has been established, the simulation models are created. This is discussed in the next section.

2.3 Create simulation models

2.3.1 Preamble

Once all the data has been obtained and compiled, faulty data has been rectified and a baseline has been established, the simulation model is created. Since the model consists of several components, each must represent its real-life counterpart accurately. This section details how the simulation model is to be developed by considering what assumptions are made, what the focus of the model is, and what the parameters for the simulation model are in terms of the simulation time frame and the step sizes. Thereafter, a discussion follows on how all the components must be modelled.

2.3.2 Determine focus

There are several parameters to consider in a thermohydraulic system including, amongst others, pressure, temperature, flow rate, humidity and enthalpy. However, it will be needlessly arduous to consider each of these individually and to obtain measurements for each. Therefore, it is important to identify the most important parameters for the simulation model. In this study, the key parameters are the compressor power, air pressure and compressed air flow rate. A brief discussion on each parameter's importance is given below.

Compressor power

To properly quantify a system's power consumption and the potential savings resulting from energy efficiency solutions, compressors in the simulation must be modelled correctly. Hence, their power consumption must match the actual data.

Pressure

As various end users have different pressure requirements, it is crucial that the pressure in the model represents the actual pressure from the data accurately. Not only must the supply pressure be correct, but the pressure throughout the network and at the end users must also be correct.

Flow

Flow is a critical parameter along with power and pressure, because flow shows how much compressed air flows to various demands. In other words, it shows how compressed air is distributed through the network. All the compressors must supply the correct flow at the correct discharge pressure. Furthermore, compressed air end users must obtain their required flow at the correct pressure.

Since these are the most important parameters in the simulation model, it is vital that their data is as accurate as possible. Table 2-4 shows the typical accuracy of the meters used to measure these parameters. As can be seen, the meters are extremely accurate, with a maximum error band of ±0.15%.

Table 2-4: Error bands of measuring equipment

Parameter	**Typical meter error band**
Flow	±0.1% [77]
Pressure	±0.075% [78]
Power	±0.15% [79]

2.3.3 Determine level of complexity

As discussed in Section 1.4.3, the complexity of simulation models varies greatly. It is therefore important to keep the model's purpose in mind when selecting the level of complexity. To determine the complexity of the simulation, different simulation boundaries are selected. The boundaries must be chosen to allow for accurate simulation. However, this should not be to the extent where the extra time spent building the model and obtaining data do not result in significantly better accuracy and insight.

For example, when a simulation's purpose is to determine the effect that an energy efficiency solution would have on a shaft's pressure, the shaft should be the boundary rather than individual levels, or even individual mining components such as rock drills. Likewise, all the compressors in a compressor house should be modelled individually for accuracy or as a single large compressor for simplicity.

As stated in Section 1.4.3, the complexity of the simulation does not have a large effect on the simulation's accuracy. For this study, the end users will be the mineshafts and not their respective mining levels. The reason for this is threefold: First, it will add greatly to the complexity of the simulation model to model the mining levels of all the shafts individually. Second, if the shafts get an adequate supply of compressed air, it is assumed that the individual mining levels also have an adequate supply of compressed air. Third, data is not available for all underground consumers, but it is available for all mineshafts. The reason for the lack of data availability for underground consumers is due to out-of-date and inaccurate equipment, or a lack of cabling for measuring equipment. Moreover, harsh underground conditions mean that maintenance is challenging. Compressors, however, will be modelled individually to ensure that they are as accurate as possible.

2.3.4 Determine simulation parameters and make assumptions

Simulation parameters

Once the complexity of the simulation model has been established, the time period which the model represents must be determined. As compressed air systems are transient, the simulation model must be also transient. Moreover, the operational schedule, as discussed in Section 1.2.5, must be considered since compressed air consumption varies during different shifts.

Compressed air simulations from past studies used a 24-hour profile because the operational schedule does not change much day by day; therefore, it is needless to simulate longer periods. A properly calibrated model should remain accurate when subsequent or preceding days are used, except if the system changes drastically.

Simulation time frame

As discussed in Section 2.2.5, a baseline of a single day will be used. The simulation will also make use of a day in accordance with past studies.

Step size

PTB requires step sizes to determine how much time there is between subsequent simulation data points. Smaller step sizes result in more accurate, albeit more time-consuming, simulations. Larger step sizes result in faster calculations in the simulation package but do affect the accuracy negatively.

The size of the steps is dictated by the resolution of the data (how large the time intervals are between subsequent data points). This, in turn, is determined by how frequently the data of process parameters is logged on the database. A large minimum step size will not represent the system accurately since small changes in process parameters might be averaged out. Should the minimum step size be too large for the simulation, the data can be interpolated. However, this may decrease the simulation's accuracy.

Along with the 24-hour simulation time frame, previous studies used a step size of 30 minutes. This study will also use 30 minutes as the step size. This is small enough to model process changes accurately, yet large enough to facilitate fast simulation and be feasible to obtain without interpolation. Therefore, the 24-hour period will be divided into 48 steps of 30 minutes each. For increased accuracy, two initial steps will be added at the beginning, which repeat the first hour's data. This will allow the simulation to stabilise earlier, making it more accurate. Therefore, there will be 50 steps in total.

Assumptions

Assumptions must be made to avoid the model being too complex. These assumptions include thermodynamic assumptions, such as heat transfer and assumptions for the temperatures at different stages of the compressors. To simplify the simulation model in this study the following assumptions are made:

- Heat transfer in pipes will be disregarded.
- Compressor efficiency will remain constant, even under changing loads.
- The ambient air conditions (pressure, temperature and relative humidity) will not be dynamic, but will follow standard trends.
- The effect of aftercooling on compressed air properties will be disregarded.
- The compressor discharge temperature is approximately 100 °C.
- The compressor's aftercooler reduces the compressor discharge temperature to approximately 40 °C.

2.3.5 Model components

As discussed in Section 1.4.2, PTB uses several different components to build compressed air simulations. All these components must be modelled individually to ensure that they are representative of their real-life counterparts. This section describes how all the individual components will be modelled, which are subsequently used to create the compressed air simulation models in this study. These components include nodes, pipes, ambient conditions (air pressure boundaries), compressed air demands, compressors, aftercoolers (heat exchangers) and PI controllers [70], [74].

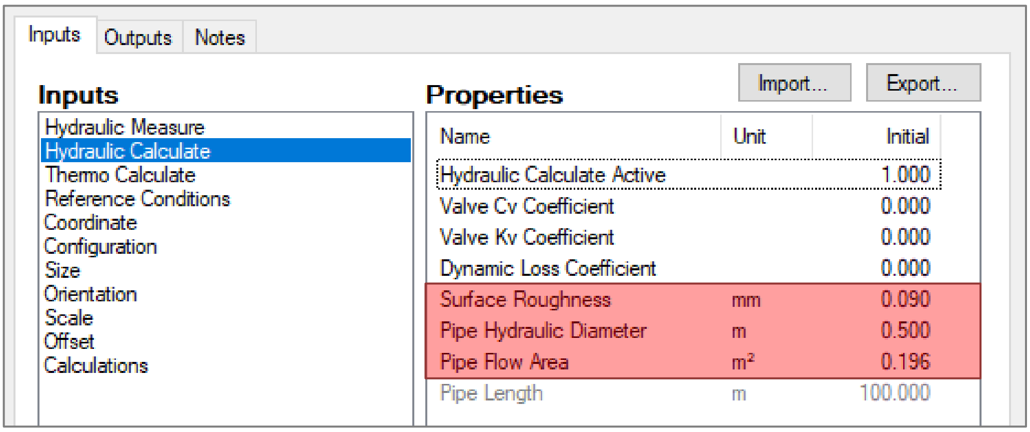
Nodes

In PTB, nodes are the basic building blocks of compressed air networks since they are used to connect subsequent components. For instance, a node is used to connect one pipe to another pipe or a compressor to an aftercooler.

Pipe length and diameters

The system layouts contain all the pipe diameters and pipe lengths required for this study. The pipe lengths and pipe diameters are verified respectively by using satellite views of the mine and manual measurements. Should the pipe diameters on the system layout and the pipe lengths on the satellite views be inconclusive, the manual measurements can be used.

Figure 2-1 shows the required input parameters to model a pipe in PTB. The important parameters are highlighted in red. The hydraulic diameter is the pipe's flow diameter, which is equal to the pipe's diameter for a circular pipe. The flow area is calculated as the area of flow across the hydraulic diameter. The surface roughness dictates how much friction there is in the pipe and, subsequently, the pressure loss in the pipe.



Name	Unit	Initial
Hydraulic Calculate Active		1.000
Valve Cv Coefficient		0.000
Valve Kv Coefficient		0.000
Dynamic Loss Coefficient		0.000
Surface Roughness	mm	0.090
Pipe Hydraulic Diameter	m	0.500
Pipe Flow Area	m²	0.196
Pipe Length	m	100.000

Figure 2-1: PTB pipe interface for inputs

Once the entire model has been constructed, the surface roughness is determined by changing it incrementally until the correct pressure losses are obtained. The other parameters, which are not highlighted in red, are not a necessity to specify for standard piping. Pipe length, which is greyed out, is determined automatically as the distance between nodes (nodes are used to indicate the start and end positions of pipes).

Ambient conditions (air pressure boundaries)

In PTB, air pressure boundaries are used to represent ambient conditions. These components are placed at the beginning and end of the piping network. In other words, an air pressure boundary is placed at a compressor's inlet and at an end user's outlet. Temperature, humidity and atmospheric pressure are required for the ambient conditions to be modelled [70], [74]. As noted earlier, this can be found on the mine's database or a weather database.

Compressed air demand

In PTB, compressed air demand components represent compressed air end users. For each end user, which are mineshafts in this study, a compressed air demand is required. Here, the mineshaft's compressed air flow demand and the pressure demand must be provided. This is the flow the mineshaft must receive and the pressure at which the flow must be provided.

Compressor modelling

Several parameters are required to model a compressor accurately in PTB. The most important parameters are the compressor's characteristic curve and efficiency. Van Helvoirt [81] states that a quadratic curve can be used to represent a compressor's characteristic curve for stable flows. This quadratic curve can therefore be calculated by making use of three operating points. These operating points represent the compressor's pressure ratio and the corrected mass flow. The pressure ratio, which is the ratio between the compressor's discharge pressure and the inlet pressure, is calculated with Equation 2.1.

Equation 2.1: Compressor pressure ratio (adapted from [73])

$$PR = \frac{P_{discharge}}{P_{inlet}}$$

Where

PR	=	Pressure ratio	[–]
$P_{discharge}$	=	Compressor discharge pressure	[kPa]
P_{inlet}	=	Compressor inlet pressure	[kPa]

The corrected mass flow, which is the mass flow for standard reference conditions (where the temperature is 0 °C (273.15 K) and the atmospheric pressure is 101.325 kPa), is calculated by using Equation 2.2.

Equation 2.2: Corrected mass flow (adapted from [80])

$$\dot{m}_c = \frac{\left(Q \times \left(\frac{P}{R \times T_{ref}}\right) \times \sqrt{\frac{T_{total}}{T_{ref}}}\right)}{\left(\frac{P_{discharge}}{P_{inlet}}\right)}$$

Where

$\dot{m}_c$ = Corrected flow kg/s/bar/K]

Q = Volumetric airflow [m³/s]

P = Air pressure [kPa]

R = Universal gas constant [kJ/kg·K]

T_{ref} = Reference temperature [K]

T_{total} = Total temperature [K]

$P_{discharge}$ = Compressor discharge pressure [kPa]

P_{inlet} = Compressor inlet pressure [kPa]

The pressure ratio of three operating points for a compressor and its corrected mass flow must be determined. Hereafter, the formula for a quadratic line that passes through all three points is determined, which is the compressor's characteristic curve. This can be seen in Figure 2-2.

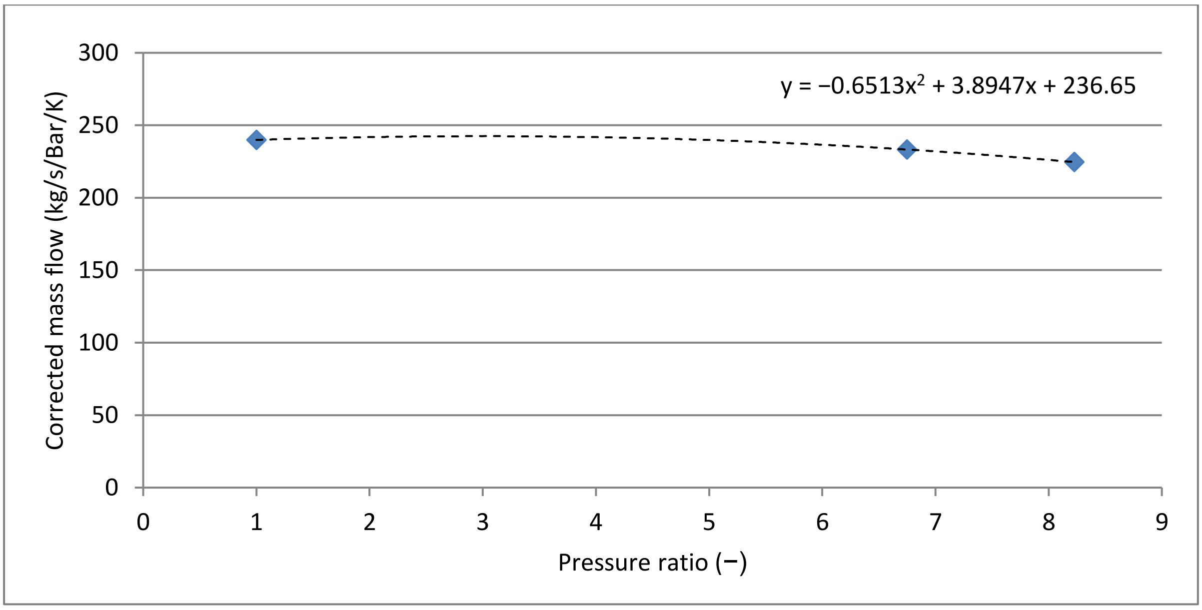
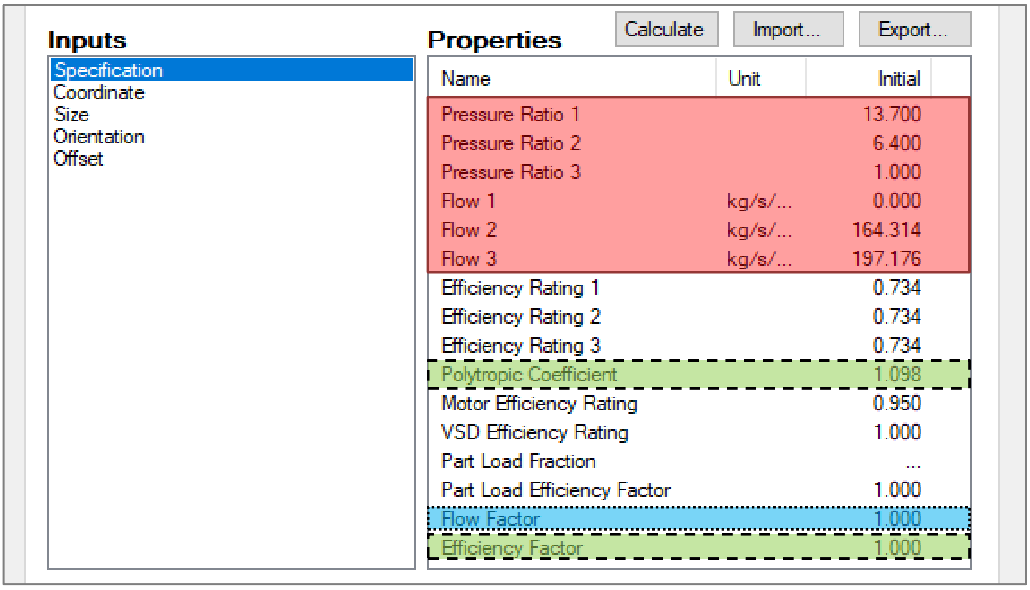


Figure 2-2: Compressor corrected mass flow vs pressure ratio

In Figure 2-2, the corrected mass flow is on the y-axis and the pressure ratio is on the x-axis. The line passing through the three points is the characteristic curve, which allows the corrected mass flow to be calculated when only the pressure ratio is available. Conversely, the pressure ratio can be calculated when only the corrected mass flow is available. If the pressure ratio has been determined and the inlet pressure is known, the discharge pressure can be calculated.

Various types of compressors, for instance VK32 and VK50 compressors, can be used on mines [32]. These compressors have respective installed capacities of 2.9 MW and 5.1 MW [45], [47]. The characteristic curve of each type of compressor must be established, since they have different characteristic curves. After each type of compressor has been characterised, each compressor is calibrated individually to ensure that it delivers the correct flow at the correct discharge pressure. Furthermore, the compressor's power consumption and discharge temperature must be accurate.

Figure 2-3 shows the required input parameters to model a compressor in PTB. The parameters highlighted in red (with the solid outline) are used to determine the characteristic curve of the compressor. After the compressor has been characterised, the polytropic coefficient and efficiency factor (as shown in green with the dashed outline) are changed iteratively until the compressor's power output and discharge air temperature match the actual values. The flow factor (shown in blue with a dotted outline) can be changed to fine-tune the compressor discharge flow.



Name	Unit	Initial
Pressure Ratio 1		13.700
Pressure Ratio 2		6.400
Pressure Ratio 3		1.000
Flow 1	kg/s/...	0.000
Flow 2	kg/s/...	164.314
Flow 3	kg/s/...	197.176
Efficiency Rating 1		0.734
Efficiency Rating 2		0.734
Efficiency Rating 3		0.734
Polytropic Coefficient		1.098
Motor Efficiency Rating		0.950
VSD Efficiency Rating		1.000
Part Load Fraction		...
Part Load Efficiency Factor		1.000
Flow Factor		1.000
Efficiency Factor		1.000

Figure 2-3: PTB compressor interface for inputs

Figure 2-4 shows the expected compressor discharge pressures and the relevant components for calibrating the compressor. Air is drawn from the air intake and is compressed via the compressor. The temperature should be approximately 100 °C at the compressor discharge node. The compressed air flows through an aftercooler, whereafter the temperature should be approximately 40 °C. Once the compressor has been calibrated correctly, it is connected to the pipelines feeding into the network.

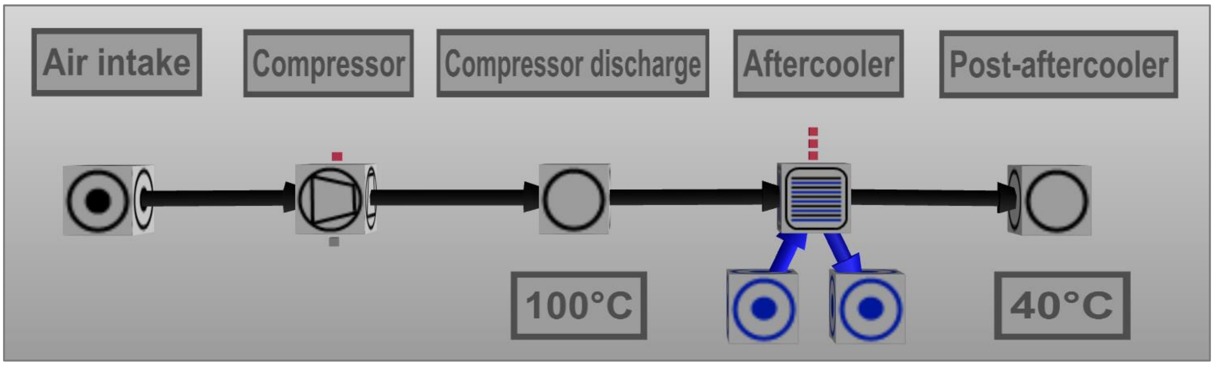
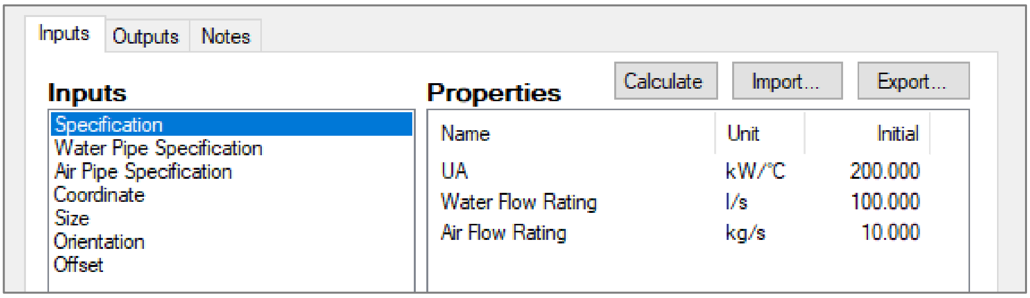


Figure 2-4: PTB compressor configuration

Aftercooler (heat exchanger)

As discussed in Section 1.2.3, aftercoolers are used to reduce the temperature of compressed air to protect equipment from excessive heat and moisture. To model an aftercooler in PTB, a water-air heat-exchanger component is used. Figure 2-5 shows the input interface in PTB.



Inputs

- Specification
- Water Pipe Specification
- Air Pipe Specification
- Coordinate
- Size
- Orientation
- Offset

Properties

Name	Unit	Initial
UA	kW/°C	200.000
Water Flow Rating	l/s	100.000
Air Flow Rating	kg/s	10.000

Figure 2-5: Water-air heat exchanger interface for inputs

For this component, the overall heat transfer coefficient (UA) value must be specified, which determines how effectively the heat is transferred between the water and air. In other words, the higher the UA value is, the more effectively the water cools the compressed air.

The water flow rating and air flow rating must also be specified. The higher the water flow rating is, the more effective the heat transfer is that occurs. This is because more water flows through the system to cool the compressed air with. Contrariwise, the slower the air flow rating is, the more effectively the heat is transferred since the air is allowed more time to transfer its excessive heat to the water.

The aftercooler is connected to water pressure boundaries in PTB, which represent the atmospheric conditions of the water. The temperature of compressed air leaving the heat exchanger must be 40 °C; therefore, the atmospheric temperature of the water is determined by changing the water temperature iteratively until the air temperature after the heat exchanger is 40 °C. The temperature of the water, however, must be below the desired compressed air temperature of 40 °C.

PI controllers

In PTB, PI controllers are used to start and stop compressors. To do so, the compressors' running statuses are required to ensure that they are running during the correct times. PI controllers are further used to simulate guide-vanes by controlling the discharge pressure of compressors to a certain operating value. Lastly, PI controllers can simulate control valves by ensuring that a certain downstream pressure is obtained by controlling a pipe's opening.

2.4 Verify models

2.4.1 Preamble

The previous section detailed how components must be modelled. Once the compressed air network has been constructed and the components have been modelled, the model must be calibrated. To ensure that the simulation model is accurate, the simulation results must be compared with actual data and the difference between the two must be minimised. The actual data is in the form of the baselines as discussed in Section 2.2.5. This section discusses how the simulation results will be compared with the actual data. Thereafter, a discussion on how the model must be calibrated follows.

2.4.2 Determine data accuracy

There are several methods for comparing two sets of data [82]. The two methods which will be used in this study to determine the accuracy of the simulation model are the mean absolute error (MAE) method and the coefficient of determination.

Mean absolute error

The MAE method calculates the error of each data point throughout the series, where the simulated value is subtracted from the actual value. This is done for each data point whereafter all data are summated. This is shown in Equation 2.3.

Equation 2.3: MAE

$$MAE = \frac{1}{N} \times \sum_{n=1}^{N} |A_n - S_n|$$

Where

MAE	=	Mean absolute error	[–]
N	=	Total number of data points	[–]
n	=	Data point	[–]
A	=	Actual data points	[–]
S	=	Simulated data points	[–]

The subsequent percentage error is calculated as the MAE divided by the actual value of the data point, as shown in Equation 2.4.

Equation 2.4: Percentage error for MAE

$$Error\% = \frac{1}{N} \times \sum_{n=1}^{N} \left| \frac{A_n - S_n}{A_n} \right| \times 100$$

Where

N	=	Total number of data points	[–]
n	=	Data point	[–]
A	=	Actual data points	[–]
S	=	Simulated data points	[–]
$Error\%$	=	Absolute percentage error	[%]

To determine the error, the MAE method is used rather than the mean residual difference (MRD) method which is discussed in Appendix A. The reason being that in the MRD method, positive and negative percentage errors cancel one another out. For instance, a percentage error of −5% for one data point and a percentage error of +5% for another data point will result in a total average percentage error of 0%.

Once the percentage error of the data sets has been determined, the correlation between the two data sets is determined by using the coefficient of determination as discussed next.

Coefficient of determination

To measure the extent to which a linear relationship exists between two data sets, a coefficient of determination is used. A data set (x) is compared with another data set (y). The linear relationship between the two sets is represented as the formula for a linear model $(y = mx + c)$, where c is a constant offset and y is the gradient of the relationship.

The coefficient of determination has a minimum value of −1, which indicates a relationship that is perfectly negative linear. Conversely, the maximum value is +1, which indicates a perfect linear relationship. The closer the value is to 0, the worse the correlation is between the two data sets. The coefficient of determination is calculated with Equation 2.5.

Equation 2.5: Coefficient of determination

$$r^2 = \left[\frac{\sum_{n=1}^{N}(A_n - \bar{A})(S_n - \bar{S})}{\sqrt{\sum_{n=1}^{N}(A_n - \bar{A})^2 \times \sum_{n=1}^{N}(S_n - \bar{S})^2}}\right]^2$$

Where

r^2 = Coefficient of determination [–]

N = Total number of data points [–]

n = Data point [–]

A = Actual data points [–]

S = Simulated data points [–]

In this study, the coefficient of determination is used to determine the linear relationship between the actual data and the simulated data to ensure that the profiles match and to identify specific points where there are outliers. For instance, Figure 2-6 shows a data set with the actual values on the x-axis and the simulated values on the y-axis. The equation of the linear trendline and the value of the coefficient of correlation are also given. There are two prominent outliers, which are encircled in red. These outliers exist because the simulation is not properly calibrated at the times the data points represent. The cause of this is that a compressor was active in the simulation for longer than it was in real life. This resulted in the simulated pressures being larger than they should be. These outliers detract from the coefficient of determination, which is 0.701.

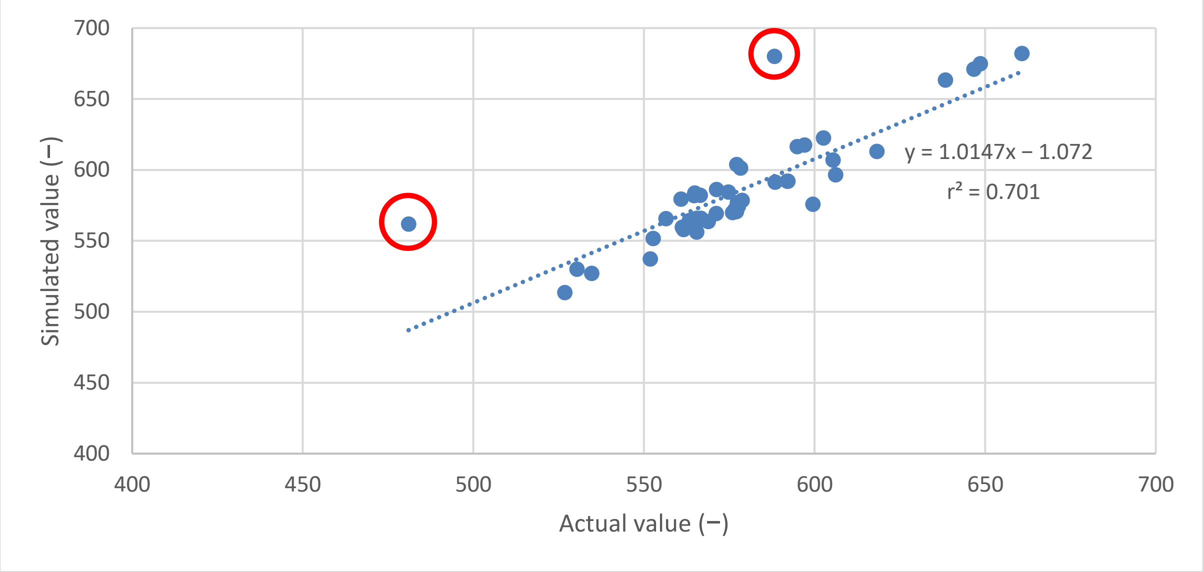


Figure 2-6: Original coefficient of determination

Figure 2-7 is obtained by investigating the two encircled data points in the simulation model and further calibrating the model. This is done by switching off the compressor that was running erroneously in the simulation model and ensures that the simulated values also correlate with the actual values for these data points. The changes increase the coefficient of determination to 0.9, which means a better correlation between the simulated values and actual values.

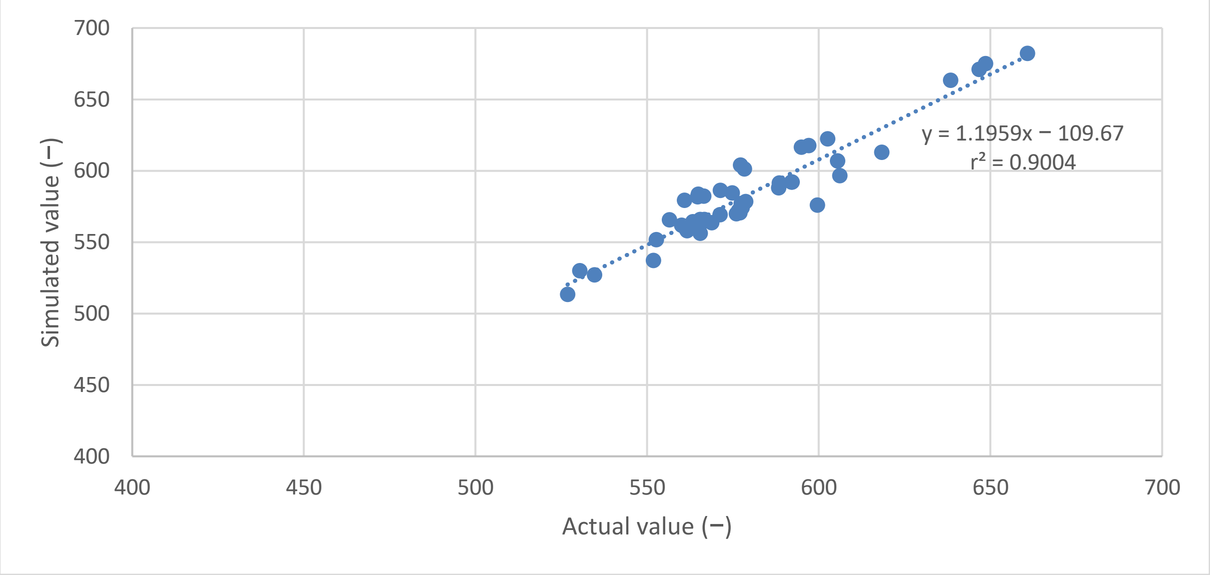


Figure 2-7: Rectified coefficient of determination

The coefficient of determination for the pressure of compressors is disregarded in this study for two reasons: Firstly, the simulated compressor pressure is taken as the pressure of the node after the compressor in the simulation model. If the compressor is not operational, this takes on the pressure of the compressed air network. Conversely, the actual pressure is measured in the compressor, which is zero if the compressor is switched off. Subsequently, the coefficient of determination is affected negatively, because when the compressor is switched off, the non-zero values from the simulation are compared with the actual measured values which are equal to zero.

Secondly, the system pressures during the blasting shift can be unstable as a result of the compressors switching off and the valves closing. This will affect the coefficient of determination adversely. Therefore, only the percentage error is used to calibrate the shaft and compressor pressures, and not the coefficient of determination. The coefficient of determination, however, is used to calibrate the remaining two key parameters, namely all compressed air flows and compressor powers.

In the case where a compressor does not have a distinct profile and remains operational throughout the entire day, only the percentage error is used. This is because there is no zero value to serve as the absolute minimum value, which means that even the slightest difference in profile between the simulated and the actual value detracts from the coefficient of determination.

2.4.3 Calibrate models

The section above discussed the methods for comparing simulated values with the actual data. These methods are used to calibrate the model. In other words, they are used to verify the model by ensuring that the simulated values are within an acceptable range of the actual values.

As discussed in Section 2.3.2, the key parameters in this study are pressure, flow and power. Equation 2.6 shows the error percentage and coefficient of determination requirements that are used in this study.

Equation 2.6: Calibration requirements for parameters

$$Error\% < 5\%$$
$$r^2 \quad > 0.9$$

Where

$Error\%$ = Absolute percentage of error [%]

r^2 = Coefficient of determination [–]

To calibrate the models, the following steps must be taken for each component and for the entirety of the simulation period:

1. Populate simulation with known input and output conditions.
2. Estimate an initial value for a parameter that must be determined.
3. Run the simulation.
4. Determine the error of the simulated parameter compared with the actual value.
5. Update parameter value.
6. Repeat Step 3 through Step 5 until the error percentage is within the acceptable limit.
7. Identify and rectify outliers in simulated data until the coefficient of determination is above the predetermined limit.

Once the steps have been completed for all components and parameters, the simulation is considered calibrated. This means that the models are considered accurate and can be used to simulate compressed air systems. The next section considers how the simulation model will be used and how the implementation order of energy efficiency solutions will be prioritised.

2.5 Determine implementation priority

2.5.1 Preamble

As discussed in the problem statement in Section 1.5.1, uncertainty may exist about which energy efficiency solution must be implemented first. Therefore, it is imperative that an investigation must be conducted regarding the most feasible order of implementation before energy efficiency solutions are implemented.

This section considers how the simulations are used to determine the potential savings of energy efficiency solutions. Furthermore, a methodology is created for determining the feasibility of implementing potential energy efficiency solutions. Thereafter, the energy efficiency solutions are ranked and implemented according to the priority.

2.5.2 Calculate potential savings

Once the simulation model has been calibrated, it is representative of the actual system and can, therefore, be used to quantify the potential saving of energy efficiency solutions. The simulation outputs are compared with the baseline to determine the potential demand reduction of an energy efficiency solution at any point of the day. This is shown in Equation 2.7 where the demand reduction is the difference between the simulated baseline demand and the simulated scenario demand.

Equation 2.7: Demand reduction of energy efficiency solution

$$\mathbb{P}_{reduction} = \mathbb{P}_{baseline} - \mathbb{P}_{scenario}$$

Where

$\mathbb{P}_{reduction}$	=	Demand reduction	[kW]
$\mathbb{P}_{baseline}$	=	Simulated baseline demand	[kW]
$\mathbb{P}_{simulated}$	=	Simulated scenario demand	[kW]

Once the demand reduction for each time step has been obtained, the daily cost savings due to the energy efficiency solution can be determined. However, it is important to note that the Eskom TOU tariffs not only vary throughout the day, but also between different the Eskom seasons, namely the high-demand (June–August) and low-demand (September–May) season. Figure 2-8 gives a breakdown of the costs for the high-demand and low-demand seasons. As shown, the costs for the high-demand season are greater than the corresponding costs for the low-demand season, especially the tariffs during peak times.

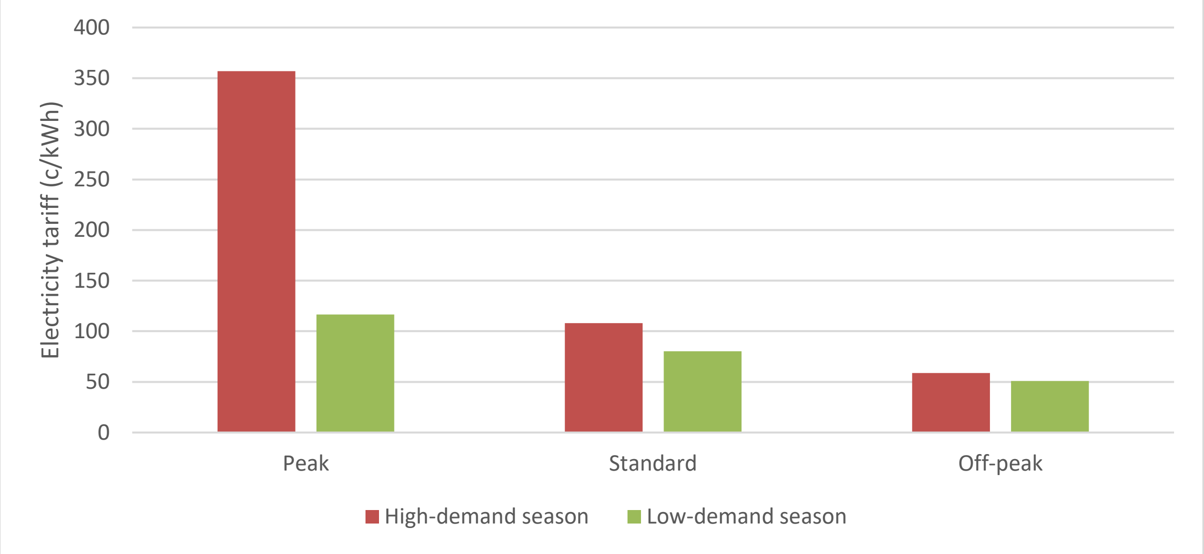


Figure 2-8: Electricity cost breakdown

Figure 2-9 shows how these tariffs are distributed throughout the day for the low-demand and high-demand season. The green areas indicate off-peak tariffs, the yellow areas indicate standard tariffs, and the red areas indicate peak tariffs. The peak tariffs start an hour earlier during the high-demand seasons than during the low-demand seasons.

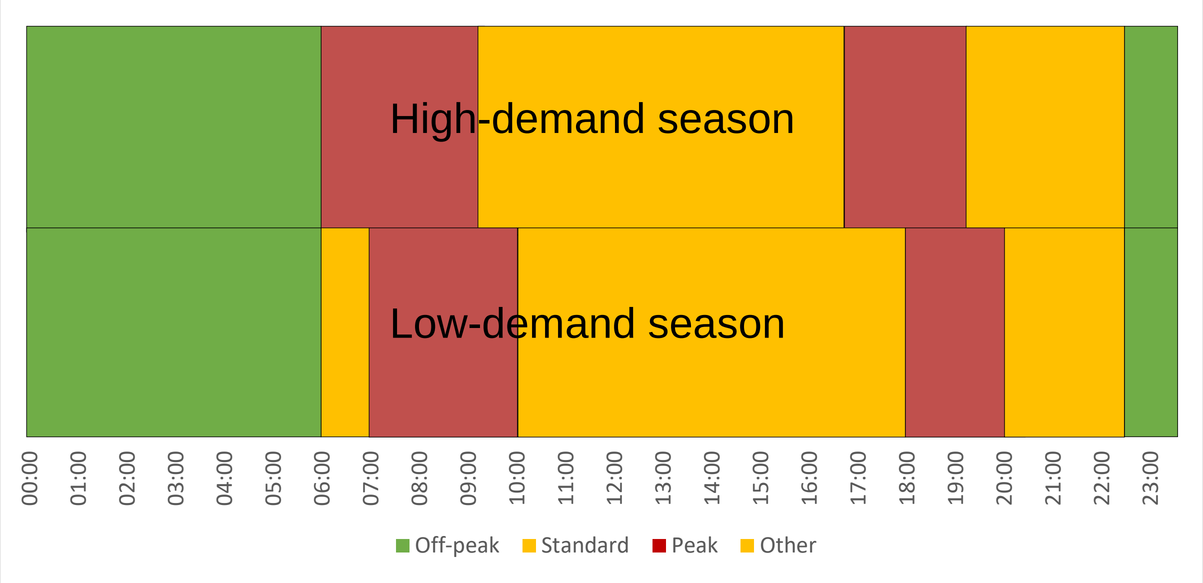


Figure 2-9: Eskom seasonal weekday tariff types

Furthermore, there are additional administration costs on these tariffs that must be added to the aforementioned tariffs, as given in Table 2-5. The ancillary service charge is the charge to cover the cost of the ancillary services that Eskom provides. The electrification and rural network subsidy charge entails the contribution towards socio-economic network subsidies. The affordability subsidy charge entails the contribution towards socio-economic electricity supply subsidies [17].

Table 2-5: Additional costs

Administration cost	**Cost (c/kWh)**
Ancillary service charge	0.47
Electrification and rural network subsidy charge	9.22
Affordability subsidy charge	4.34
Total	14.03

Due to the different tariffs for the different seasons, daily savings must be calculated for both low-demand and high-demand seasons. Daily savings are calculated by multiplying the demand reduction during an interval with the duration of the interval and the applicable Eskom tariff. Thereafter, the values for all the intervals are summated. This is shown in Equation 2.8.

Equation 2.8: Daily energy savings

$$Saving = \sum_{n=1}^{N} P_{reduction_n} \times t_{interval} \times (tariff_i + admin) \times 100$$

Where

$Saving$ = Daily energy saving [R]

$P_{reduction}$ = Demand reduction during an interval [kW]

$t_{interval}$ = Duration of interval [h]

$tariff_i$ = Applicable Eskom TOU tariff for interval [c/kWh]

$admin$ = Additional cost [c/kWh]

N = Total number of data points [–]

n = Data point [–]

As mentioned above, the daily savings must be calculated for both the winter and the summer months. Subsequently, the annual savings are determined by multiplying the number of days in each season with the daily savings for both seasons, and adding the values for both seasons together, as shown in Equation 2.9.

Equation 2.9: Annual savings

$$Saving_{annual} = Saving_{low} \times Days_{low} + Saving_{high} \times Days_{high}$$

Where

$Saving_{annual}$ = Total annual saving of measure [R]

$Saving_{low}$ = Daily savings for low-demand season [R]

$Days_{low}$ = Number of days in low-demand season [–]

$Saving_{high}$ = Daily savings for high-demand season [R]

$Days_{high}$ = Number of days in high-demand season [–]

2.5.3 Determine payback period

The payback period (PBP) is used to determine how long an energy efficiency solution takes after becoming operational to provide enough savings to cover its cost. The PBP is the number of months that the accumulated savings from the energy efficiency solution will be able to account for its total cost. The PBP of an energy efficiency solution is determined by Equation 2.10.

Equation 2.10: PBP of energy efficiency solution

$$PBP = \frac{Saving_{annual}}{Cost} \times 12$$

Where

PBP	=	Payback period of measure	[months]
$Saving_{annual}$	=	Total annual saving of measure	[R]
$Cost$	=	Implementation cost of measure	[R]

For the purpose of this study, the effect of electricity cost inflation on the PBP of energy efficiency solutions is disregarded because the inflation of electricity cost is unpredictable. This is substantiated by Figure 1-2 (Section 1.1.2), which shows that significant but non-linear inflation of electricity cost took place between 2010 and 2019.

2.5.4 Determine implementation time

Implementation time is another important factor when considering energy efficiency solutions. If only the PBP is considered, some energy efficiency solutions may appear to be extremely beneficial. However, it is not always possible to implement them immediately due to factors such as a lengthy procurement process, equipment lead time, installation time and optimisation time (the time it takes to ensure that the energy efficiency solution is providing its maximum impact).

For instance, commissioning new control valves to restrict compressed air flow during non-drilling periods may result in substantial cost savings and a short PBP. However, due to the large cost of the valves, strict and time-consuming procurement processes could be in place. Furthermore, the lead times on the valves mean that they could only be delivered after several months due to a long manufacturing process (which often happens overseas). Lastly, it may be time-consuming to install the valves and to optimise the philosophy that is used to control the valves.

Therefore, the implementation time is used to determine how long energy efficiency solutions will take to be implemented. Equation 2.11 shows how the implementation time is calculated by considering the procurement time, equipment lead time, installation time and optimisation time.

Equation 2.11: Implementation time of the energy efficiency solution

$$t_{implement} = t_{procurement} + t_{lead} + t_{installation} + t_{optimisation}$$

Where

$t_{implement}$	=	Time to implement energy efficiency measure	[months]
$t_{procurement}$	=	Time for procurement process to obtain approval	[months]
t_{lead}	=	Lead time for required equipment	[months]
$t_{installation}$	=	Time to install required equipment	[months]
$t_{optimisation}$	=	Time to optimise energy efficiency measure	[months]

2.5.5 Determine level of automation

Some energy efficiency solutions, such as using compressor pressure set points or valve control, are not completely automated and rely on human intervention. This may detract from an energy efficiency solution’s feasibility, since savings may be mitigated due to human error or hesitance to implement the energy efficiency solution. Therefore, the level of an energy efficiency solution’s automation must also be considered. The level of automation ranges from none, where constant human intervention is required, to maximum, where no human intervention is required.

The next section details how the implementation methodology must be determined.

2.5.6 Determine implementation priority

Once the annual savings, PBP, implementation time and the level of automation of the energy efficiency solutions have been determined, their implementation order is prioritised. To take all the aforementioned factors (henceforth referred to as ‘implementation factors’) into account and rank the energy efficiency solutions, each factor is assigned a specific weight.

Appendix B-1 and Appendix B-2 elaborate on how the weights are determined. A Likert scale, as shown in Table 2-6, is used to assign scores [83], [84]. The table also lists the weight of each factor. A score is assigned to each factor as a value between 1 and 5, with 1 being the worst score and 5 being the best score. Appendix B-3 discusses how the ranges used in the scoring are determined.

Table 2-6: Likert scale for determining implementation score

Implementation Factor	**Weight**	**Score**				
		1	**2**	**3**	**4**	**5**
Annual savings	42%	< R1.8 M	R1.8 M to R3.8 M	R3.8 M to R6.3 M	R6.3 M to R9.8 M	> R9.8 M
PBP (months)	37%	> 24	18–24	12–18	6–12	0–6
Level of automation	8%	None	Minimal	Moderate	Significant	Maximum
Implementation time (weeks)	13%	> 11.5	8.5-11.5	5.5-8.5	2.5-5.5	0-2.5

To determine the implementation score of an energy efficiency solution, the aforementioned ranges must be used to establish the score for each factor. Thereafter, the scores are multiplied by the respective factor weights. This is shown in Equation 2.12.

Equation 2.12: Implementation score

$$S_{implement} = S_{saving} \times 0.42 + S_{PBP} \times 0.37 + S_{automation} \times 0.08 + S_{time} \times 0.13$$

Where

$S_{implement}$ = Score of energy efficiency measure [Score out of 5]

S_{saving} = Score for energy efficiency measure [Score out of 5]

S_{PBP} = Score for PBP [Score out of 5]

$S_{automation}$ = Score for adjusted PBP [Score out of 5]

S_{time} = Score for implementation time [Score out of 5]

For instance, if an energy efficiency solution has annual savings of between R6.3 million and R9.8 million, a PBP of less than six months, no automation, and an implementation time between 5.5 and 8.5 weeks, it will achieve respective scores of 4, 5, 1 and 3. These scores have respective weights of 42%, 37%, 8% and 13%. Multiplying each score with its weight and then summating the answers give the energy efficiency solution an implementation score of 4 out of 5.

If an energy efficiency solution does not result in an improvement to the compressed air system's efficiency or affects the system's performance negatively during the drilling shift, it is assigned an implementation score of 0. This means that the energy efficiency solution is not feasible and it will not be implemented.

2.5.7 Implementation according to priority

Once the implementation scores of all energy efficiency solutions have been determined, the solutions are ranked from highest to lowest. The energy efficiency solution with the highest score will be implemented first. Thereafter, the other energy efficiency solutions will be implemented according to their rank.

2.6 Summary

This chapter developed a four-step methodology using simulation to prioritise the implementation of energy efficiency solutions. The first step entailed analysing the system, where a thorough understanding of the system's requirements must be attained. Data must be obtained and any faulty data must be rectified. Finally, a baseline must be established that represents the typical operation on the mine. This baseline is compared with the simulation model.

The second step was the creation of the simulation model, where the focus and complexity of the simulation model have to be decided. Furthermore, the simulation parameters, such as the simulation time frame and step sizes, must be chosen. Hereafter, assumptions are made, whereafter the individual components are modelled.

The third step of the methodology was the verification of the models. This step entailed the data accuracy to be determined by means of the MAE method and the coefficient of determination. Hereafter, the models are calibrated.

The final step entailed determining the implementation priority of energy efficiency solutions. Four implementation factors were considered. First, potential savings are calculated, which are subsequently used to determine the PBP of an energy efficiency solution. The level of automation and implementation time of an energy efficiency solution are also determined. All these four factors are considered to calculate an overall implementation score. A Likert scale is used with specific scores for specific ranges for each factor. Each factor further carries a specific weight. By summating the product of each factor's weight with its score, an energy efficiency solution's implementation score can be determined.

When the implementation scores of multiple energy efficiency solutions have been determined, the energy efficiency solutions are ranked according to their score, and their implementation is prioritised according to the order.

CHAPTER 3 – RESULTS FROM CASE STUDIES

3.1 Introduction

In Chapter 2, a methodology was developed to prioritise the implementation order of platinum mine compressed energy efficiency solutions. To test this methodology, it was implemented on two compressed air systems of a South African platinum mining group. As discussed in Chapter 1, platinum mine compressed air systems are often inefficient and large consumers of electricity, which result in ample opportunity for improving their energy efficiency.

Two systems with different sizes were selected to ensure that the methodology can be used on various systems, irrespective of their size. This section discusses the results of both case studies. Four energy efficiency solutions were investigated in each case study. The energy efficiency solutions were guide-vane control and schedule optimisation, the use of smaller compressors, network reconfiguration and, finally, the use of control valves. Leak repair was not considered as an energy efficiency solution because it is time-consuming and it must be done perpetually. Rather, the energy efficiency solutions focused on reducing the pressure during off-peak mining periods and, subsequently, reducing compressed air wastage through leaks.

First, the case study results for a large compressed air ring (System A) are presented. This is followed by the case study results for a small compressed air ring (System B). In each case study, the system's simulation model was developed and verified, whereafter it was used to determine the effect of the four energy efficiency solutions noted above. Subsequently, the implementation score for each energy efficiency solution was determined and ranked according to their implementation score. The compounding effect of the energy efficiency solutions is investigated. Hereafter, the results of the potential savings for the energy efficiency solutions were extrapolated to the entire South African platinum industry to predict the benefit that the methodology could have when applied to the industry as a whole.

Finally, a critical discussion and validation of the results are given.

3.2 System A: Large compressed air ring

3.2.1 System overview

System A is the older of the two compressed air rings of a mining group. By the end of 2018, four shafts were closed and several other shafts were approaching the end of their lifespans.

System A's compressed air network spanned 38 km and connected 19 compressors (in seven compressor houses) to seven shafts and one processing plant. Figure 3-1 shows the compressor houses, shafts and processing plant. The average temperature and relative humidity profiles of this system are given in Figure C-1 in Appendix C-1. A detailed system layout and a SCADA view of System A's compressed air ring are respectively given in Figure C-2 and Figure C-3 of Appendix C-2.

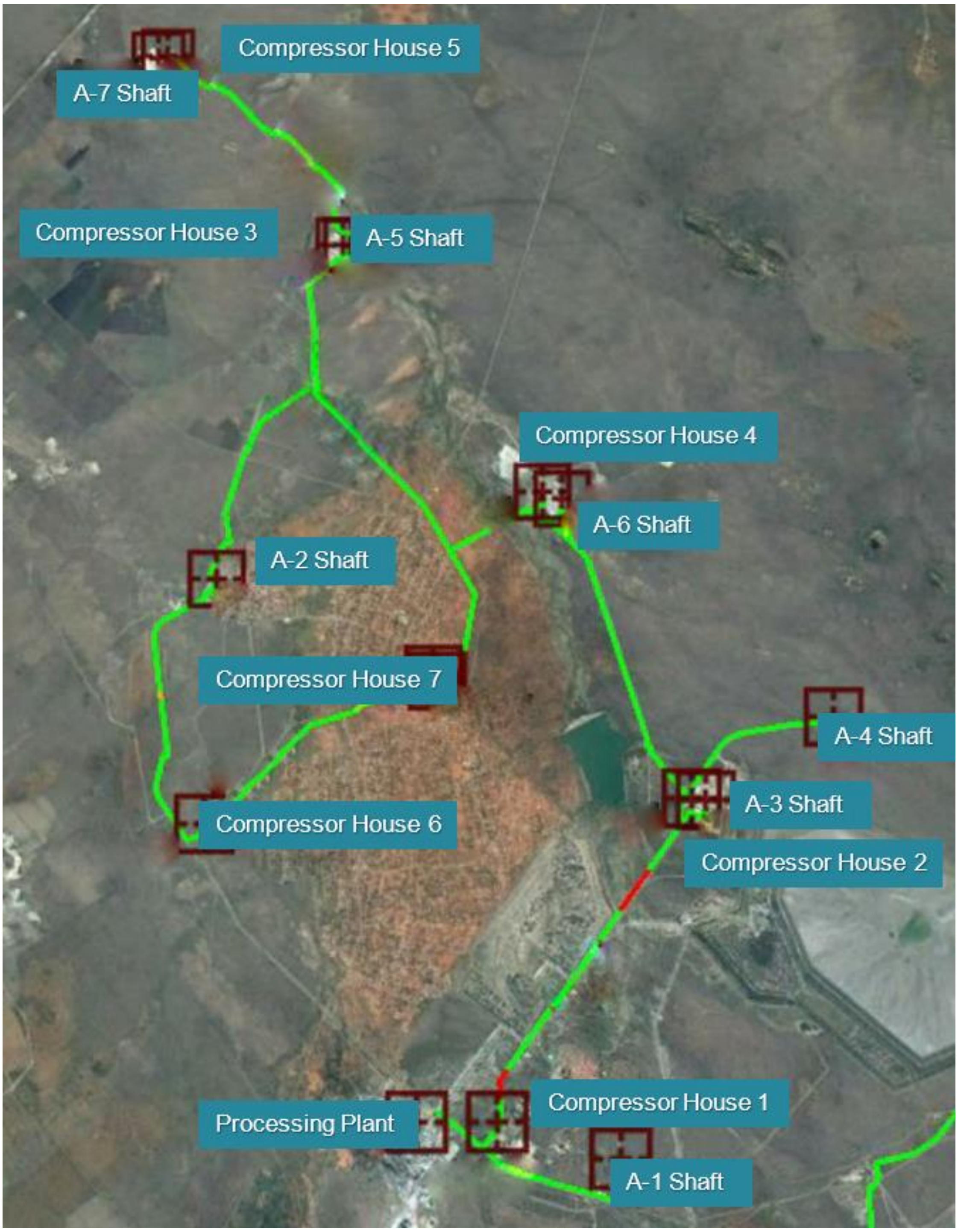


Figure 3-1: System A – satellite view

The 19 compressors comprised 15 VK32 compressors and four VK50 compressors with individual installed capacities of 2.9 MW and 5.1 MW, respectively. The total installed capacity of all the compressors was 63.1 MW. Although all these compressors had guide-vanes installed, they were not used. Barring the 19 compressors, no smaller compressors were available on System A.

Three of the shafts, namely A-2 Shaft, A-4 Shaft and A-6 Shaft, had control valves available. However, A-2 Shaft and A-6 Shaft only used the valves to control the compressed air to a very limited extent, whilst A-4 Shaft did not implement any control whatsoever. The reason for the lack of control for A-4 Shaft's valve is that it generated a great deal of noise when it was used to control the flow of compressed air. Control on the valve was aborted since the valve was located in an area frequented by mining personnel who would be exposed to the noise.

The lack of guide-vane control and valve control resulted in System A's compressed air ring being inefficient, especially during off-peak mining times where excessive compressed air was consumed needlessly.

Figure 3-2 gives a typical power profile of all the compressors. During the drilling shift (08:00 to 13:00), the profile reached its peak as more compressors were switched on. During the blasting shift (18:00 to 21:00), the minimum number of compressors were running, as evident in the dip in the profile. Normally during this time, three VK32 compressors and one VK50 compressor were operational.

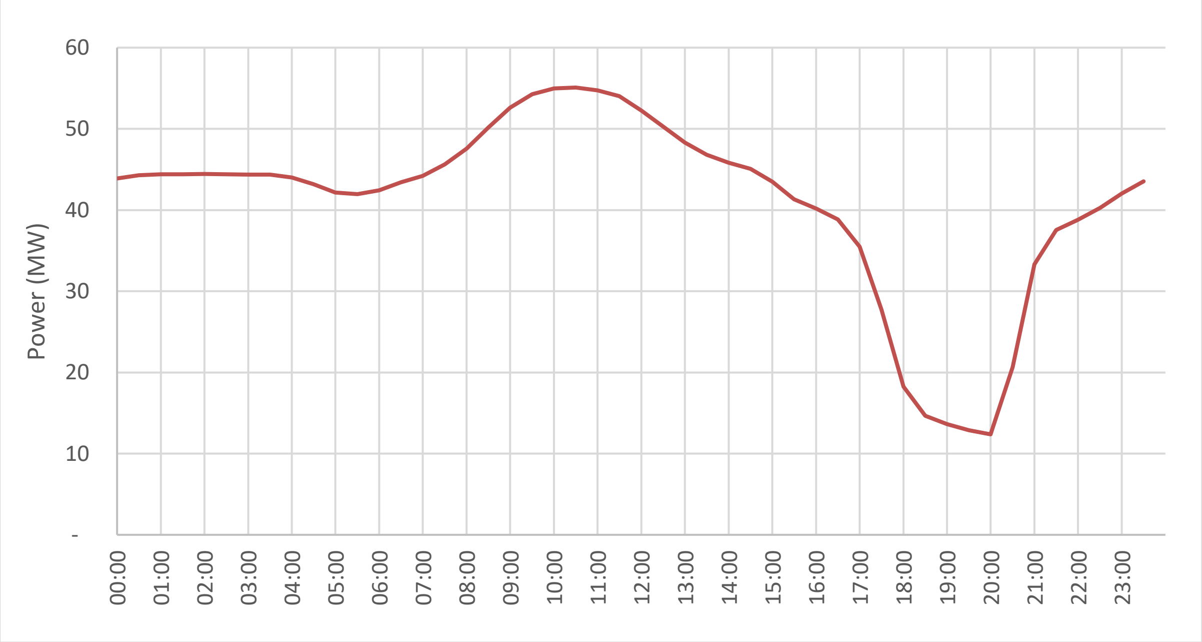


Figure 3-2: System A – power profile

As mentioned earlier, System A had a processing plant that required a constant, high-pressure supply of compressed air. This processing plant was supplied with a VK50 compressor from Compressor House 1 and excess air was fed back into the compressed air ring. This necessitated the use of said compressor for the entire day. During the blasting shift, four compressors (the aforementioned VK50 compressor included) were typically used to ensure that the ring remained pressurised and that the processing plant and essential users (such as refuge chambers) were supplied.

To investigate the effect energy efficiency solutions would have on the system's compressed air efficiency, a simulation model was developed as per the methodology discussed in Chapter 2. This section starts with a discussion on how the model was developed and verified. This is followed by a description of the use of the simulation model and the methodology from Chapter 2.5 to calculate each energy efficiency solution's implementation score. Subsequently, the energy efficiency solutions are ranked and implemented according to their priority.

3.2.2 Development and verification of simulation model

Development of model

The methodology developed in Chapter 2 was used to develop the simulation model. Prior to the creation of the simulation model, the system was investigated to ensure that it was understood properly. Data was obtained and it was ensured that the data was compatible with the simulation model. As discussed in Section 2.2.2, the step size used in this study, and consequently on both System A and System B, was 30 minutes. The 30-minute step allowed for accurate simulations that were not needlessly time-consuming. Furthermore, the assumptions discussed in Section 2.3.4 were used. In this simulation model, the boundary conditions were that of the processing plant and mineshafts. An overall and a detailed view of the simulation model is shown in Figure D-1 and Figure D-2 in Appendix D-1 respectively.

Verification of model

To ensure that the developed simulation model was accurate, it was calibrated as per Section 2.4.3. The coefficient of determination for all flow and power values (with distinct profiles) had to be greater than or equal to 0.9. The percentage error for the pressure, flow and power for all components and parameters had to be 5% or less.

Figure 3-3 compares the total flow for System A with the total flow of the simulation model. The actual value is given in blue and the simulated baseline value is given in orange. The grey area on the secondary y-axis gives the instantaneous percentage error. The close correlation between the simulated values and actual values can be seen. The overall percentage error was 2.6% and the coefficient of determination was 0.99.

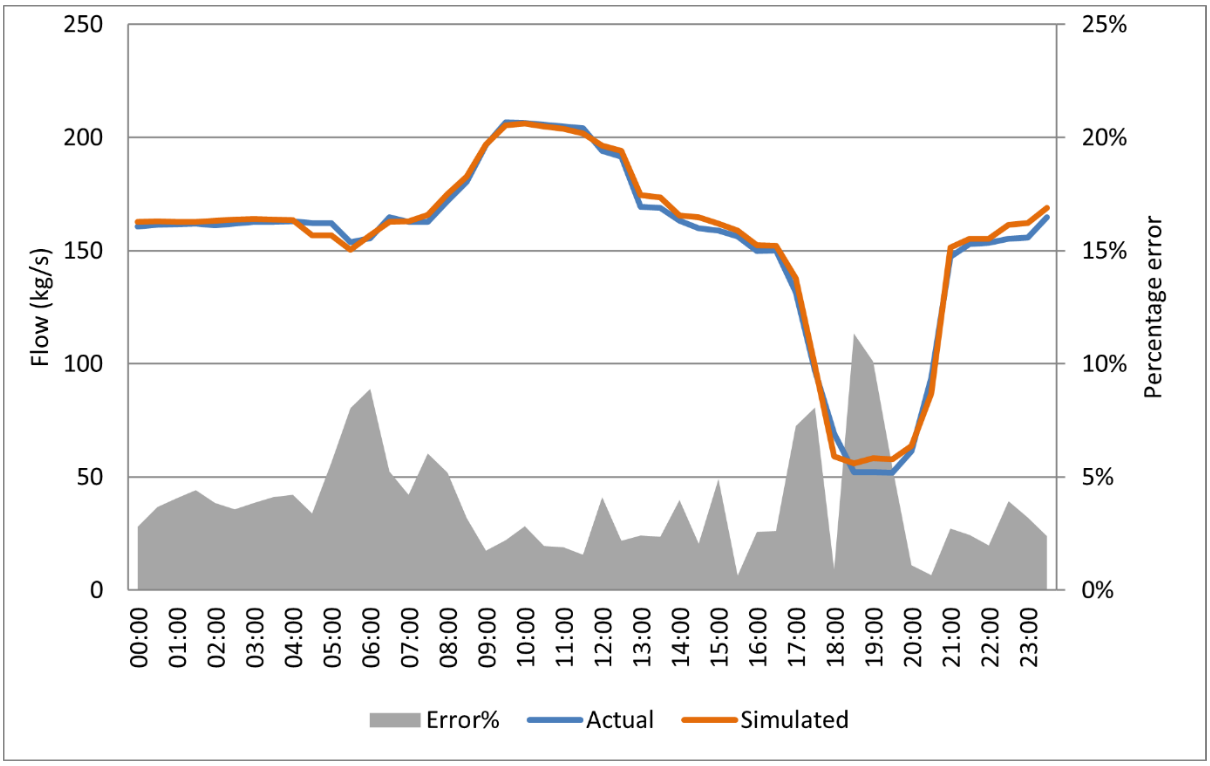


Figure 3-3: System A – total flow: actual vs simulated

Figure 3-4 compares the total power for System A with that of the simulation model. As with the figure above, Figure 3-4 gives the actual value in blue and the simulated baseline value in orange. The grey area on the secondary y-axis gives the percentage error. The overall percentage error was 2.3% and the coefficient of determination was 0.99.

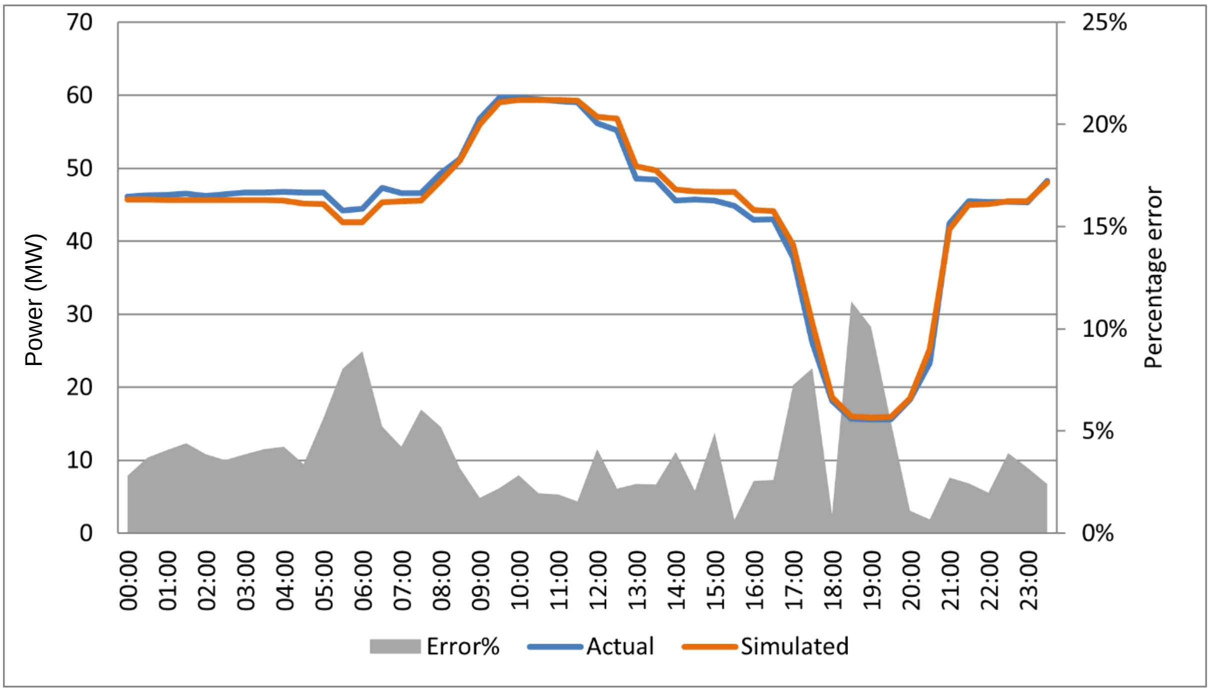


Figure 3-4: System A – total power: actual vs simulated

Figure 3-5 compares the actual average pressure of System A with that of the simulated average pressure. The actual value is given in blue and the simulated baseline value is given in orange. The grey area on the secondary y-axis gives the instantaneous percentage error. The overall percentage error was 2.0% and the coefficient of determination was disregarded as there was no distinct pressure profile.

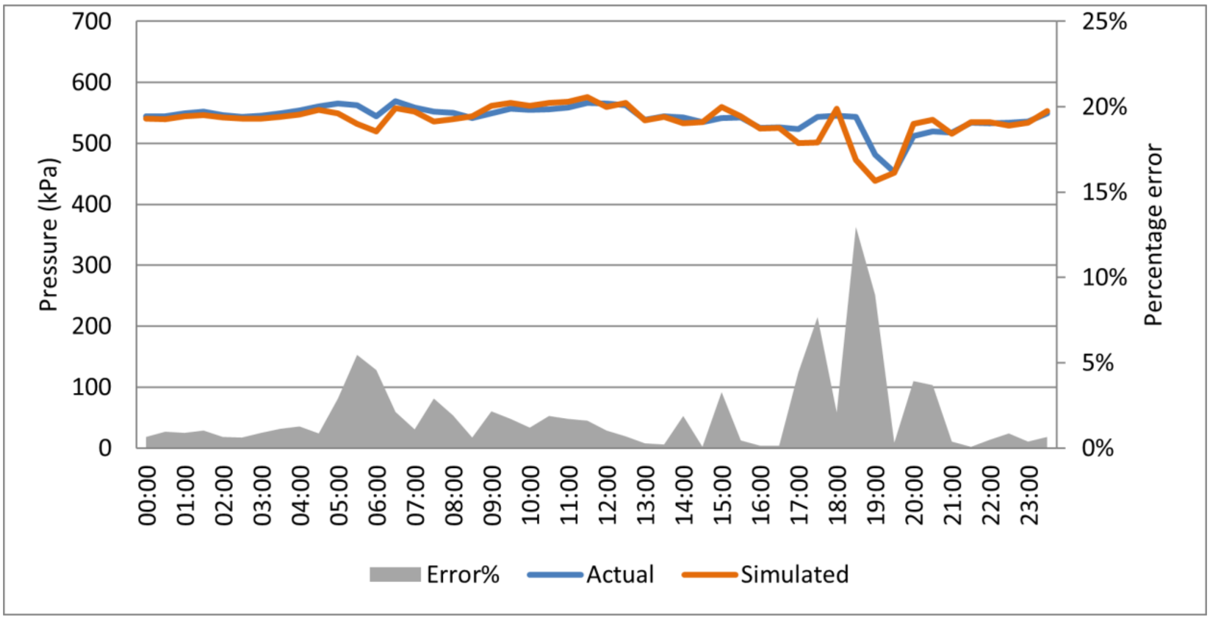


Figure 3-5: System A – average system pressure: actual vs simulated

The total flow, total power and average system pressure are summarised in Table 3-1. The percentage errors for the total flow, total power and average pressure were 2.6%, 1.9.% and 2.1%, respectively. The coefficients of determination for the total flow and the total power were both 0.99. The coefficient of determination was disregarded for the average pressure since there was no distinct profile (as discussed in in Section 2.4.2).

Table 3-1: System A – simulation model verification

Parameter	$\boldsymbol{Error}\%$	$\boldsymbol{r^2}$
Total flow (kg/s)	2.6%	0.99
Total power (MW)	2.3%	0.99
Average pressure (kPa)	2.0%	N/A

As discussed in Section 2.4, each component's power, pressure and flow percentage error had to be equal to or less than 5%. The coefficient of determination for each component's power and flow had to be 0.9 or higher. This holds true for all the components, as given in Appendix E-1. Consequently, the accuracy of System A's simulation model was adequate and the simulation model was verified. Therefore, the simulation could be used to investigate various scenarios in the process of determining the implementation scores.

3.2.3 Implementation scores

In the previous section, the simulation model was developed and calibrated. This section describes how the simulation model was used to investigate the effect of the four energy efficiency solutions. The results from the simulation and the methodology from Section 2.5 were used to prioritise the implementation order of the energy efficiency solutions. The energy efficiency solutions were as follows:

- Guide-vane control and schedule optimisation.
- Smaller compressors.
- Network reconfiguration.
- Valve control.

The sections below describe how each energy efficiency solution's annual savings, PBP, level of automation and implementation time were determined. Thereafter, it is discussed how each energy efficiency solution's implementation score was calculated.

Energy efficiency solution 1: Guide-vane control and schedule optimisation

As noted earlier, pressures during the off-peak mining times on System A were needlessly high. This ensued due to the use of unnecessary compressors during these times, coupled with the lack of guide-vane control to curb the supply of compressed air. The scenario discussed here considered the effect of reducing the ring pressure during off-peak mining times (excluding the blasting shift) to approximately 500 kPa. The processing plant, which was supplied by a single compressor, was left unaffected and the said compressor would not be switched off nor would guide-vane control be used thereon.

The ring pressure was dictated by the user that required the highest pressure (as discussed in Section 1.3.3). For this reason, 500 kPa was used to ensure that the users with the highest pressure requirements received sufficient supply. The supply was 50 kPa above the 450 kPa required by pneumatic loaders, as given in Table 1-2, which allowed for leaks and pressure drops. Excluding the blasting shift from this scenario ensured that the compressed air network remained pressurised and avoided compressor surge during this period.

The simulation model was used to investigate the effect of switching unnecessary compressors off and using guide-vanes to reduce the ring pressure to 500 kPa during off-peak mining periods. The simulation model showed that switching any compressors off resulted in the ring pressure dropping too low. However, the use of guide-vanes proved optimal in reducing the ring pressure to 500 kPa.

Figure 3-6 shows the simulation results for the average ring pressure by using guide-vane control. The average ring pressure for the baseline simulation is given in red, whilst the average ring pressure when guide-vane control and schedule optimisation were applied is given in green. As can be seen, the pressure during off-peak mining times was reduced to approximately 500 kPa.

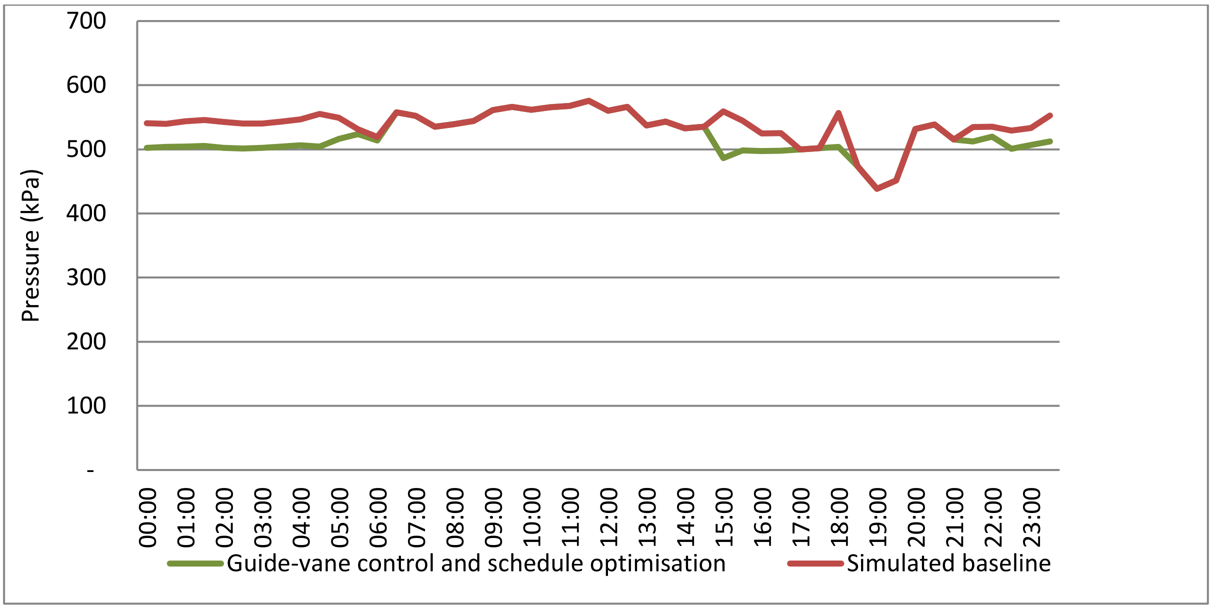


Figure 3-6: System A – simulated pressure using guide-vane control

Using guide-vane control to reduce the system pressure resulted in a reduction in compressor power. This reduction in compressor power is apparent in Figure 3-7, which compares the simulated baseline total power (in red) with the guide-vane control scenario (in green). The demand reduction is given as the blue area on the secondary vertical axis. The use of guide-vane control reduced the power consumption during off-peak mining times by a substantial amount. The reduction in demand is given as the blue area on the secondary vertical axis. As can be seen, significant demand reductions of roughly 6 MW were obtained during off-peak mining times (blasting shift excluded).

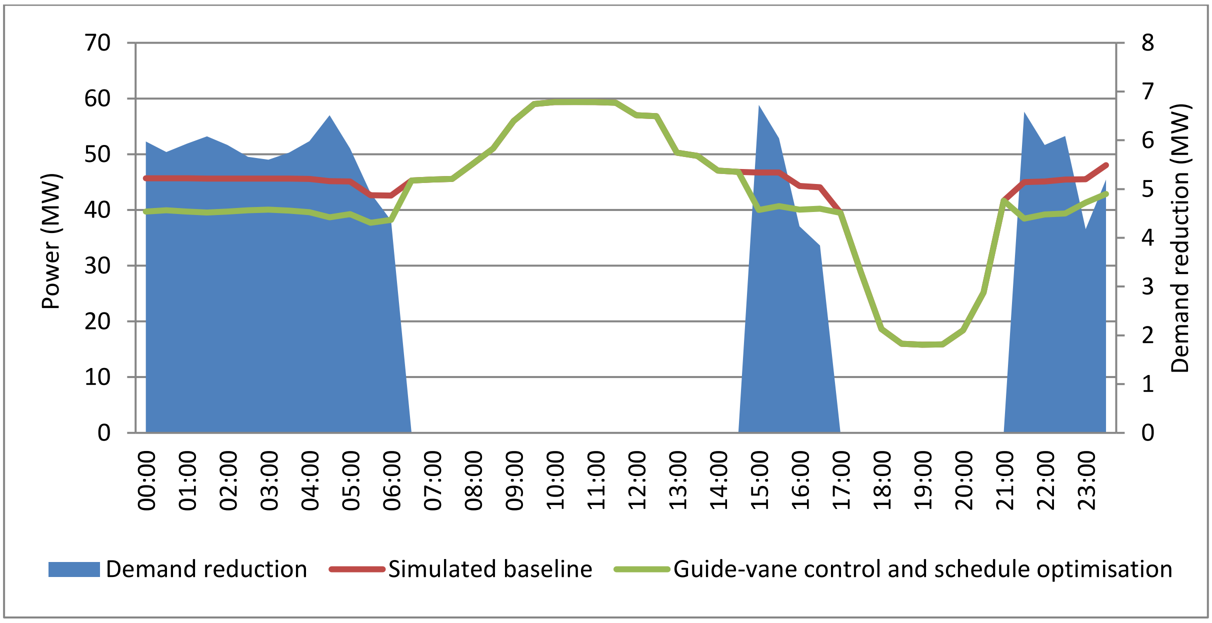


Figure 3-7: System A – guide-vane control and schedule optimisation simulation results

Annual savings

The annual savings of implementing guide-vane control was determined by using the simulation results. The savings were calculated as R10.46 million per annum as per Section 2.5.2. This fell in the range of > R9.8 million per annum, which resulted in an annual savings score of **5 out of 5**.

Payback period

No additional expense had to be incurred for this energy efficiency solution since all the compressors already had guide-vanes installed. As a result, the use of guide-vane control and schedule optimisation had a PBP of zero months, which meant a PBP score of **5 out of 5**.

Level of automation

Systems were not in place for automating compressor control and the mining personnel were reluctant to implement such systems. This meant that control room operators, who had the responsibility of starting and stopping compressors, would also be tasked with using compressor guide-vanes to limit the supply of compressed air. Thus, this energy efficiency solution required fast action, dedicated personnel and continuous follow-ups. This means that all three of the criteria for the level of automation (from Table B-6) are applicable and that this energy efficiency solution scores a **1 out of 5** for the level of automation.

Implementation time

No time was allocated to the procurement period, lead period or installation period since the compressors have already been fitted with guide-vanes. However, the optimisation time entailed training the control room operators to implement this energy efficiency solution properly. Eight weeks was allocated as the implementation time for training control room operators and rectifying problems. Six of the eight weeks were chosen to allow for three training sessions with all control room operators, who were all on duty every two weeks. The final two weeks were allocated for identifying and rectifying problems. The estimated implementation period of eight weeks resulted in a score of **3 out of 5**.

Once the scores for the implementation factors for using guide-vane control and schedule optimisation were known, the implementation score was determined. Table 3-2 gives each implementation factor’s value, range and score. The overall implementation score for using guide-vane control and schedule optimisation as an energy efficiency solution was **4.42**.

Table 3-2: System A – implementation factor scores for guide-vane control and schedule optimisation

Implementation factor	Value	Range	Score out of 5
Annual savings	R10.46 M	> R9.8 M	5
PBP	0 months	0–2 months	5
Level of automation	Minimal	Minimal	1
Implementation time	8 weeks	5.5–8.5 weeks	3
		Implementation score:	4.42

Energy efficiency solution 2: Smaller compressors

Although System A did not have any smaller compressors available, three VK32 compressors were typically run during the blasting shift along with a VK50 compressor to supply the processing plant. Thus, the only option for using a smaller compressor, barring buying a new compressor, was using a VK32 compressor rather than the VK50 compressor during the blasting shift. Since the blasting shift occurred during the Eskom peak TOU period (as per Figure 2-8 from Chapter 2.5.2), the power reduction by using a VK32 compressor rather than a VK50 compressor could result in a substantial monetary saving. However, the processing plant had to be amply supplied otherwise a VK32 compressor would not be feasible for replacing the VK50 compressor during this time.

The simulation model was used to ascertain whether the VK32 compressor could supply the processing plant sufficiently during the blasting shift. Figure 3-8 shows the impact of using a VK32 compressor rather than one of the VK50 compressors during the blasting shift. The red line gives the average processing plant pressure from the simulated baseline, whilst the green line gives the average processing plant pressure when a VK32 compressor was used instead of the VK50 compressor. The difference in pressure between the two is given as the blue area on the secondary y-axis. As apparent in the figure, the pressure difference due to using a smaller VK32 compressor rather than a VK50 pressure during the blasting shift was a maximum of approximately 45 kPa at 20:30. Furthermore, the pressure dropped below 500 kPa between 19:00 and 20:30 when the smaller VK32 compressor was used.

As a result of the pressure dropping too low, the VK32 compressor was deemed inadequate for supplying the processing plant in place of the VK50 compressor. For this reason and the lack of availability of other smaller compressors, the energy efficiency solution of using smaller compressors was not considered feasible on System A. As discussed in Section 2.5.6, it was assigned an implementation score of 0 and was not considered for implementation.

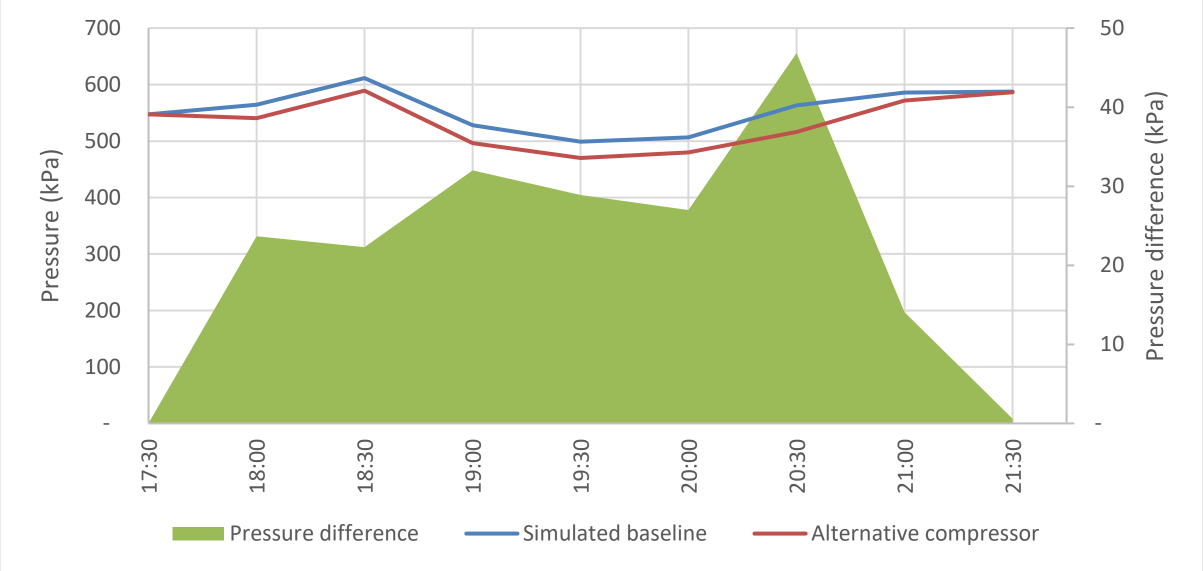


Figure 3-8: System A – impact of smaller compressors on processing plant blasting shift pressure

Energy efficiency solution 3: Network reconfiguration

System A is a compressed air ring that has seen the closure of several shafts. This means that the ring, which was designed for a specific arrangement of shafts, had been altered and might become inefficient. As noted in Section 2.2.2, the energy efficiency solution, however, must not affect production. Therefore, if reconfiguring System A's network had a detrimental effect on the drilling shift pressures, it would not be deemed feasible and would not be implemented. The simulation model of System A was used to investigate several permutations of the network and determine what benefit it would have on the network, if any. The following network reconfigurations were investigated (see Figure 3-9):

- Option 1: Isolate A-5 Shaft, A-7 Shaft, Compressor House 3 and Compressor House 5 from the rest of the compressed air ring (blue cross)
- Option 2: Close the pipeline between Compressor House 7 and A-6 Shaft (yellow cross)
- Option 3: Close the pipeline between Compressor House 6 and Compressor House 7; close the pipeline between Compressor House 7 and A-6 Shaft; and commission 500 mm pipeline between Compressor House 7 and A-3 Shaft (purple line and crosses)
- Option 4: Close the pipeline between A-3 Shaft and A-6 Shaft (orange cross)

- Option 5: Close the pipeline between A-3 Shaft and A-6 Shaft and commission a 500 mm pipeline between Compressor House 7 and A-3 Shaft (red line and red cross)

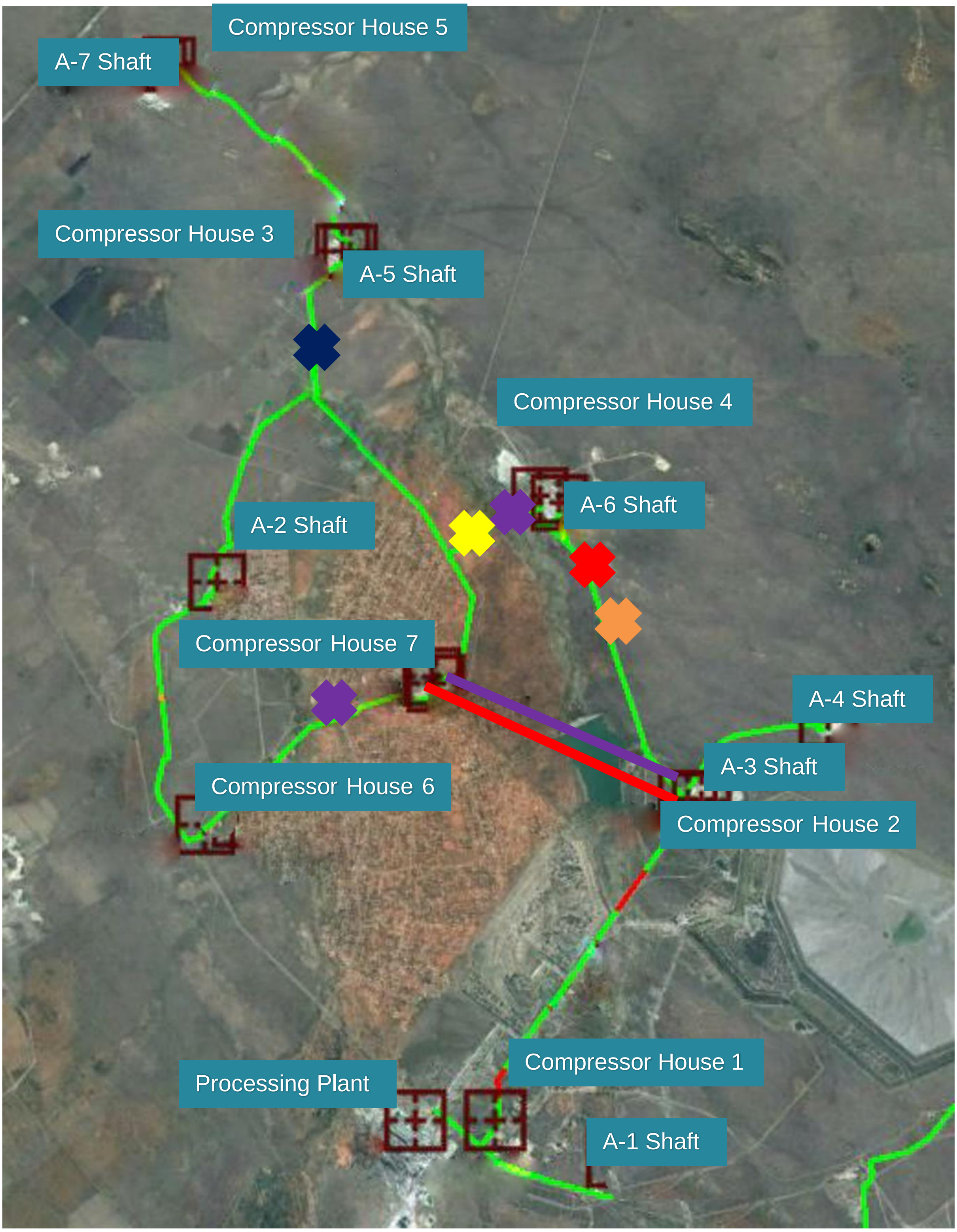


Figure 3-9: System A – options for network reconfiguration

Table 3-3 shows the effect that reconfiguring the network with each option had on the drilling shift pressures of all the shafts. The drilling shift pressures of the shafts that were affected negatively are shown in red, whilst the drilling shift pressures that benefitted from network reconfiguration are given in green. The symbols used to indicate the network reconfiguration in Figure 3-9 are given in the table for reference.

As shown in Table 3-3, all the network reconfiguration options reduced the drilling shift pressures at some shafts. In other words, all the shafts did not benefit from the network reconfiguration, which would result in production being affected negatively at some shafts. For this reason, network reconfiguration was not considered a viable energy efficiency solution on System A (as discussed in Section 2.5.6). Consequently, it was assigned an implementation score of 0 and would not be implemented.

Table 3-3: System A – drilling shift changes resulting from network reconfiguration

Drilling shift pressure difference (kPa)					
Shaft	**Option 1** ✖	**Option 2** ✖	**Option 3** ✖ /	**Option 4** ✖	**Option 5** ✖ /
A-1 Shaft	−5	−16	16	16	11
A-2 Shaft	−25	42	−55	−30	−25
A-3 Shaft	−9	−29	49	43	35
A-4 Shaft	−8	−26	42	37	30
A-5 Shaft	31	−29	−32	−18	−14
A-6 Shaft	−19	−58	−22	−7	2
A-7 Shaft	27	−27	−30	−16	−13
Processing plant	−5	−16	16	16	11

Energy efficiency solution 4: Valve control

As discussed in Section 3.3.1, only A-2 Shaft, A-4 Shaft and A-6 Shaft had compressed air control valves installed. As a result, valve control had to be applied to all the shafts and four additional control valves had to be acquired for the remainder of the shafts (processing plant excluded). A-6 Shaft already controlled the compressed air, albeit to a small extent. The control philosophy was updated incrementally to ensure that the pressure set point during each shift coincided with the shift's requirements. During the incremental updates to the control philosophy, complaints from mining personnel were managed and considered to ensure that compressed air was supplied adequately for the entire day.

The resulting pressure set points from the updated control philosophy are given in Table 3-4 along with the relevant shift and the start and end time thereof. This information is also displayed graphically in Figure 3-10.

Table 3-4: System A – updated pressure set points of A-6 Shaft

Shift	**Start time**	**End time**	**Pressure set point (kPa)**
Morning cleaning shift	00:00	04:30	450
Morning shift changeover	04:30	06:00	370
Drilling shift	06:00	14:30	No pressure set point
Afternoon shift changeover	14:30	17:30	370
Blasting shift	17:30	21:00	200
Night shift changeover	21:00	22:30	370
Night cleaning shift	22:30	00:00	450

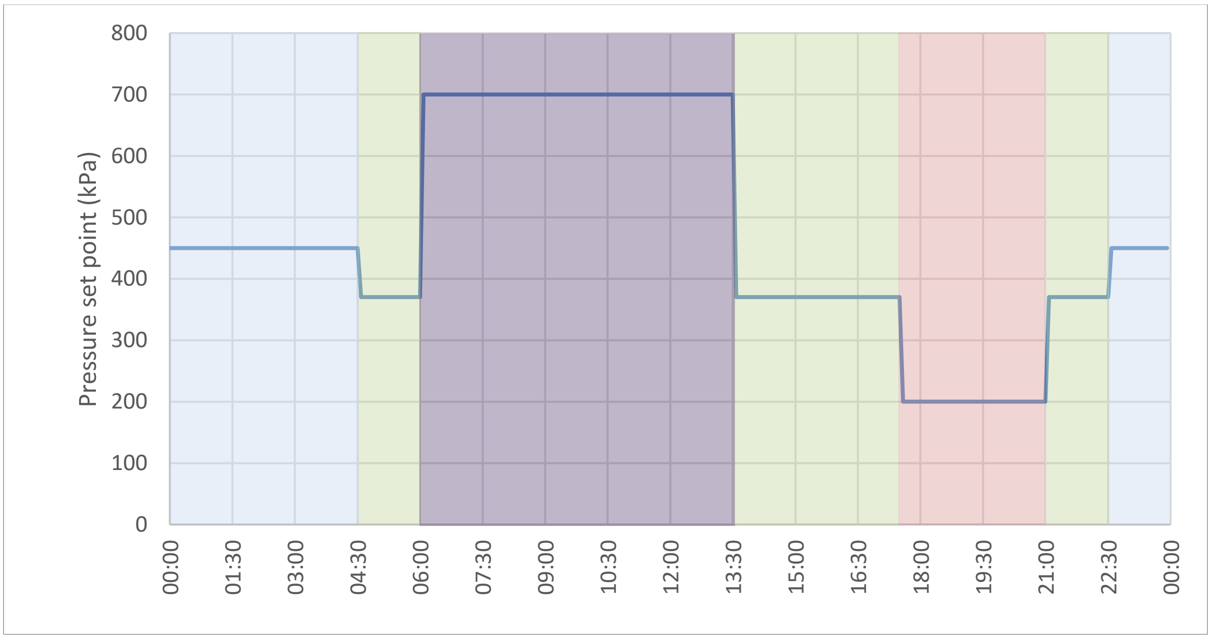


Figure 3-10: System A – updated pressure set points of A-6 Shaft

As can be seen in Table 3-4 and Figure 3-10, different shifts had different pressure set points. The control started and ended with cleaning shift pressure set points, which were 450 kPa during the morning and evening cleaning shifts to ensure that the pneumatic loaders (as discussed in Section 1.2.4) received ample compressed air. The drilling shift had a set point of 700 kPa to ensure that the pneumatic rock drills could be used to their utmost efficacy.

During the blasting shift when only refuge chambers had to be pressurised, a set point of 200 kPa was used. During shift changeovers (between the three main shifts), a set point of 370 kPa was used to ensure that the loading boxes, pneumatic cylinders and pneumatic actuators could be used effectively.

Figure 3-11 compares the old compressed air flow profile at A-6 Shaft (in red), with the flow profile resulting from the updated control philosophy (in green). The flow reduction from using the updated set points is given as the blue area. As can be seen, a reduction in compressed air consumption resulted from the updated set points.

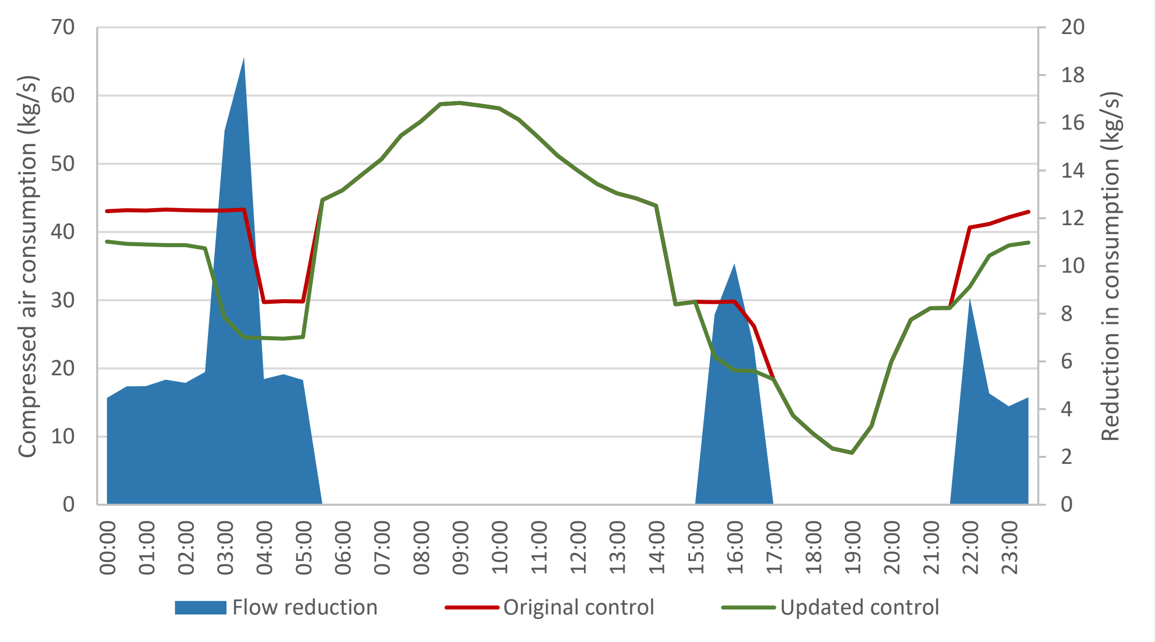


Figure 3-11: System A – A-6 Shaft's previous vs updated control philosophy

These aforementioned pressure set points were used at all the shafts to control the compressed air because the set points had set a precedent at A-6 Shaft, where the solution proved to work effectively. System A's simulation model was used to show the effect that using these valve control set points would have on the total compressor power, as shown in Figure 3-12. The simulated baseline power is given in red, whilst the green line shows the power profile where valve control was used. As can be seen in the blue area on the secondary vertical axis, there were substantial reductions in the total power of System A's compressors during off-peak mining periods. Demand reductions up to 8 MW were obtained.

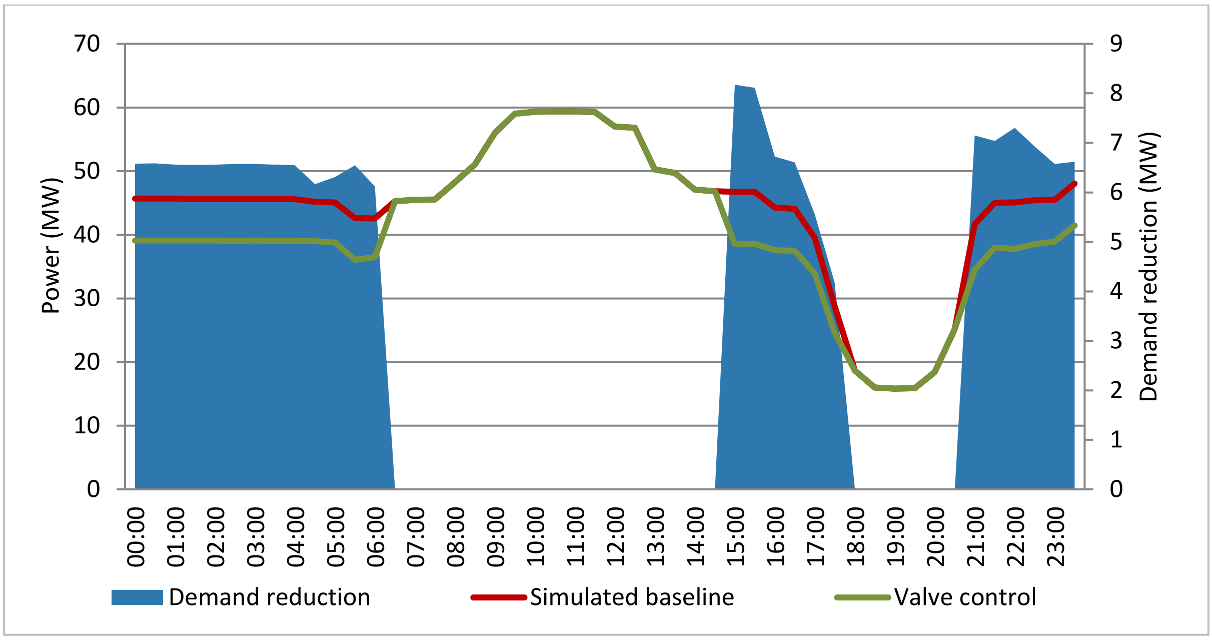


Figure 3-12: System A – valve control simulation results

Annual savings

Calculating the saving due to the reduction in the system's total compressor power consumption (as per Section 2.5.2) showed that R17.85 million could be saved per annum. This fell in the range of > R9.8 million per annum, giving the use of valve control on System A a score of **5 out of 5** for annual savings.

Payback period

Since only three of the seven shafts had compressed air control valves, four extra control valves would have to be procured. The total price for the four valves was R7.7 million, which included all the required equipment (such as actuators and pressure transmitters), installation (such as labour and crane hire), and a 10% contingency. By using Equation 2.10 (from Section 2.5.3), the PBP was calculated as six months. This fell in the range of zero to six months given in the Likert scale in Table 2-6, which meant that valve control has a PBP score of **5 out of 5**.

Level of automation

Before control valves can be used, a control philosophy must be created and programmed. After the control philosophy is completed, human intervention is only required if changes have to be made to said philosophy. Therefore, it does not require continuous check-ups nor fast action (from Table B-6), but only dedicated personnel. Consequently, it scored **3 out of 5** for the level of automation for a moderate level of automation.

Implementation time

As compressed air control valves were not present at all of the shafts, they had to be acquired. This meant that the implementation time consisted of several different components. Four weeks were allocated to the procurement time since approval was required at a monthly procurement meeting. Once approval was obtained for all the valves, the orders could be placed and the lead time started, which was given as 18 weeks by the valve suppliers.

Valves could only be installed once the shafts have been isolated and closed temporarily. This would have to take place on an off-weekend when no compressed air would be required. Typically, every second weekend classifies as an off-weekend. The installation of the valves must be overseen by specific mining personnel. Therefore, two weeks were attributed for each valve's installation, or eight weeks in total for the installation of all four valves.

After the installation of the valves, the control would have to be optimised. Since the control philosophy of the valves could be done whilst the valves were being manufactured, it was not considered as optimisation time. A period of four weeks was estimated to ensure that all the valves operated effectively and that the control was optimised.

Summating the time for procurement, lead time, installation time and optimisation time, the total estimated implementation time was 34 weeks. This fell in the range of more than 11.5 weeks from Table 2-6, which meant that the use of control valves as an energy efficiency solution had an implementation time score of **1 out of 5**.

Table 3-5 shows each implementation factor's range and score as well as the implementation score calculated as per Equation 2.12 (from Section 2.5.6). It can be seen that using guide-vane control had an implementation score of **4.32**.

Table 3-5: System A – implementation factor scores for valve control

Implementation factor	**Value**	**Range**	**Score out of 5**
Annual savings	R17.85 M	> R9.8 M	5
PBP	6 months	< 6 months	5
Level of automation	Moderate	Moderate	3
Implementation time	34 weeks	> 11.5 weeks	1
		Implementation score:	4.32

3.2.4 Implementation priority

The previous section determined the implementation scores for each of the four energy efficiency solutions on System A. This section discusses the implementation priority of the energy efficiency solutions and their implementation. The values for each energy efficiency solution's implementation factor and corresponding implementation score for System A are summarised in Table 3-6.

Table 3-6: System A – implementation factor values and implementation scores

Energy efficiency solution	Annual savings	PBP	Level of automation	Implementation time
Guide-vane control and schedule optimisation	> R9.8 M (5)	0−6 months (5)	Minimal (1)	5.5-8.5 weeks (3)
Smaller compressors	Not feasible			
Network reconfiguration	Not feasible			
Valve control	> R9.8 M (5)	< 6 months (5)	Moderate (3)	> 11.5 weeks (1)

The final implementation scores for each energy efficiency solution and their implementation priorities are given in Table 3-7. The energy efficiency solution of schedule optimisation and guide-vane control had the highest implementation score (4.42) and had to be implemented first. This was followed by valve control (with a score of 4.32), which was to be implemented second. Neither network reconfiguration nor the use of smaller compressors was feasible. Network reconfiguration was unfeasible because it affected production at the shafts negatively. The use of smaller compressors was unfeasible since the use of a smaller compressor resulted in the pressures dropping too low at the processing plant.

Table 3-7: System A – implementation scores and priorities

Energy efficiency solution	Implementation score (out of 5)	Implementation priority
Schedule optimisation and guide-vane control	4.42	1
Smaller compressors	0	Not to be implemented
Network reconfiguration	0	Not to be implemented
Valve control	4.32	2

3.2.5 Implementation of energy efficiency solutions

The preceding section determined the implementation priorities of four energy efficiency solutions. This section discusses the implementation of these energy efficiency solutions according to their implementation priority. A detailed discussion of the results and the validation thereof are given in Section 3.4.

Guide-vane control and schedule optimisation

The energy efficiency solution of guide-vane control and schedule optimisation had the highest implementation score of the energy efficiency solutions considered. Therefore, it was implemented first. The actual annual savings obtained from the energy efficiency solution were R8.8 million.

Control valves

The use of control valves was the second-highest scoring energy efficiency solution and was implemented second. As noted earlier, A-4 Shaft's valve could not be used since it was noisy and situated in an area with a high amount of foot traffic. To address this, the valve was moved to an area less frequented by miners, which meant that the valve could be used.

A business case was created to motivate the installation of control valves at the four shafts that did not have control valves. Approval was obtained for the procurement and installation of the control valves. At the time of writing, however, delivery of three control valves was still pending due to shipping delays. Although one of the control valves was installed, its full control still had to be optimised. Therefore, the system could not be controlled according to the proposed control philosophy and the savings could not be obtained systemwide. However, savings of R7 million per annum were obtained at the shafts where the compressed air valves were installed.

To determine what the existing control valve savings potential was on the shafts where valves were already installed, a simulation was conducted for this situation. When valve control was simulated on these shafts, savings of R7.9 million per annum were obtained. A reason for the difference between the actual annual savings of R7 million and the simulated annual savings of R7.9 million is discussed in Section 3.4.1.

Smaller compressors and network reconfiguration

It was shown that the use of smaller compressors and the use of network reconfiguration were not feasible on System A. Consequently, neither was implemented. This meant that time was not needlessly wasted on feasibility studies or investigations to determine if these energy efficiency solutions would work.

3.2.6 Compounding effects of implemented energy efficiency solutions

To investigate the additional benefits from the compounding effects of one energy efficiency solution on another, the existing simulation model was used. As discussed above, guide-vane control was the first energy efficiency solution to be implemented and thereafter valve control was to be implemented. To determine the compounding effect, the simulation outputs from guide-vane control can be used to serve as inputs for the valve control simulation.

Figure 3-13 shows the total impact on the power consumption when these two energy efficiency solutions are compounded. The red line shows the baseline simulation and the green line shows the results for the compounded simulation. The blue area shows the compounded demand reduction when both guide-vane control and valve control are active. The total simulated savings are R23.2 million per annum.

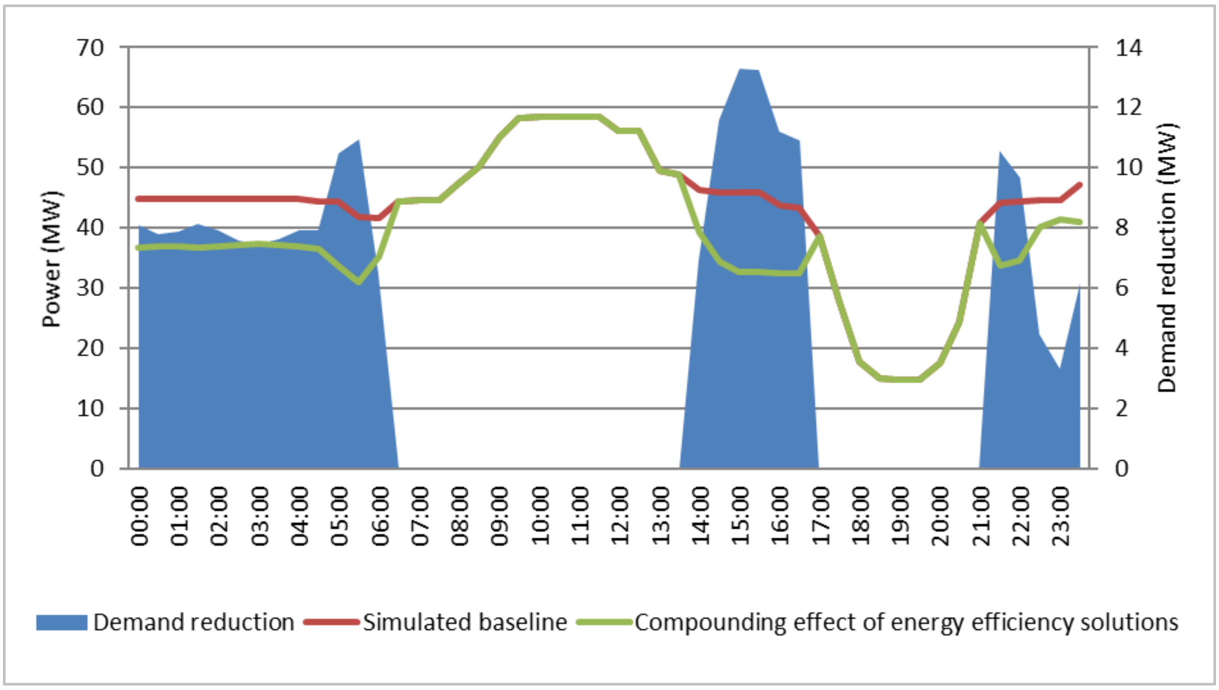


Figure 3-13: Compounding effect of energy efficiency solutions on System A

3.2.7 Summary

This section focused on four energy efficiency solutions on System A that were prioritised by using the simulation model and the methodology as established in Chapter 2. The first energy efficiency solution implemented was guide-vane control and schedule optimisation, which had an implementation score of 4.42. The simulation model predicted annual savings of R10.46 million; R8.8 million of which was realised.

Valve control was the second energy efficiency solution implemented, which had an implementation score of 4.32. Annual savings of R17.85 million were predicted by the simulation model; however, all the valves have not been installed at the time of writing. For the shafts where the compressed air valves were installed, annual savings of R7 million were obtained.

Neither smaller compressors nor network reconfiguration proved to be feasible energy efficiency solutions and were consequently not implemented. This meant that time and resources were not wasted on feasibility studies or investigations.

Finally, the potential compounding savings of the energy efficiency solutions were determined by means of simulation. It was shown that the total savings for guide-vane control and valve-control could amount to R23.2 million per annum.

3.3 System B: Small compressed air ring

3.3.1 System overview

The methodology was used secondly on the smaller compressed air ring of the platinum mining group, henceforth referred to as System B. It is a more recent compressed air ring than System A, since it only reached its maximum capacity in 2018. Figure 3-14 gives a satellite view of System B's compressed air ring, which shows the four shafts and the five compressor houses. The total length of pipe spanning the system was 17 km. Figure C-4 and Figure C-5, both in Appendix C-3, respectively give a detailed system layout and a SCADA view of System B. The average temperature and relative humidity profile of this system (which is the same as System A) are given in Figure C-1 in Appendix C-1.

The five compressor houses had 11 compressors: five VK32 compressors and six VK50 compressors with respective individual installed capacities of 2.9 MW and 4.9 MW, although the actual power outputs differed due to inefficiencies. The total installed capacity of System B was 43.9 MW. Sixteen smaller L250 compressors with capacities of 0.25 MW were to be commissioned on the system.

Figure 3-14: System B – satellite view of compressed air layout

Figure 3-15 shows a typical power profile of System B, which was taken as the weekday average for the year before the implementation of the energy efficiency solutions. Most, if not all, of the compressors were operational during the peak drilling shift. Conversely, during blasting shift, if all the shafts closed their compressed air valves, only one compressor was required to maintain the surface pressure. Only one control valve was present on the system, which was situated at B-2 Shaft. Any additional control valves had to be purchased and installed.

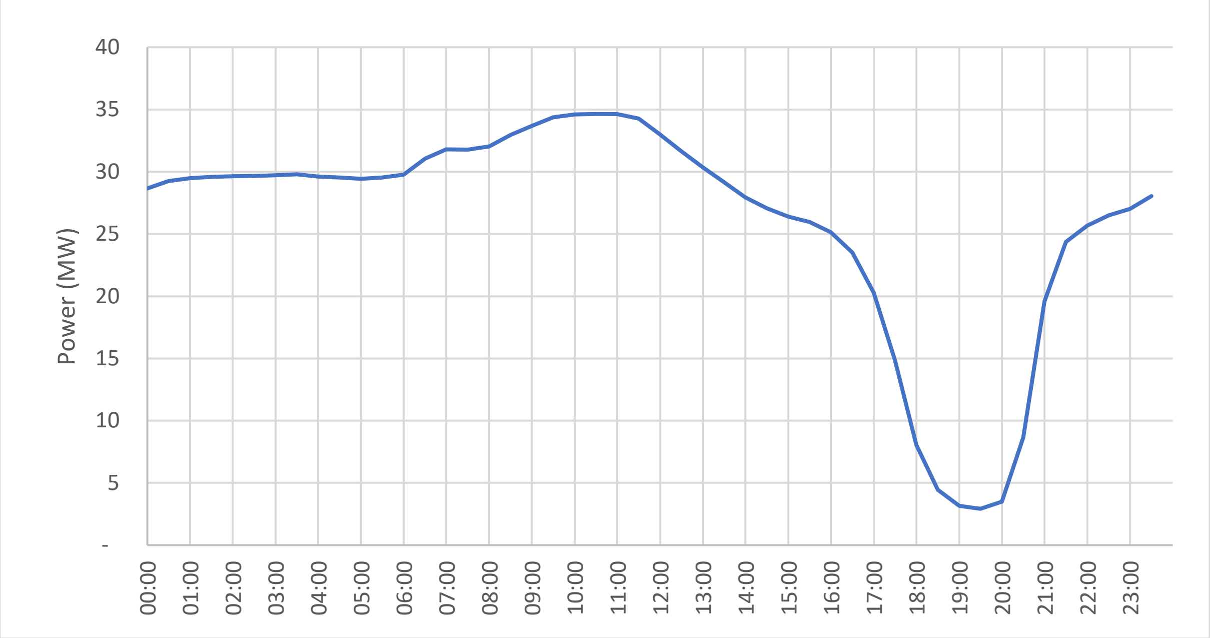


Figure 3-15: System B – power profile

As discussed earlier in Section 1.2.5, the compressed air requirements changed throughout the day and less compressed air and lower pressures were required during periods of lower demand. However, System B's lower requirements during periods of lower demand were not considered, which meant that switching off unnecessary compressors was not emphasised. Furthermore, even though guide-vane control was available, it was not used to reduce compressor supply when possible. This meant that energy efficiency solutions could be used to potentially improve the system's efficiency. Since production had to be left unaffected by not reducing the shafts' drilling shift pressures, the focus of the energy efficiency solutions was on improving the compressed air network efficiency during off-peak mining times. The blasting and cleaning shifts were identified as the key periods.

Before the energy efficiency solutions could be implemented on the system, a simulation model was developed to determine the effects of the energy efficiency solutions. This section commences by elaborating on the development and verification of the model. Thereafter, this section discusses how the simulation model was used, along with the methodology discussed in Section 2.5, to determine the implementation score of the energy efficiency solutions. The energy efficiency solutions were ranked according to their implementation score. The results are provided and discussed.

3.3.2 Development and verification of simulation model

Development of model

By using the methodology developed in Chapter 2, the system was investigated to ensure that the system was understood thoroughly. Data for the simulation model was acquired and subsequently verified. The simulation model was developed as per the assumptions noted in Section 2.3.4. Mineshafts were selected as the boundary conditions since the focus in this study was on determining the effect of implementing energy efficiency solutions on mineshafts. Figure D-3 and Figure D-4 in Appendix D-2 shows an overall view and a detailed view of the simulation model respectively. As with System A, the step size used in the simulation was 30 minutes.

Verification of model

After the simulation model was created, it was calibrated to ensure that it was accurate. As discussed in Section 2.4.3, the simulation model was calibrated to have a percentage error of 5% or less and a coefficient of determination of 0.9 or more. This held true for all component parameters (power, pressure and flow).

Figure 3-16 compares the total actual flow for System B with the model flow of the simulation. The actual value is given in blue and the simulated baseline value is given in orange. The grey area on the secondary y-axis gives the instantaneous percentage error. The overall percentage error was 3.4% and the coefficient of determination was 0.99.

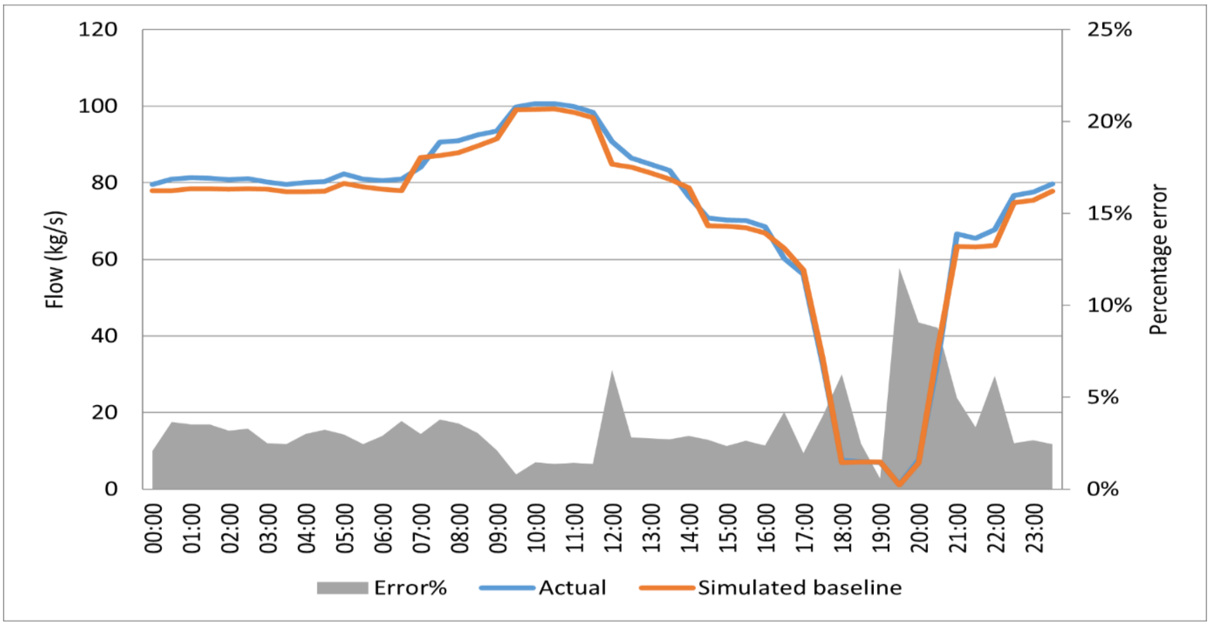


Figure 3-16: System B – total flow: actual vs simulated

Figure 3-17 compares the total actual power of System B with the total power of the simulation model. As with the figure above, Figure 3-17 shows the actual total power in blue and the simulated baseline's total power in orange. The grey area on the secondary y-axis gives the percentage error. The overall percentage error was 2.5% and the coefficient of determination was 0.99. The percentage error spike shown at 17:00 was due to the transition to the blasting shift, where compressors were switched off rapidly.

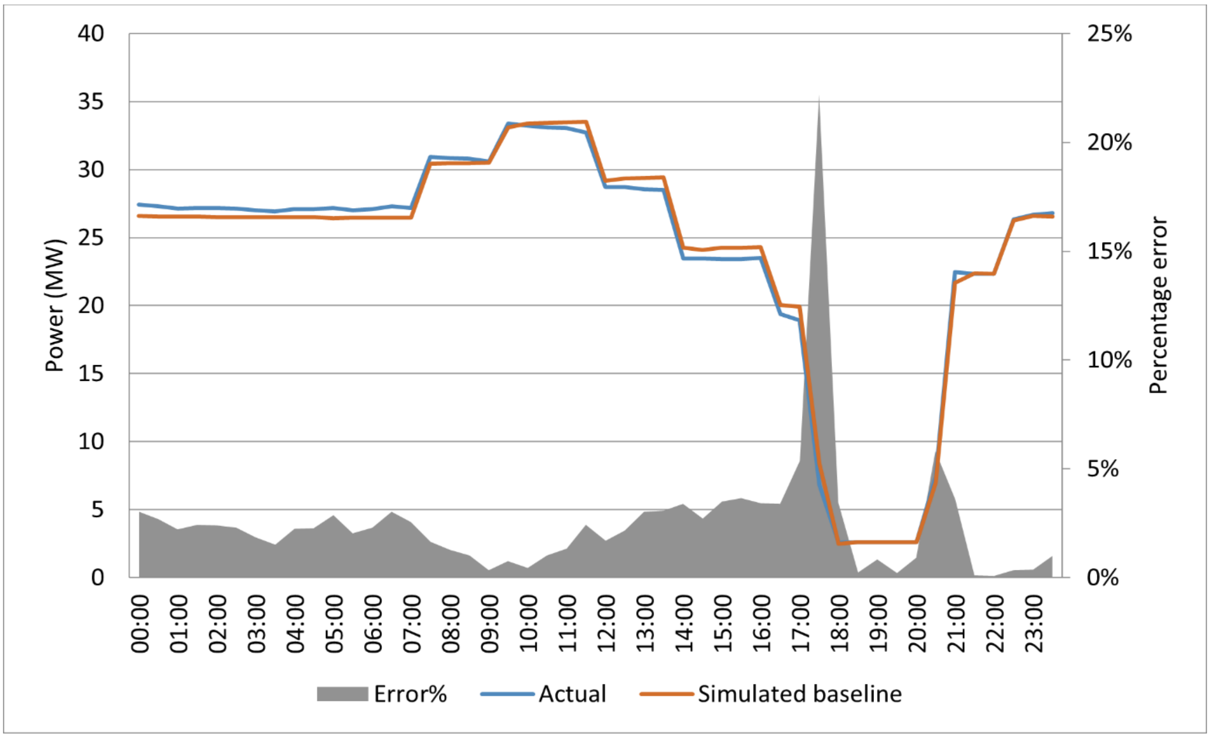


Figure 3-17: System B – total power: actual vs simulated

Figure 3-18 compares System B's actual average pressure with the simulated average pressure. The actual value is given in blue and the simulated value is given in orange. The grey area on the secondary y-axis gives the instantaneous percentage error. The overall percentage error was 2.4%. The coefficient of determination was disregarded due to the lack of a distinct profile as discussed in Section 2.4.2.

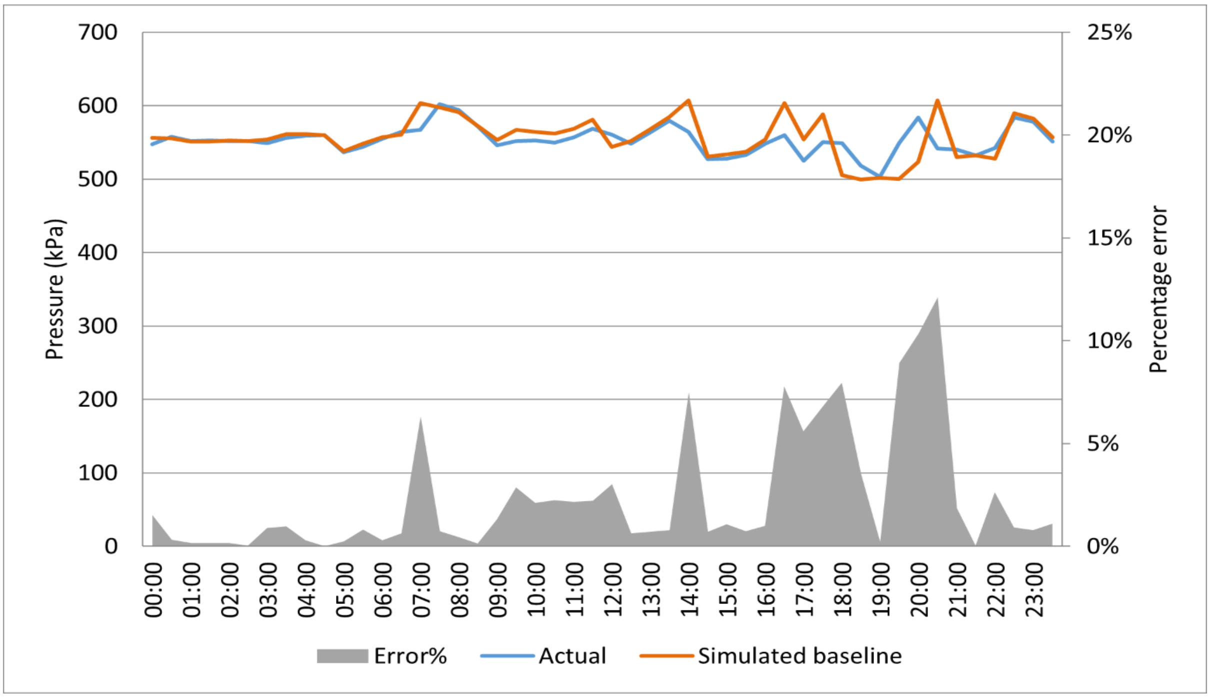


Figure 3-18: System B – average system pressure: actual vs simulated

The percentage errors and coefficients of determination of the total flow, total power and average pressure of System B are given in Table 3-8. As shown, the respective error percentages for the total flow, total power and average pressure were 3.6%, 2.2% and 2.4%. The coefficients of determination for the total flow and total power were both 0.99.

Table 3-8: System B – simulation model verification

Parameter	$Error\%$	r^2
Total flow (kg/s)	3.4%	0.99
Total power (MW)	2.5%	0.99
Average pressure (kPa)	2.4%	N/A

As with System A, the percentage error of each component's power, pressure and flow had to be equal to, or less than 5%, whilst each component's coefficient of determination for the flow and power had to 0.9 or higher. As Appendix E-2 elaborates, this was the case for all the components; therefore, the simulation was deemed accurate and representative of System B's compressed air ring. Consequently, the simulation model was verified and could be used to determine the implementation scores of energy efficiency solutions.

3.3.3 Implementation scores

After the simulation model was developed and calibrated, it was applied. This section describes how the simulation model was used to investigate the effect of four energy efficiency solutions on System B. The simulation results were used in conjunction with the methodology discussed in Section 2.5 to prioritise the implementation order of the energy efficiency solutions on System B. The four energy efficiency solutions that were investigated are:

- Guide-vane control and schedule optimisation.
- Smaller compressors.
- Network reconfiguration.
- Valve control.

This section discusses the annual savings, PBP, level of automation and implementation time of each energy efficiency solution, whereafter it describes how the implementation score was determined.

Energy efficiency solution 1: Guide-vane control and schedule optimisation

As mentioned earlier, the pressures on System B were not reduced during off-peak mining times. This meant that the compressors were often used needlessly and guide-vane control was not used to match the demand. The simulation determined what the effect would be of switching unnecessary compressors off and using guide-vanes to reduce the compressor discharge pressure and maintain a pressure of 500 kPa during periods of lower demand. A pressure of 500 kPa was selected to maintain the ring pressure since the ring pressure stabilises and specific pressures cannot be maintained without valve control.

Switching compressors off resulted in the pressures dropping below 500 kPa. In other words, the mine already used the optimal number of compressors during these periods and switching off more compressors would affect the operation of shafts. Schedule optimisation, therefore, was not feasible since the minimum number of compressors was already being used during the off-peak mining periods. However, using guide-vane control proved to be ideal for reducing the pressure to approximately 500 kPa during the off-peak mining periods.

Figure 3-19 gives the simulation results for the overall power profile when guide-vanes were used and unnecessary compressors were not used on System B. The baseline total power profile is given in red, whilst the scenario where guide-vane control is used is given in green. The demand reduction is given as the blue area on the secondary y-axis.

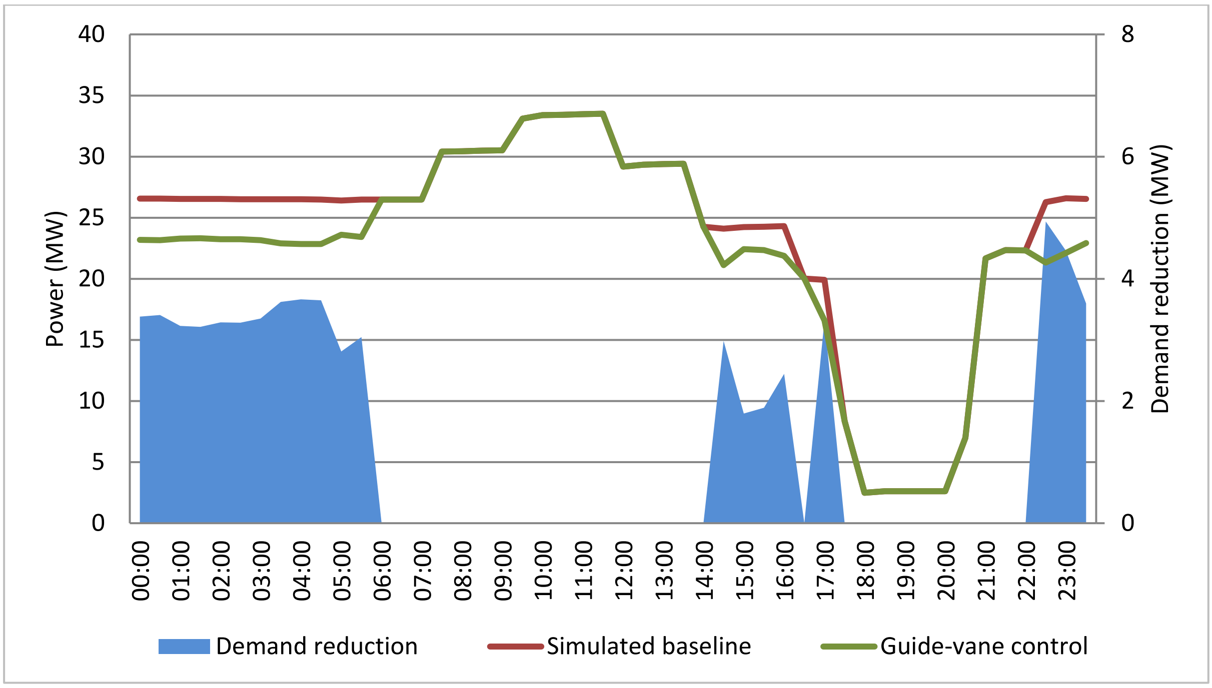


Figure 3-19: System B – guide-vane control simulated power

During the off-peak mining periods, the power consumption drastically reduced by between 3 MW and 5 MW. This excluded the blasting shift (from 18:00–21:00) since the consumption of compressed air was minimal during this time and no cutting back was done to ensure that the compressed air ring remained pressurised. Figure 3-20 shows how the use of the guide-vane control reduced the ring pressure to approximately 500 kPa outside of the drilling shift.

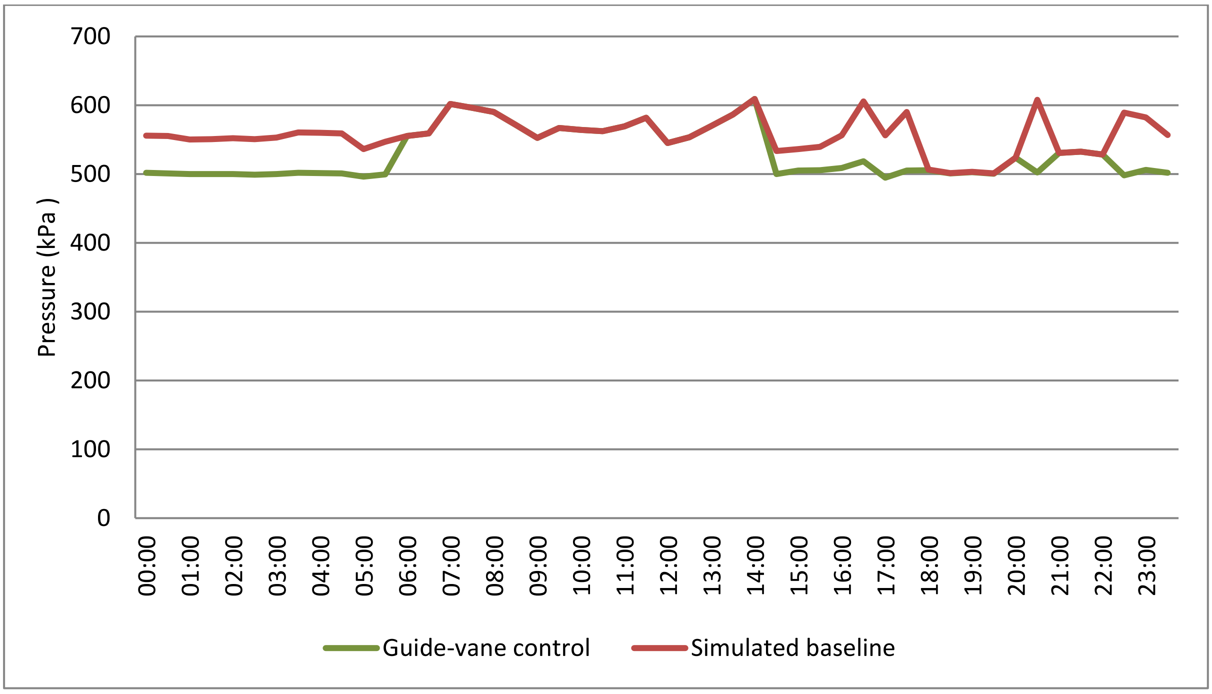


Figure 3-20: System B – guide-vane control simulated pressure

Annual savings

Annual savings of R5.6 million per annum were calculated from the simulation results between the simulated baseline and the scenario where the guide-vane control and schedule optimisation solution was implemented. This saving fell in the range of between R3.8 million and R6.3 million per annum, giving the annual savings of guide-vane control and schedule optimisation a score of **3 out of 5**.

Payback period

All the compressors on System B already had guide-vanes installed. Therefore, there was no additional expense to use guide-vanes. Subsequently, using guide-vane control and optimising the schedules was free and had a PBP of zero months and a score of **5 out of 5**.

Level of automation

On System B, the control room operators were tasked with switching compressors on and off and using guide-vane control to limit the compressor supply. As a result, the actual control would not necessarily align with the ideal control scenario. As with System A, the mining personnel did not want to automate the use of guide-vanes or the starting and stopping of compressors.

This meant that compressors would possibly not be switched off precisely when they were no longer required. Furthermore, guide-vanes were not used to limit compressors to the greatest possible extent (whilst still providing ample compressed air). This meant that this energy efficiency solution required dedicated personnel, fast action and continuous check-ups. Since it adhered to all three criteria from Table B-6, it scored **1 out of 5** for the level of automation.

Implementation time

Since no additional equipment was required to optimise the compressor running schedules or implement guide-vane control, no procurement time, lead time or installation time was necessary. For the optimisation time, the training of control room operators was vital. Over a two-week period, all the control room operators are generally on duty. The goal was to have at least three training sessions with all the control room operators on implementing the schedule optimisation and using the guide-vanes. This amounted to six weeks, which, coupled with two weeks to identify and address problems, resulted in an estimated implementation time of eight weeks. This was in the range of 5.5-8.5 weeks given in Table 2-6, which resulted in a score of **3 out of 5**.

Table 3-9 summarises the range and score for each implementation factor and also gives the implementation score (as calculated per Equation 2.12). The implementation score of using guide-vane control and schedule optimisation was **3.58**.

Table 3-9: System B – implementation factor scores for guide-vane control and schedule optimisation

Implementation factor	Value	Range	Score out of 5
Annual savings	R5.6 M	R3.8 M–R6.3 M	3
PBP	0 months	0–2 months	5
Level of automation	Minimal	Minimal	1
Implementation time	8 weeks	5.5-8.5 weeks	3
		Implementation score:	3.58

Energy efficiency solution 2: Smaller compressors

As discussed earlier, System B had 16 smaller L250 compressors available. These compressors had to be installed and optimised fully by the middle of 2020. The purpose of these compressors was to increase the drilling shift pressures on the ring to maximise production. Nonetheless, these compressors could also be used during the blasting shift in lieu of the one VK32 compressor that maintained the ring pressure and fed essential users. The L250 compressors have higher discharge pressures than the VK32 compressor, meaning that the ring pressure could be maintained better with the smaller compressors.

Figure 3-21 shows the impact of using ten L250 compressors instead of the VK32 compressor during the blasting shift when only one compressor was operational (18:00–20:00). Using the L250 compressors (shown in green) closely matched that of the simulated baseline (shown in red). The difference in pressure between the two was 12 kPa, which is given as the blue area on the secondary vertical axis. The small difference in pressure meant that the ten L250 compressors could be used to maintain the ring pressure rather than the single VK32 compressor.

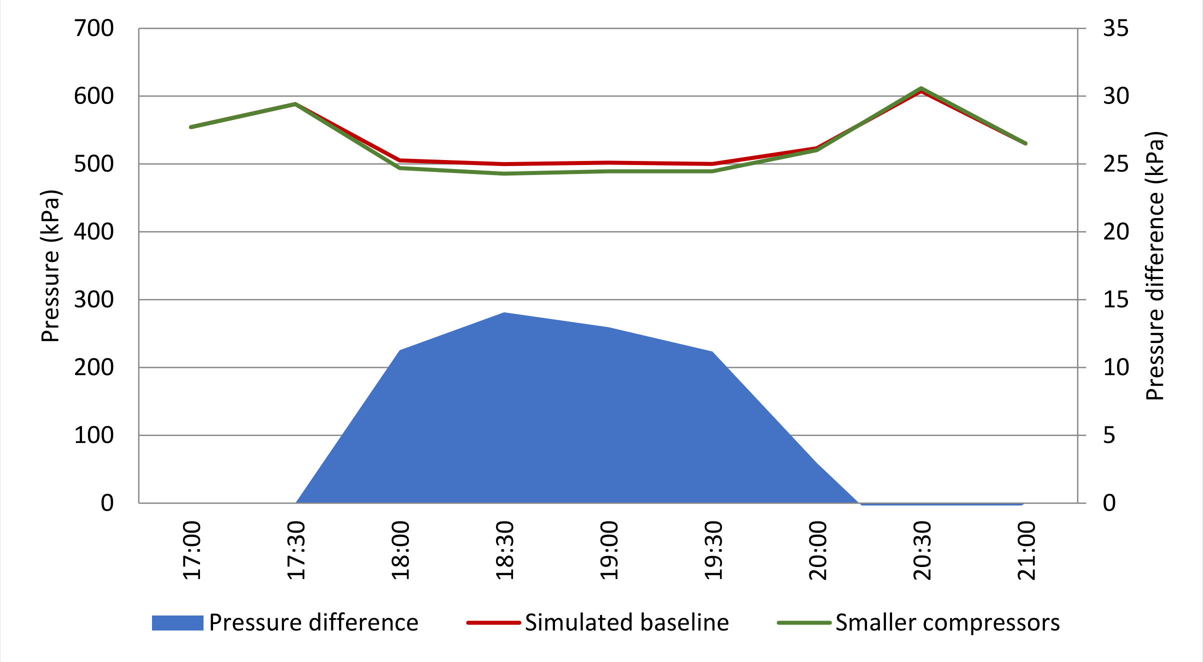


Figure 3-21: System B – impact of smaller compressors on blasting shift pressure

Figure 3-22 gives the impact on the power demand of using the L250 compressors during System B's blasting shift rather than the VK32 compressor. The simulated baseline is given in red, whilst the use of the smaller compressors is given in green. The demand reduction is given as the blue area on the secondary vertical axis. It can be seen that the demand reduced slightly (by approximately 0.4 MW) between 18:00 and 20:00.

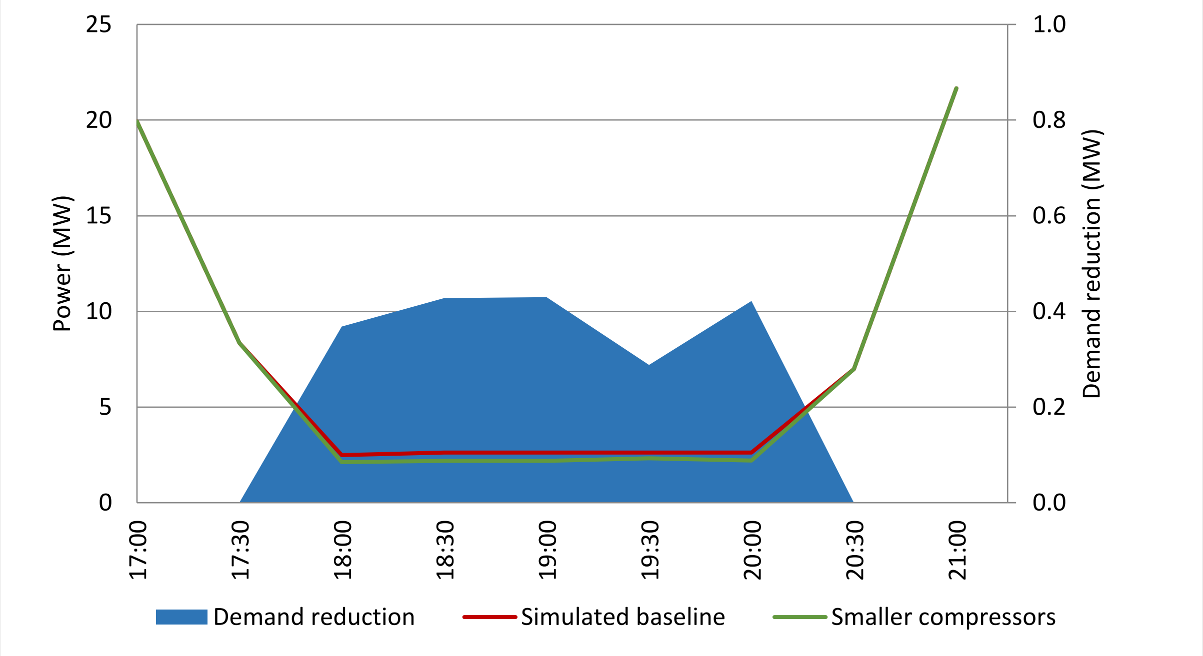


Figure 3-22: System B – impact of smaller compressors on power consumption

Annual savings

By calculating the annual savings resulting from the aforementioned demand reduction of using the ten smaller L250 compressors, annual savings of R0.36 million could be obtained per annum. This gave the use of smaller compressors a score of **1 out of 5** for annual savings.

Payback period

As noted in Section 3.3.1, the L250 compressors were to be installed on the system prior to the implementation of any energy efficiency solution; therefore, no additional expenses were incurred. As a result, the PBP of using the smaller compressors on System B had a PBP of zero months, resulting in a PBP score of **5 out of 5**.

Level of automation

Once the control room operators have been trained to use the smaller compressor in lieu of the larger VK32 compressor during the blasting shift, no further intervention would be required. This will only happen once per day, therefore it will not be considered as to requiring dedicated personnel, continuous check-ups or fast action. Hence, using a smaller compressor had a significant level of automation (according to Table B-6), which earned a score of **4 out of 5**.

Implementation time

Although the procurement process for the L250 compressors had already been completed, the lead time was eight weeks. This was followed by two weeks to ensure that the compressors were running optimally and a further two weeks to train the control room operators to use the compressors. The total implementation time was therefore roughly twelve weeks, which fell in the range of > 11.5 weeks (from Table 2-6), giving it a score of **1 out of 5**.

Table 3-10 shows the range and score for each implementation factor, as well as the implementation score, which was calculated as per Equation 2.12. As shown, the use of smaller compressors on System B had an implementation score of **2.72**.

Table 3-10: System B – implementation factor scores for smaller compressors

Implementation factor	**Value**	**Range**	**Score out of 5**
Annual savings	R0.36 M	< R1.8 M	1
PBP	0 months	0–6 months	5
Level of automation	Significant	Significant	4
Implementation time	12 weeks	> 11.5 weeks	1
		Implementation score:	2.72

Energy efficiency solution 3: Network reconfiguration

As discussed earlier, System B was a compressed air network that had been commissioned recently. Furthermore, there were no shafts on the ring that have been decommissioned. This could have resulted in the network not being feasible to reconfigure; however, using the simulation model, this could be ascertained. There were a few possible options for reconfiguring System B’s network, which are given in Figure 3-23 (where the green lines show the current pipelines) and summarised as follows:

- Option 1: Connect B-1 Shaft and B-4 Shaft with a 500 mm diameter pipeline (blue line)
- Option 2: Connect B-2 Shaft and B-3 Shaft with a 500 mm diameter pipeline (orange line)
- Option 3: Connect B-2 Shaft and B-4 Shaft with a 500 mm diameter pipeline (purple line)
- Option 4: Close pipeline between Compressor House 2 and B-3 Shaft (yellow cross)
- Option 5: Close pipeline between Compressor House 2 and B-3 Shaft, connect B-2 Shaft and B-3 Shaft with a 500 mm diameter pipeline (orange line and orange cross)
- Option 6: Close pipeline between Compressor House 2 and B-3 Shaft, connect B-2 Shaft and B-4 Shaft with a 500 mm diameter pipeline (purple line and purple cross)
- Option 7: Close pipeline between Compressor House 2 and B-3 Shaft, connect B-1 Shaft and B-4 Shaft with a 500 mm diameter pipeline (blue line and blue cross)

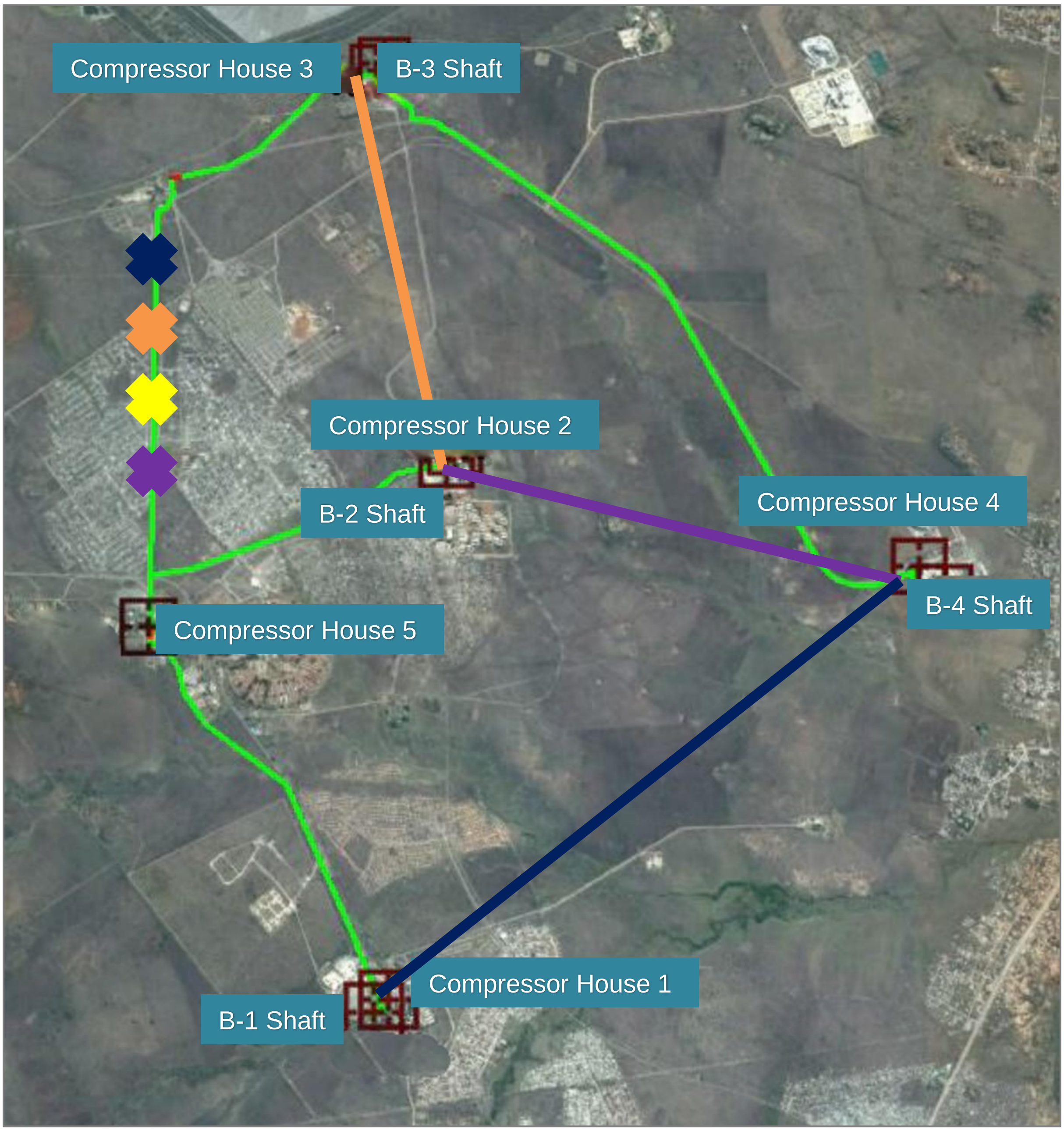


Figure 3-23: System B – options for network reconfiguration

Since reconfiguring a compressed air network changes the compressed air distribution as a whole and not only during certain times, it was also important to consider the effect that reconfiguration would have on all of the shifts. This was especially true for the drilling shift, where it could hinder production. As discussed in Section 1.2.5, it was vital to leave production unaffected. In other words, the drilling shift pressures had to be maintained or improved for an energy efficiency solution to be feasible. The simulated results for the effect of the different reconfigurations on the drilling shift pressures are given in Table 3-11. The symbols used in Figure 3-23 to show the network reconfiguration are given in the table for reference.

Table 3-11: System B – drilling shift changes resulting from network reconfiguration

Drilling shift pressure difference (kPa)							
Shaft	**Option 1** ✖	**Option 2** ✖	**Option 3** ✖	**Option 4** ✖	**Option 5** ✖ /	**Option 6** ✖ /	**Option 7** ✖ /
B-1 Shaft	−10	−1	2	67	17	27	3
B-2 Shaft	−5	−3	4	70	−4	12	14
B-3 Shaft	4	2	2	−64	−8	−31	−22
B-4 Shaft	8	2	−4	−47	−6	−5	8

It is clear that all the options for network reconfiguration benefitted some shafts, whilst other shafts were affected negatively. There was no option that benefitted all the shafts. For this reason, reconfiguring System B's compressed air network was not feasible since it impaired production. Hence, an implementation score of 0 was assigned (as discussed in Section 2.5.6) and network reconfiguration was not considered in this study.

Energy efficiency solution 4: Valve control

Only B-2 Shaft had a compressed air control valve, which meant that three additional control valves had to be acquired. Specific pressure set points were used during each shift. Table 3-12 and Figure 3-24 show the set points that were tested at A-6 Shaft from System A (which already had a control valve).

Table 3-12: System B – pressure set points for valve control

Shift	Start time	End time	Pressure set point (kPa)
Morning cleaning shift	00:00	04:30	450
Morning shift changeover	04:30	06:00	370
Drilling shift	06:00	14:30	No set point
Afternoon shift changeover	14:30	17:30	370
Blasting shift	17:30	21:00	200
Night shift changeover	21:00	22:30	370
Night cleaning shift	22:30	00:00	450

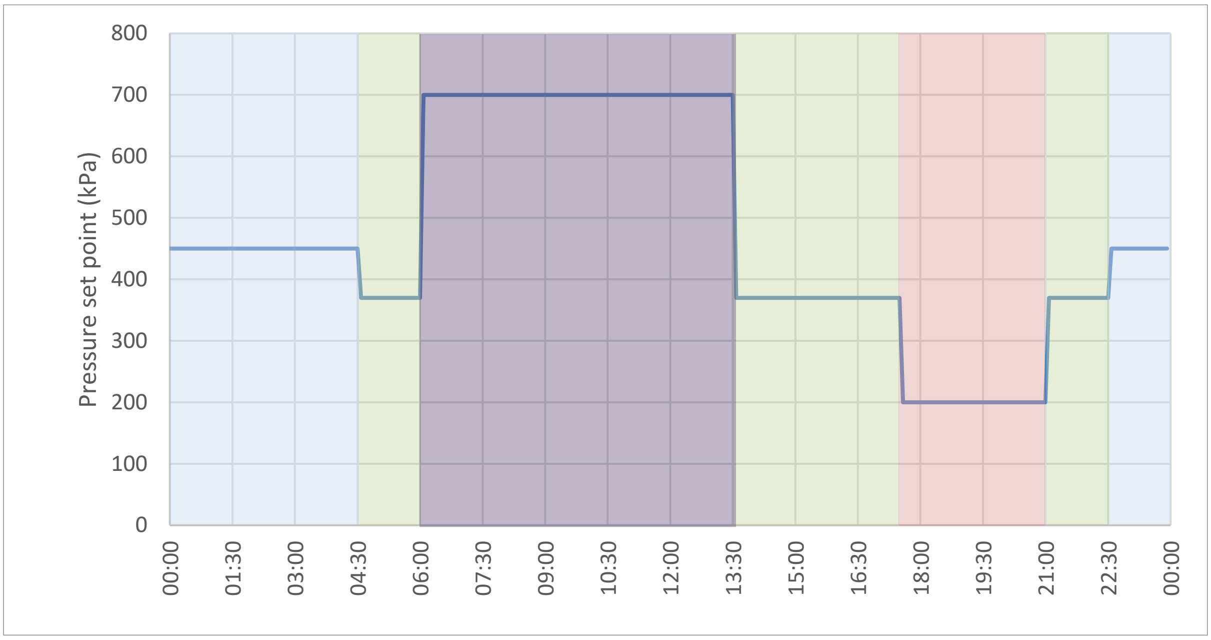


Figure 3-24: System B – pressure set points for valve control

During the morning and night cleaning shift (as shown in blue in both Table 3-12 and Figure 3-24), a pressure set point of 450 kPa was used to ensure that the required equipment, especially the loaders, received an adequate supply of compressed air. During the morning, afternoon and night shift changeovers, pressure set points of 370 kPa were used to maintain essential operations. This is shown in the green areas in both Table 3-12 and Figure 3-24.

No pressure set points were used during the drilling shift since a maximum amount of compressed air was supplied. The specified amount of 700 kPa during this time was chosen to be above the maximum pressure in the compressed air ring during the drilling shift, meaning that no control would be done. During the blasting shift (shown in red), a pressure set point of 200 kPa was used to ensure that the refuge chambers were pressurised.

Figure 3-25 gives the simulation results for using the aforementioned valve control at all of System B’s shafts. The power of the simulated baseline is given in red, whilst the green shows the power profile when valve control was used. The reduction in demand is given by the blue area on the secondary vertical axis. From this figure, it is apparent that using valve control had a substantial impact on the power consumption during off-peak mining periods with demand reductions in excess of 5 MW.

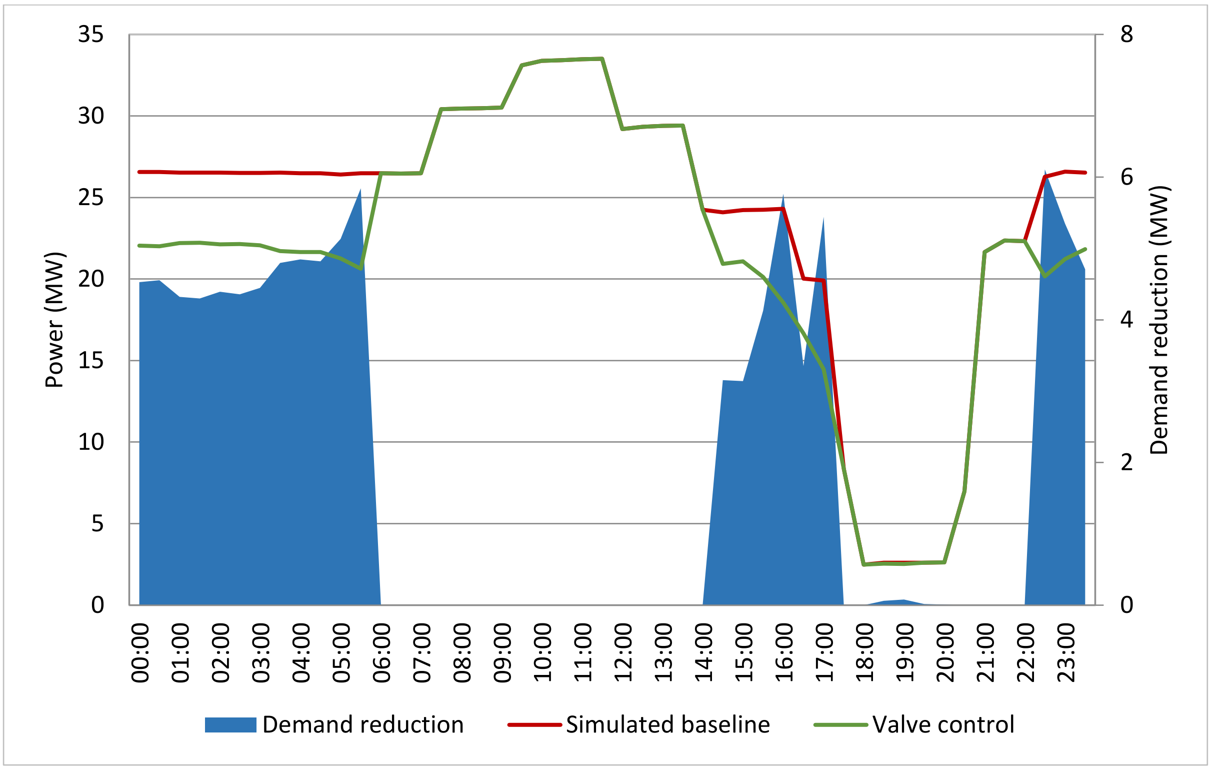


Figure 3-25: System B – valve control simulation results

Annual savings

Annual savings of R8.62 million were calculated from the simulation results. This fell in the range of R6.3 million – R9.8 million per annum, giving the annual savings of valve control a score of **4 out of 5**.

Payback period

Since control valves were not available on three of the four shafts on System B, quotations were obtained for three control valves. The total cost (including all installation and auxiliary equipment) with a 10% contingency was R4 million. Equation 2.10 was used to calculate the PBP, which was six months. The PBP fell in the range of 6–12 months given in the Likert scale in Table 2-6. This meant that valve control has a PBP score of **4 out of 5**.

Level of automation

Initially, the use of control valves required significant human intervention to create a control philosophy. However, once the control philosophy was operational, only occasional human intervention was required, which ensured that the control philosophy was as effective as possible and included contingencies when more compressed air was required during isolated incidents. The use of control valves was classified as having a moderate level of automation since it was automated, but required additional and occasional human intervention. Thus, it scored **3 out of 5** for the level of automation.

Implementation time

Since additional control valves had to be procured and installed on this system, the implementation time relied on several factors. Firstly, approval to start with procurement could only take place during a monthly meeting. For this reason, four weeks were allocated to the procurement time.

After the valves were approved, the order was placed for the valves to be manufactured, which could take up to 18 weeks. Hereafter, the valves could be installed, but installation had to take place on an off-weekend when the shaft could be closed temporarily. Two weeks were allocated for the installation time of each valve, since off-weekends typically occur bi-weekly. However, installation of the valves could not be conducted simultaneously, since specific mining personnel had to oversee the installation of each valve.

Consequently, six weeks were assigned to the total installation time (two weeks for each of the three valves). Once the valves were installed, any problems in their control philosophies had to be addressed and incremental improvements made. Four weeks were allocated to the optimisation time, which would allow ample time for the control philosophy and set points to be perfected.

An implementation time of 32 weeks was obtained by adding all the allocated times together. This implementation time fell in the range of more than 11.5 weeks from Table 2-6. Consequently, for the implementation time score, the use of control valves scored **1 out of 5**.

Table 3-13 gives the value, range and score for each implementation factor. The implementation score of using valve control on System B (as calculated with Equation 2.12 from Section 2.5.6) was **3.53**.

Table 3-13: System B – implementation factor scores for valve control

Implementation factor	Value	Range	Score out of 5
Annual savings	R8.62 M	R6.3 M – R9.8 M	4
PBP	6 months	6–12 months	4
Level of automation	Moderate	Moderate	3
Implementation time	32 weeks	> 11.5 weeks	1
		Implementation score:	3.53

3.3.4 Implementation priority

The implementation scores of four energy efficiency solutions were determined in the preceding section. This section focuses on the implementation of these energy efficiency solutions according to their implementation priority. Table 3-14 summarises the values for each of the four energy efficiency solutions' implementation factors and their subsequent implementation scores.

Table 3-14: System B – implementation factor values and implementation scores

Energy efficiency solution	**Annual savings**	**PBP**	**Level of automation**	**Implementation time**
Guide-vane control and schedule optimisation	R3.8 M –R6.3 M (3)	0–6 months (5)	Minimal (1)	5.5 - 8.5 weeks (3)
Smaller compressors	< R1.8 M (1)	0–6 months (5)	Significant (4)	> 11.5 weeks (1)
Network reconfiguration	Not feasible			
Valve control	R6.3 M - R9.8 M (4)	6–12 months (4)	Moderate (3)	> 11.5 weeks (1)

By using the scores for each factor determined above and the weights given in Equation 2.12 and Table 2-6, the implementation scores of the energy efficiency solutions were calculated. Subsequently, the energy efficiency solutions were ranked according to their implementation scores. The implementation priorities of the energy efficiency solutions are given in Table 3-15.

Table 3-15: System B implementation scores and priorities

Energy efficiency solution	**Implementation score (out of 5)**	**Implementation priority**
Schedule optimisation and guide-vane control	3.58	1
Smaller compressors	2.72	3
Network reconfiguration	0	Not to be implemented
Valve control	3.53	2

Table 3-15 shows that schedule optimisation and guide-vane control had the highest implementation score of 3.58, which meant that it had to be implemented first. This was followed closely by valve control with an implementation score of 3.53, which meant that it had to be implemented second. The use of smaller compressors had an implementation score of 2.85 and had to be implemented third. Network reconfiguration was not to be implemented.

3.3.5 Implementation of energy efficiency solutions

In the previous section, the implementation priorities of the various energy efficiency solutions were determined. This section discusses the actual implementation of said solutions according to their priorities. This discussion, however, is limited to the savings that were obtained and/or challenges that were experienced. The results are discussed at length later in the chapter.

Guide-vane control and schedule optimisation

Since schedule optimisation and guide-vane control had the highest implementation score, it was implemented first. The actual annual savings delivered were R4.4 million.

Control valves

The second energy efficiency solution implemented was valve control. Control valves were not available at three of the four shafts on System B and had to be procured and installed. A business case was created to motivate the installation, which was subsequently approved. At the time of writing, delivery of the compressed air valves was not completed due to shipping delays. This meant that valve control could only be implemented at one of the shafts (which is the smallest shaft on the ring), where the annual savings totalled R1 million.

A simulation was conducted on the savings potential of using this valve. When valve control was simulated on this shaft, the simulation results showed annual savings of R1.3 million. This is more than the actual savings of R1 million per annum that were achieved. Section 3.4.1 discusses possible reasons for this discrepancy.

Smaller compressors

The third energy efficiency solution to be implemented was that of using smaller compressors. Although there were L250 compressors available, there were complications with their piping, which the mine was addressing at the time of writing. The complications arose from the pipes being too small for supporting the combined flow of the L250 compressors. This resulted in a substantial pressure drop, which meant that the compressors could not feed into the network. As a result, the L250 compressors could not be put to use as an energy efficiency solution.

Network reconfiguration

The simulation model deemed that network reconfiguration was not a viable energy efficiency solution on System B. Therefore, network reconfiguration was not implemented. As with System A, this meant that neither time nor resources were wasted on feasibility studies for these projects.

3.3.6 Compounding effects of implemented energy efficiency solutions

The simulation model developed for System B can be used to determine what the compounding effects are of concurrent energy efficiency solutions. This section investigates what the effect is on the total power consumption when these energy efficiency solutions run in parallel.

As noted earlier, guide-vane control was the first energy efficiency solution to be implemented on System B. Thereafter, valve control and smaller compressors were to be implemented. The simulation results from the first of these (guide-vane control) can be used as inputs for the second (valve control). Hereafter, the simulation results for the valve control can be used as the inputs for the smaller compressors simulation.

Figure 3-26 visualises how the power consumption is impacted when guide-vane control, valve control and smaller compressors are compounded. The red line shows the baseline simulation, the green line shows the results for the compounded simulation. The blue area shows the compounded demand reduction when guide-vane control, valve control and smaller compressors are active. The total simulated annual savings are R11.9 million.

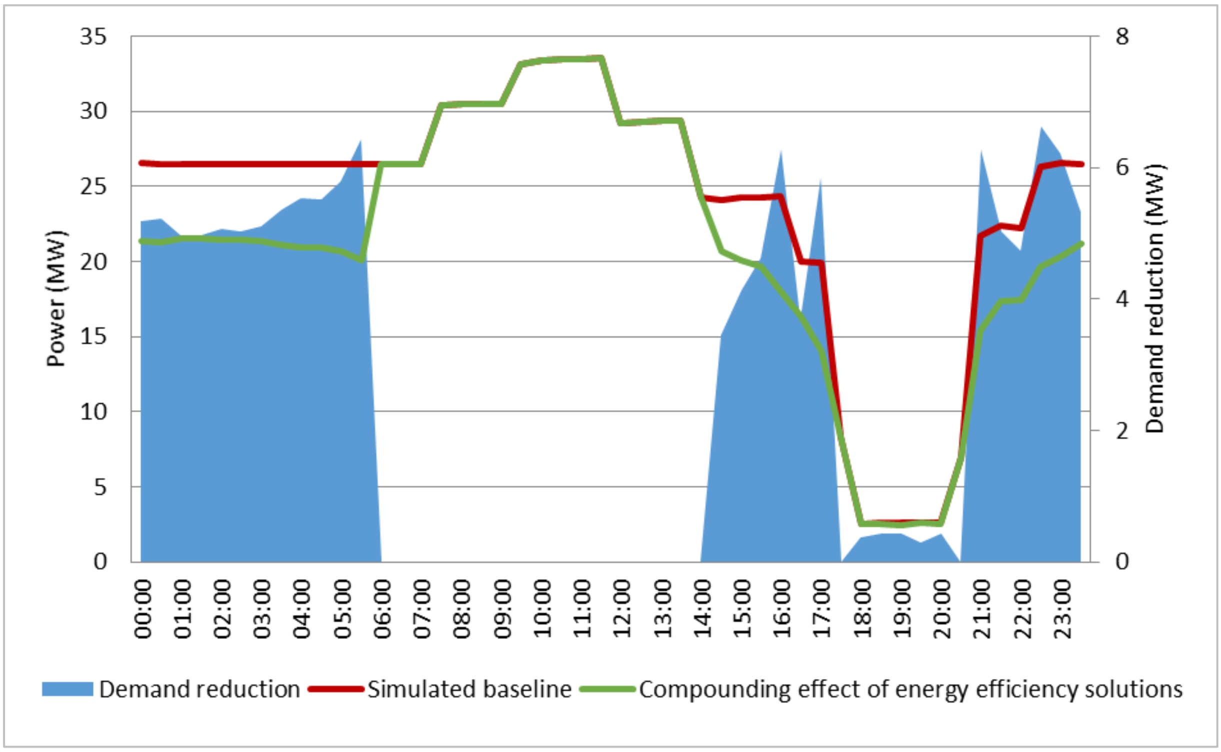


Figure 3-26: Compounding effect of energy efficiency solutions on System B

3.3.7 Summary

In this section, the implementation priority of four compressed air energy efficiency solutions was determined by using the methodology created in Chapter 2. The implementation scores of the energy efficiency solutions from best to worst were: guide-vane control and schedule optimisation scored 3.58 out of 5; valve control scored 3.53 out of 5; and using smaller compressors scored 2.6 out of 5.

The simulation results showed that reconfiguring the network could have benefitted some shafts, but that the drilling shift pressures of some shafts were affected adversely. Since the purpose of energy efficiency solutions in this study was to improve the compressed air efficiency but leave production unaffected, reconfiguring the network was not a suitable energy efficiency solution for System B.

The use of guide-vane control and schedule optimisation resulted in actual savings of R4.4 million per annum. Control valves were ordered, but at the time of writing these valves were still to be installed due to shipping delays. This meant that valve control could only be implemented at one shaft, where the annual savings amounted to R1 million. Also, at the time of writing, the smaller compressors were still in the process of being optimised and were therefore not put to use practically. Because network reconfiguration was not feasible, time and resources which would have been invested in calculations and feasibility studies were avoided.

Finally, the simulation model was used to determine the potential compounding savings of the energy efficiency solutions. It was shown that the total annual savings for guide-vane control, valve-control and smaller compressors could amount to R11.9 million per annum.

3.4 Discussion of results and validation

3.4.1 Discussion of results

The methodology that was developed in Chapter 2 was applied to two systems, namely System A and System B. Four energy efficiency solutions were investigated on both systems by using the methodology. The methodology showed that the use of guide-vane control was the most feasible energy efficiency solution when considering all the implementation factors. This energy efficiency solution delivered actual annual savings of R8.8 million and R4.4 million on System A and System B, respectively.

The reason the annual savings differed from the R10.46 million predicted by the simulation model for System A and the R5.6 million for System B is twofold. First, the simulation model was developed to match a day that resembled normal operation (as discussed in Section 2.2.5). The actual day-to-day operation differed from this. This same reason applies to the difference between the simulated and actual savings of controlling on the actual valves available. The second reason for these differences is that control room operators were tasked with implementing this energy efficiency solution. As a result of human error, guide-vane control was used too late or not to the required extent. This could have had a detrimental effect on the annual savings.

Another reason for differences in actual and simulated savings is the error band of the simulation model. Although the model was calibrated to have an error band of less than 5%, this error can still contribute to the difference between the actual and simulated savings.

The methodology showed that the use of valve control was the second energy efficiency solution to be implemented on both System A and System B. The respective annual savings predicted by the model were R17.85 million (System A) and R8.62 million (System B). These savings were more substantial than the savings from guide-vane control, which was the first energy efficiency solution to be implemented.

However, due to the substantial implementation time of valve control as an energy efficiency solution, the methodology showed that valve control had to be implemented only after using guide-vane control. The implementation times for System A and System B were nine months and eight months, respectively.

Actual savings could not be achieved entirely through valve control due to the long implementation time of the valves that were ordered. Shipping delays further lengthened the delivery time of the valves and they could not be installed at the time of writing. Consequently, practical savings could only be obtained on the valves that were already available. This amounted to savings of R7 million per annum on System A and R1 million per annum on System B.

The methodology showed that the use of smaller compressors was feasible on System B. However, due to this energy efficiency solution’s low annual savings, it was to be implemented only after guide-vane control and valve control. At the time of writing, the mine was in the process of addressing the incorrect piping on the L250 compressors, which prohibited these compressors from being used as an energy efficiency solution. The pipes connecting the compressors into the network were too small, which meant that the resultant pressure drop was too great. Therefore, the simulated annual savings of R0.36 million could not be verified practically with the implementation of the energy efficiency solution.

It was shown that network reconfiguration was not feasible on System A or System B because it affected the drilling shift pressures on the shafts negatively.

On both System A and System B, network reconfiguration was not implemented. This meant that time and resources were not needlessly spent on further investigations and feasibility studies.

The simulation model developed in this study was used on both systems to determine the possible benefit of the compounding effect of the energy efficiency solutions. This amounted to R35.1 million per annum for the two case studies.

3.4.2 Validation of results

As discussed above, the actual savings that were achieved with guide-vane control were less than that of the savings predicted by the simulation model. The difference was firstly attributed to the control room operators having to implement the control and, secondly, to the difference between the simulated and day-to-day operation. However, the methodology already accounted for human error since it considered the level of automation as one of the factors when evaluating energy efficiency solutions.

The compressed air valves were not installed due to delays in the shipping of the valves. The methodology successfully accounted for the long implementation times of valve control as energy efficiency solutions on both systems. Had the methodology not been applied and valve control was implemented first, savings for the control valves would only have been achieved at a later stage than first determined. Additionally, the energy efficiency solution of guide-vane control would have delivered savings later than first estimated.

Furthermore, because the energy efficiency solution of guide-vane control was implemented first (rather than valve control) and no capital expenditure was required, the savings obtained could be used to help fund the valves. This goes to show that guide-vane control was the correct energy efficiency solution to implement first since it allowed savings to be accrued whilst the control valves were still to be delivered.

It was shown that both energy efficiency solutions, namely reconfiguring the compressed air networks and using smaller compressors, were not feasible on System A. The same was true for network reconfiguration on System B. This meant that wasteful energy efficiency solutions were avoided and neither time nor money was wasted on implementing these energy efficiency solutions. More importantly, these energy efficiency solutions did not detract from the funding of the feasible energy efficiency solutions and did not occupy valuable resources. The compounding effects of these energy efficiency solutions were investigated and delivered substantial savings.

Therefore, the research objectives that were outlined in Chapter 1 are met. Not only were simulation models developed and verified, but these models were used to identify feasible energy efficiency solutions. Moreover, a method was developed which could successfully prioritise the implementation order of energy efficiency solutions. This method was able to avoid unfeasible energy efficiency solutions and prioritise the implementation of energy efficiency solutions. This enabled savings to be obtained in the shortest possible time with the smallest payback period.

To further validate this study, its results are compared with that of the study done by Maré *et al.* [73]. As noted earlier, these authors weighed several energy efficiency solutions against one another to determine which was the most feasible to implement. When the methodology developed in this dissertation is applied to the energy efficiency solutions that the authors considered, it identified an energy efficiency solution to implement. It had a shorter payback period and a shorter implementation time, although its average power savings was slightly less than the other solution. This solution is selected above the other feasible solution because the payback period, annual savings, implementation time and level of automation are considered. The authors implemented the same solution as this dissertation's methodology suggested, therefore, they implemented the correct energy efficiency solution.

3.5 Application: industry benefit

There are 26 platinum mining groups in South Africa [85], as shown in Figure 3-27. Although hydraulic systems are found at some of these mines, compressed air is used at most of them [50].

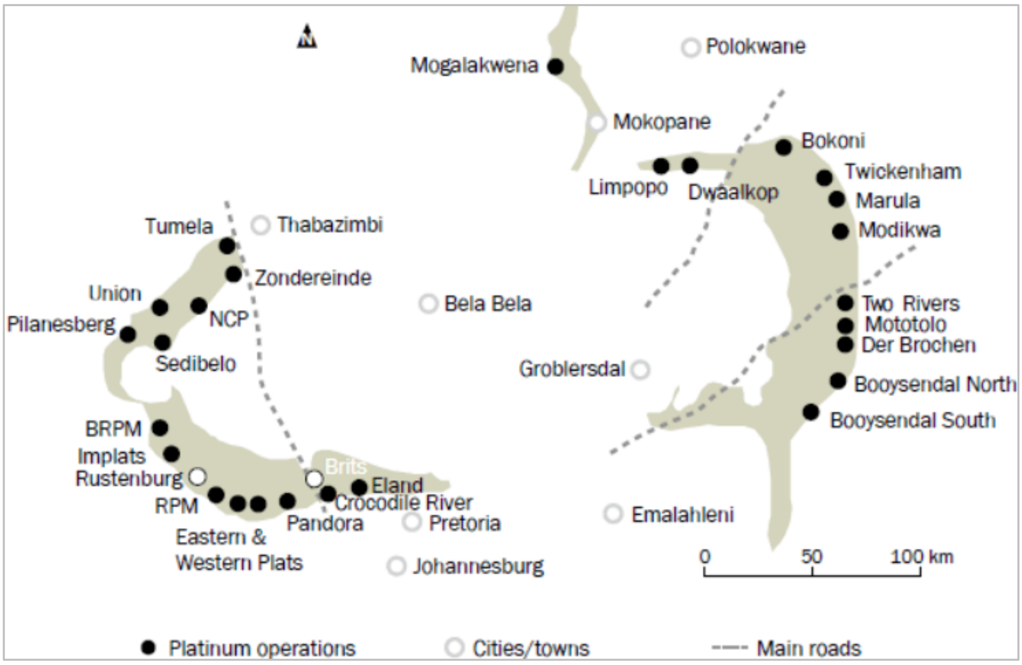


Figure 3-27: Platinum mines in South Africa [85]

The potential impact on the South African platinum industry can be calculated when the following assumptions are made:

- The 26 PGM operations are all 75% of the size of the mining group used in the two case studies.
- 50% of the savings obtained in this study can be obtained.

In the two case studies in this study, the total savings due to the compounding effect of the energy efficiency solutions predicted by the simulation model amounted to a total of R35.1 million per annum. When the aforementioned assumptions are made, the total potential savings in the South African platinum industry can be calculated as roughly R342 million per annum. Furthermore, the industry will benefit from not spending valuable resources and time on conducting manual calculations and feasibility studies for projects that are not feasible.

3.6 Summary

The purpose of this chapter was to provide results from two case studies to test the methodology developed in Chapter 2. The two case studies were conducted on two compressed air rings of a South African platinum mining group. System A is a large compressed air ring that consists of a processing plant and seven shafts, which are fed by 19 compressors. System B is a smaller compressed air ring with four shafts and 11 compressors. Simulation models were developed for both systems, which were verified by ensuring that all components met the predetermined criteria. The simulation models were used in conjunction with the methodology developed in Chapter 2 to investigate the effect of four energy efficiency solutions and, subsequently, to determine their implementation priority.

On System A, the use of guide-vane control was the most feasible energy efficiency solution and amounted to actual annual savings of R8.8 million. The second energy efficiency solution implemented was the use of valve control. The simulation results showed potential annual savings of R17.6 million, but this could only be achieved partially due to shipping delays on the valves. The total savings of the shafts where valves were already available amounted to R4 million per annum. The simulation results showed that reconfiguring the network and using smaller compressors were not feasible on System A, since both would hinder production.

On System B, the energy efficiency solutions to be implemented, ranked from highest to lowest priority, were guide-vane control and schedule optimisation, followed by valve control and then smaller compressors. The guide-vane control amounted to actual savings of R4.4 million per annum. The simulation results showed potential annual savings of R8.62 million for valve control. R1 million annual savings were achieved on the shaft where a control valve was already available. Delivery of the other three valves was pending at the time of writing. The simulation results predicted annual savings of R0.36 million per annum with the use of smaller compressors. However, due to the installed pipes being too small, the smaller compressors could not be used. It was shown that reconfiguring the network was not feasible on System B since it would affect production negatively.

After the implementation priorities of the energy efficiency solutions were determined on both case study systems and the implementation of the energy efficiency solutions were discussed, a critical discussion of the case study results followed. Here, limitations in the results were noted and the success of the methodology was underlined. Hereafter, the results were validated.

Finally, the potential benefit of the methodology was discussed when it is extrapolated to the South African platinum industry as a whole. It was estimated that savings of R342 million per annum could be obtained.

CHAPTER 4 – CONCLUSION

4.1 Preamble

The purpose of this chapter is to provide a synopsis of the study. Key findings from each of the previous chapters are highlighted and the accomplishment of the research objectives is substantiated. Finally, the study limitations are noted and recommendations are made for future work.

4.2 Summary of study

The South African platinum mining industry is facing several challenges – the most prominent being the above-inflation increase in operational costs. This increase in operational costs is further incited by significant increases in electricity tariffs. The generation of compressed air accounts for large percentages of the electricity expenditure of platinum mines, which, in turn, accounts for a large part of the operational costs.

Not only is compressed air generation a large expense on platinum mines, but these systems are also often managed inefficiently. This makes compressed air systems ideal candidates for implementing energy efficiency solutions that aim to improve their efficiency and, consequently, reduce the expenditure on compressed air generation.

Several energy efficiency solutions exist to do so, as proven in the literature review. These solutions include guide-vane control, compressor schedule optimisation, leak repairs, the use of smaller compressors, network reconfiguration, and valve control. A prominent omission to the literature, however, was the lack of prioritisation of these methods. Therefore, the problem statement was that when mines are tasked with implementing energy efficiency solutions, there was no clarity regarding the order in which these solutions must be implemented.

Recent advances in simulation software mean that it can be used to model compressed air systems accurately. It has been shown that simulation can be used to various extents in compressed air systems, where most studies considered used simulation to determine the effect that energy efficiency solutions would have on a compressed air system.

When considering the lack of clarity regarding the prioritisation of energy efficiency solutions during their implementation and the accurate modelling of compressed air systems by means of simulation, the research objective was identified. The primary objective of this study was to create a methodology that uses simulation to prioritise the implementation order of energy efficiency solutions. For this to be achieved, the following study objectives were to be addressed:

- Create and verify simulation models.
- Identify feasible energy efficiency solutions by using simulation model.
- Develop method to determine impact of energy efficiency solutions and prioritise their implementation order.

To meet these objectives, a four-step methodology was developed in Chapter 2. The first step was to analyse the system. Thereafter, the second and third steps were to create and verify the simulation models, respectively. The final (and most critical) step was to determine the priority of the energy efficiency solutions and to implement the energy efficiency solutions accordingly. This step entailed quantifying the effect of an energy efficiency solution on the system by using the simulation model. Thereafter, the annual savings and PBP, level of automation and implementation time were to be determined. All these factors were weighted according to a Likert scale, which was used to determine the implementation score. The implementation score was subsequently used to determine the implementation priority of the energy efficiency solutions.

The methodology was applied to two case study compressed air systems on a South African platinum mine group. Simulation models were created for both compressed air systems, namely System A and System B. Both simulation models were calibrated according to the methodology from Chapter 2, with percentage errors of less than 5% and coefficients of determination of 0.9 or higher (where applicable).

On System A, the methodology showed that guide-vane control was the most feasible energy efficiency solution to implement when the four factors were considered. Actual savings of R10.46 million per annum were predicted by the simulation model, of which R8.8 million per annum was realised. According to the methodology, the second energy efficiency solution to implement was that of valve control. Here, the simulation model predicted annual savings of R17.85 million. At the time of writing, delivery and installation on the valves were still pending; therefore, these savings could only be realised on the shafts where control valves were already available. This amounted to savings of R7 million per annum. The methodology showed that both using smaller compressors and reconfiguring the compressed air network were not feasible on System A.

The methodology delivered a similar implementation priority for System B. In this system's case study, guide-vane control was also the first energy efficiency solution to be implemented and projected simulated potential annual savings of R5.6 million. In reality, R4.4 million savings were achieved per annum. The second energy efficiency solution to be implemented was valve control, where annual savings of R8.62 million per annum were predicted. As with System A, System B’s valves were still in the process of being delivered at the time of writing; therefore, the savings could not be realised fully. The one shaft where valve control was available resulted in annual savings of R1 million per annum.

Implementing smaller compressors was the third energy efficiency solution that was prioritised. The simulation results showed annual savings of R0.36 million if ten L250 compressors were to be used in lieu of the VK32 compressor during the drilling shift. This, unfortunately, could not be realised due to the pipes feeding the compressors into the network being too small.

The simulation model was used to predict the annual savings due to the compounding effect of the energy efficiency solutions. This amounted to R35.1 million per annum over the two case studies. The potential benefit of the methodology was extrapolated to the South African platinum industry at large and annual savings of R342 million were calculated.

When considering the objectives that were outlined for the study, simulation models were created and verified to be accurate. These simulation models were used to determine which energy efficiency solutions would be feasible. Furthermore, a method was developed and used to prioritise the implementation order of the energy efficiency solutions. This not only meant that unfeasible energy efficiency solutions were avoided, but also that the most feasible energy efficiency solutions were implemented first. To further validate the methodology, it was applied to the energy efficiency solutions of a past study. The methodology developed in this dissertation provided the same energy efficiency solution to implement as that which the authors of the past study implemented.

Not only can this methodology benefit the industry by ensuring that the most feasible energy efficiency solutions are implemented to deliver maximum savings, but it can also help to avoid energy efficiency solutions that are not feasible. In other words, valuable time and resources will not be wasted on such energy efficiency solutions. Hence, the research objective has been accomplished. Nevertheless, there were limitations to this study, as well as recommendations that are made for future work. These are discussed in the next section.

4.3 Study limitations and recommendations

A prominent limitation in this study was the delayed availability of the control valves due to shipping delays. A simulation investigation was done on how the simulation results of controlling with the existing valves differ from that of the actual control. However, it is recommended that the simulated annual savings from using the control valves are determined practically once the valves have been installed.

This study only investigated the combined effect of energy efficiency solutions theoretically. Therefore, it is recommended that a follow-up study determines what the actual effect on the system is when all the energy efficiency solutions are active.

Due to the unpredictability of electricity cost inflation, the effect of cost inflation on the PBP was disregarded. However, it is recommended that this effect is investigated since it may improve the feasibility of long-term energy efficiency solutions, especially those with longer PBPs.

This study considered the effect of an energy efficiency solution on a compressed air ring as a whole, rather than on specific shafts. It is recommended that the scale ranges that are used to weigh energy efficiency solutions are expanded so that they can be used on a per-shaft basis.

It is further recommended that the five-point Likert scale used in this study for weighing different factors of energy efficiency solutions be expanded to a ten-point Likert scale. This will allow for an even greater distinction to be made between energy efficiency solutions, which, in turn, should result in more accurate decision-making. This study used literature to back the ranges used in the Likert scale, but it is recommended that a comprehensive meta-analysis is conducted to further improve on the ranges.

Furthermore, this study focused on how the implementation order of energy efficiency solutions must be prioritised. However, finite human resources were available for implementing said solutions. Therefore, it is recommended that a follow-up study be conducted that investigates how personnel and/or resources must be distributed to ensure maximum savings in the minimum amount of time.

Leak management as an energy efficiency solution was not considered in this study because it has to be done in perpetuity. However, it is recommended that the methodology developed in this study be used for leak management and other energy efficiency solutions.

Finally, it is recommended that a follow-up study is conducted on the effect of measuring equipment on simulation accuracy. This can further increase the accuracy of simulation models by mitigating discrepancies between actual and simulated values. However, according to Table 2-4, the error bands of said equipment are negligible.

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APPENDIX A MEAN RESIDUAL DIFFERENCE METHOD

This appendix details how the mean residual difference (MRD) method works. In the MRD method, the error is calculated as the difference between the actual data and the simulated data, as shown in Equation A-1.

Equation A-1: MRD

$$MRD = \left| \frac{1}{N} \times \sum_{n=1}^{N} (A_n - S_n) \right|$$

Where

MRD	=	Mean residual difference	[–]
N	=	Total number of data points	[–]
n	=	Data point	[–]
A	=	Actual data points	[–]
S	=	Simulated data points	[–]

The subsequent percentage error is calculated as the error divided by the actual data point's value. This is shown in Equation A-2.

Equation A-2: MRD error percentage

$$Error\% = \left| \frac{1}{N} \times \sum_{n=1}^{N} \left(\frac{A_n - S_n}{A_n} \right) \right| \times 100$$

Where

N	=	Total amount of data points	[–]
n	=	Data point	[–]
A	=	Actual data points	[–]
S	=	Simulated data points	[–]
$Error\%$	=	Relative percentage of error	[%]

APPENDIX B DETERMINING FACTOR WEIGHTS AND RANGES

Appendix B-1 Calculating implementation factor weights

Saaty [86] proposed an analytic hierarchical process for determining the weights of multiple factors. This process is summarised as follows (adapted from [86]):

1. Determine the problem and the desired knowledge.
2. Create a decision hierarchy as follows:
    a. Define the goal of the decision at the top.
    b. Define the objectives from a broad perspective.
    c. Define the factors that form the basis of subsequent elements.
    d. If applicable, define alternatives.
3. Create pairwise matrices for comparison, where each element in the top level is used to compare the elements in the respective level immediately below it.
4. Use the comparisons to weigh the measures of importance in the levels immediately below.

For instance, *Item I*, *Item j* and *Item k* can be compared by using the following pairwise comparison matrix, which can be expanded to include more items.

$$\begin{array}{cc} & \begin{array}{ccc} \text{Item } i & \text{Item } j & \text{Item } k \end{array} \\ \begin{array}{c} \text{Item } i \\ \text{Item } j \\ \text{Item } k \end{array} & \left[\begin{array}{ccc} 1 & \text{Importance of } i \text{ over } j & \text{Importance of } i \text{ over } k \\ \text{Importance of } j \text{ over } i & 1 & \text{Importance of } j \text{ over } k \\ \text{Importance of } k \text{ over } i & \text{Importance of } k \text{ over } j & 1 \end{array}\right] \end{array}$$

Table B-1 details a scale of 1 to 9 for determining the importance of one item over another [84].

Table B-1: Scale to establish dominance in item comparisons (adapted from [84])

Importance	Definition	Explanation
1	*Similar importance*	Both items have equal contributions to the end goal
2	*Weak*	
3	*Moderate importance*	Judgement and experience forecast that one item will contribute slightly more to the goal than the other

Importance	Definition	Explanation
4	*Moderate plus*	
5	*Strong importance*	Judgement and experience favour one item strongly over another
6	*Strong plus*	
7	*Very strong or demonstrated importance*	One item is very strongly favoured over the other item
8	*Very, very strong*	
9	*Extreme importance*	Evidence affirms that one item is to be absolutely favoured over another
Reciprocals of assigned importance	If *Item I* has one of the integers above assigned to it when compared with *Item j*, then *Item j* has the reciprocal value when compared with *Item i*	This is a reasonable assumption to make, since the preference of *Item I* compared with *Item j* should be the inverse of *Item j* compared with *Item i*

The item importance of 2, 4, 6 or 8 is used if one item's dominance over another falls between the predetermined ranges.

Suppose *Item I* is very strongly favoured over *Item j* and slightly more than *Item k,* then, per Table B-1, *Item I* has respective measures of importance of 7 and 3 when compared with *Item j* and *Item k*. Furthermore, suppose that *Item k* is strongly favoured over *Item j*, *Item k* would then have a measure of importance of 5 when compared with *Item j*. As noted in Table B-1, the inverse of the priorities would mean a reciprocal of the measures of importance. This is subsequently filled into the matrix as follows:

$$\begin{array}{cc} & \begin{array}{ccc} Item\ i & Item\ j & Item\ k \end{array} \\ \begin{array}{c} Item\ i \\ Item\ j \\ Item\ k \end{array} & \begin{bmatrix} 1 & 7 & 3 \\ 1/7 & 1 & 1/5 \\ 1/3 & 5 & 1 \end{bmatrix} \end{array}$$

First, the matrix is raised to a high power. For the sake of simplicity, the matrix used in this example is squared, but the methodology remains the same.

$$\begin{array}{cc} & \begin{array}{ccc} Item\ i & Item\ j & Item\ k \end{array} \\ \begin{array}{c} Item\ i \\ Item\ j \\ Item\ k \end{array} & \begin{bmatrix} 3 & 29 & 37/5 \\ 37/105 & 3 & 29/35 \\ 29/21 & 37/3 & 3 \end{bmatrix} \end{array}$$

Thereafter, each row and the entire matrix are summated.

$$\begin{array}{cc}
 & \begin{array}{cccc} Item\ i & Item\ j & Item\ k & \end{array} \\
\begin{array}{c} Item\ i \\ Item\ j \\ Item\ k \end{array} & \begin{bmatrix} 3 & 29 & 37/5 \\ 37/105 & 3 & 29/35 \\ 29/21 & 37/3 & 3 \end{bmatrix}
\end{array}
\begin{array}{c} Row\ total \\ 69.500 \\ 4.181 \\ 16.714 \\ \hline \mathbf{90.395} \end{array}$$

The weight for each item is calculated by dividing the row total by the total of the matrix. These answers are given in Table B-2.

Table B-2: Weights of example comparison

Item	**Weight**
$Item\ i$	76.88%
$Item\ j$	4.63%
$Item\ k$	18.49%

Appendix B-2 Implementation factor weight calculations

The pairwise comparison matrix discussed in Appendix B-1 was used to calculate the weights of the factors used in this study to determine an energy efficiency solution's feasibility (as discussed in Section 2.5). The implementation factors used in this study were:

- Annual savings.
- Payback period (PBP).
- Level of automation.
- Implementation time.

Each factor was compared individually with the other factors to establish the comparison matrix. By using the scales in Table B-1, the factors were compared and assigned scores by making use of available literature and from consulting experienced mining personnel. The factors are compared as follows:

Annual savings vs PBP

As illustrated in the literature review (Section 1.3 and 1.4), annual savings were consistently mentioned to underline the success of a project and were the most prominent indicator of a project's performance. Once a project's cost has been covered by its savings, the PBP is reached and is not considered any more. This means that any benefits after the payback period are not considered [87]. However, the PBP of a project is a key factor when energy efficiency solutions are considered [88]. Therefore, the factor of annual savings has a "*similar importance"* (from Table B-1) to PBP and consequently has a score of 1 when compared with the PBP.

Annual savings vs level of automation

As noted above, annual savings is an important consideration to measure the success of an energy efficiency measure. A low level of automation detracts from a mine's productivity [89], therefore, it can result in a decreased impact of an energy efficiency solution. Conversely, Vermeulen [52] states that a low level of automation leads to constant supervision, and also lower infrastructure cost. For these reasons, the factor of annual savings was favoured between moderately and strongly ("*moderate plus"* from Table B-1) over the level of automation and has a score of 4 when compared with the level of automation.

Annual savings vs implementation time

Annual savings have a large influence on a project's feasibility, as mentioned earlier. When considering a long-term energy efficiency solution, savings accumulate continuously, whilst the implementation time only delays the initial savings. As time progresses, the impact of the implementation time decreases continuously [90]. Thus, the factor of annual savings was strongly favoured ("*strong importance*") over the implementation time, giving it a score of 5.

PBP vs level of automation

The PBP of a project is vital when projects are being considered, as noted earlier. However, it was found that when the ownership of projects change, it can lead to the project being less efficient, or even failing [88]. In other words, when a project is reliant on human intervention (low level of automation) it can become less effective over time. For this reason, PBP was only slightly favoured ("*moderate importance"*) and had a score of 3.

PBP vs implementation time

When mines initially consider energy efficiency solutions, PBP is a vital consideration [88]. However, implementation time has a direct bearing on how long the PBP is delayed [90]; therefore, the PBP was only favoured between slightly and strongly ("*moderate plus*" and was assigned a score of 4.

Level of automation vs implementation time

Projects with low levels of automation and short implementation times can be used to fund projects with higher levels of automation, which are often more expensive [51]. For this reason, implementation time was slightly preferred ("*moderate importance*") over level of automation. Therefore, implementation time had a score of 3 when compared with level of automation.

By considering the above and the rule that the preference of *Item i* over *Item j* is the reciprocal of the preference of *Item j* over *Item i*, the pairwise comparison matrix was constructed as follows:

$$\begin{array}{c c} & \begin{array}{cccc} Annual\ savings & PBP & Level\ of\ automation & Implementation\ time \end{array} \\ \begin{array}{c} Annual\ savings \\ PBP \\ Level\ of\ automation \\ Implementation\ time \end{array} & \begin{bmatrix} 1 & 1 & 4 & 5 \\ 1 & 1 & 3 & 4 \\ 1/4 & 1/3 & 1 & 1/3 \\ 1/5 & 1/4 & 3 & 1 \end{bmatrix} \end{array}$$

By raising the matrix to a high power, summating the rows, and dividing the summation by the total sum of the matrix (as discussed in Appendix B-1), the priority for the weights used in this study was calculated. They are given in Table B-3 as follows:

Table B-3: Weights of implementation factors used in study

Implementation factor	Weight
$Annual\ savings$	42%
PBP	37%
$Level\ of\ automation$	8%
$Implementation\ time$	13%

Appendix B-3 Determining implementation factor ranges

Appendix B-2 elaborated on how the implementation factors, which were used to evaluate the energy efficiency solutions in this study, were weighted. These weights were used to compare different energy efficiency by using a Likert scale. This section elaborates on how the ranges in the Likert scale in Table 2-6 were established. For all the factors, the best possible result received a score of 5, whilst the worst possible result received a score of 1. A standard or moderate performance was assigned a 3, which was used as the middle score. Scores of 2 and 4 were used as slightly lower and slightly higher than standard performance, respectively.

Annual savings

The annual savings of all the studies that were investigated in the literature review were considered. These annual savings were divided into five intervals by using percentiles. Values lower than the 20th percentile will be assigned a score of one. Values between the 20th and the 40th percentile will be a score of 2. Values between the 40th percentile and the 60th percentile and values between the 60th and the 80th percentile will respectively be assigned a score of 3 and 4. Values above the 80th percentile will be assigned a score of 5.

All of the studies considered in the literature review (Section 1.3 and Section 1.4) are given in Table B-4 in the order of ascending annual savings. As in the literature review, these savings are given in 2020 terms.

Table B-4: Annual savings of studies considered in literature review

Study	Study	Year	Annual savings
Mathews *et al.*	[45]	2019	R1,100,000
Friedenstein *et al.*	[50]	2018	R1,500,000
Maré *et al.*	[73]	2017	R1,800,000
Pascoe *et al.*	[25]	2017	R2,400,000
Deysel *et al.*	[28]	2015	R3,300,000
Jonker *et al.*	[65]	2017	R3,900,000
Vermeulen *et al.*	[52]	2017	R4,300,000
Shaw *et al.*	[54]	2019	R4,800,000
Fouche	[61]	2016	R6,300,000
Booysen *et al.*	[64]	2010	R6,800,000
Friedenstein *et al.*	[50]	2016	R7,800,000
Pascoe *et al.*	[25]	2017	R9,800,000
Marais	[32]	2012	R12,800,000
Bredenkamp	[47]	2014	R13,800,000

By dividing the annual savings of the studies from Table B-4 into the percentile intervals described above, the intervals can be obtained. This is shown in Table B-5.

Table B-5-: Score ranges for annual savings

Score	Percentile	Range
1	< 20th percentile	< R1.8 M
2	20th – 40th percentile	R1.8 M – R3.8 M
3	40th – 60th percentile	R3.8 M – R6.3 M
4	60th – 80th percentile	R6.3 M – R9.8 M
5	>80th percentile	> R9.8 M

Payback period

Jansen van Rensburg [88] states that new projects should ideally have a PBP of twelve months or less. However, according to Vermeulen [51], the PBP of a demand-side management project is approximately 15 months. Energy efficiency solutions with a PBP in the region of 15 months (12–18 months) were assigned a score of 3. The other scores were assigned in six-month intervals to either side.

Level of automation

Shaw [54] described a situation where a lack of automation existed and required all of the following:

1. Dedicated personnel,
2. Fast action and
3. Continuous check-ups

These three criteria will be used to score the level of automation according to how many criteria are applicable, if any. Table B-6 shows how the different levels of automation will be determined. For instance, if an energy efficiency solution requires dedicated personnel and continuous check-ups, but not fast action, it will adhere to two of the three criteria, and will have a minimal level of automation according to the table above. This will give it a score of 2 out of 5 for the level of automation.

Table B-6-: Ranges for level of automation

Criteria applicable	**Level of automation**	**Score**
All three criteria	None	1
Any two of the criteria	Minimal	2
Any one criterion	Moderate	3
No criteria	Significant	4
No criteria, nor any external inputs whatsoever (completely automated)	Maximum	5

Implementation time

The average implementation time for a DSM project is roughly 7 weeks (in calendar days) [51]. This will be used to distribute five ranges of implementation times in roughly equal intervals. Implementation times close to 7 weeks (between 5.5 weeks and 8.5 weeks will be assigned a score of three. This is a 3 week interval. Then, 3 week intervals to either side will respectively be assigned scores of 4 (between 2.5 and 5.5 weeks) and 2 (between 8.5 weeks and 11.5 weeks). Implementation times between 0 and 2.5 weeks will be assigned a score of five, whilst implementation times longer than 11.5 weeks will be assigned a score of one.

Table B-8 provides a summary of the implementation time ranges, scores and the interval sizes.

Table B-8: Ranges for implementation time

Implementation time	0 weeks - 2.5 weeks	2.5 weeks - 5.5 weeks	5.5 weeks - 8.5 weeks	8.5 weeks - 11.5 weeks	> 11.5 weeks
Score	1	2	3	4	5
Interval size	2.5 weeks	3 weeks	3 weeks	2.5 weeks	N/A

The ranges for all the implementation factors discussed above are summarised in Table B-9.

Table B-9: Summary of ranges used for the Likert scale

Factor	**Score**				
	1	**2**	**3**	**4**	**5**
Annual savings	< R1.8 M	R1.8 M – R3.8 M	R3.8 M – R6.3 M	R6.3 M – R9.8 M	> R9.8 M
PBP (months)	> 24	18–24	12–18	6–12	0–6
Level of automation	None	Minimal	Moderate	Significant	Maximum
Implementation time (weeks)	> 11.5	8.5-11.5	5.5-8.5	2.5-5.5	0-2.5

APPENDIX C OVERVIEW OF CASE STUDY SYSTEMS

Appendix C-1 Temperature and relative humidity profile

Figure C-1 shows the average temperature and relative humidity profile during 2019 used in this study for System A and System B. The solid blue line shows the ambient temperature throughout the day, whilst the dashed red line represents the relative humidity.

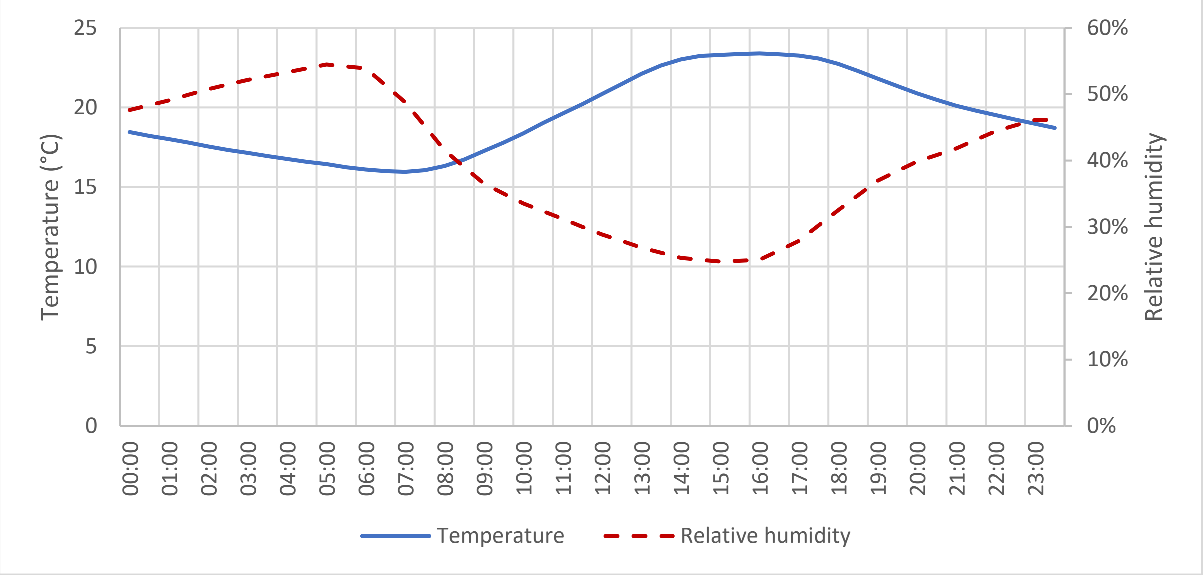

Figure C-1: Temperature and relative humidity profile for simulation (adapted from [91], [92])

Appendix C-2 System A layout and SCADA view

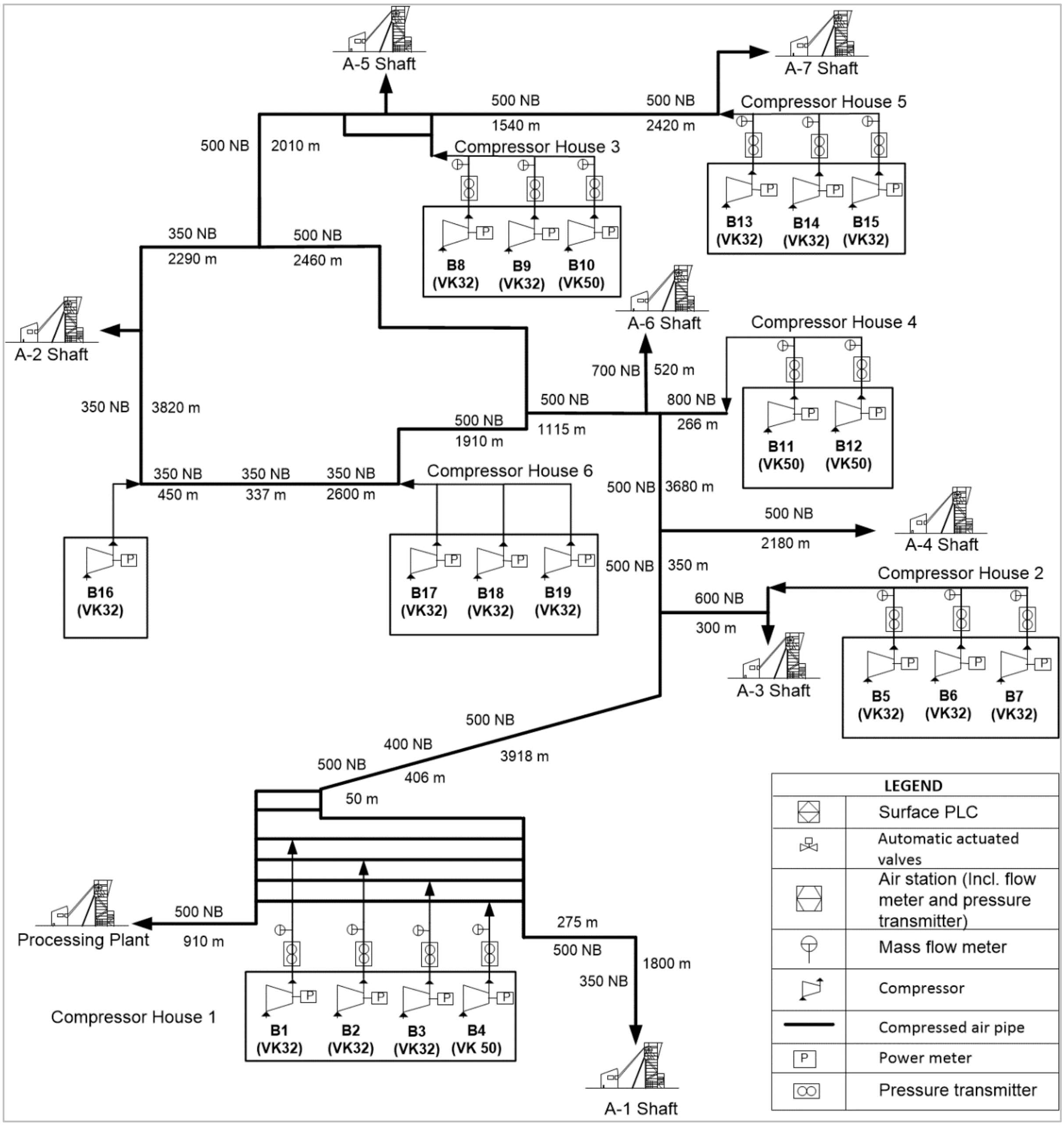

Figure C-2: System A – compressed air layout

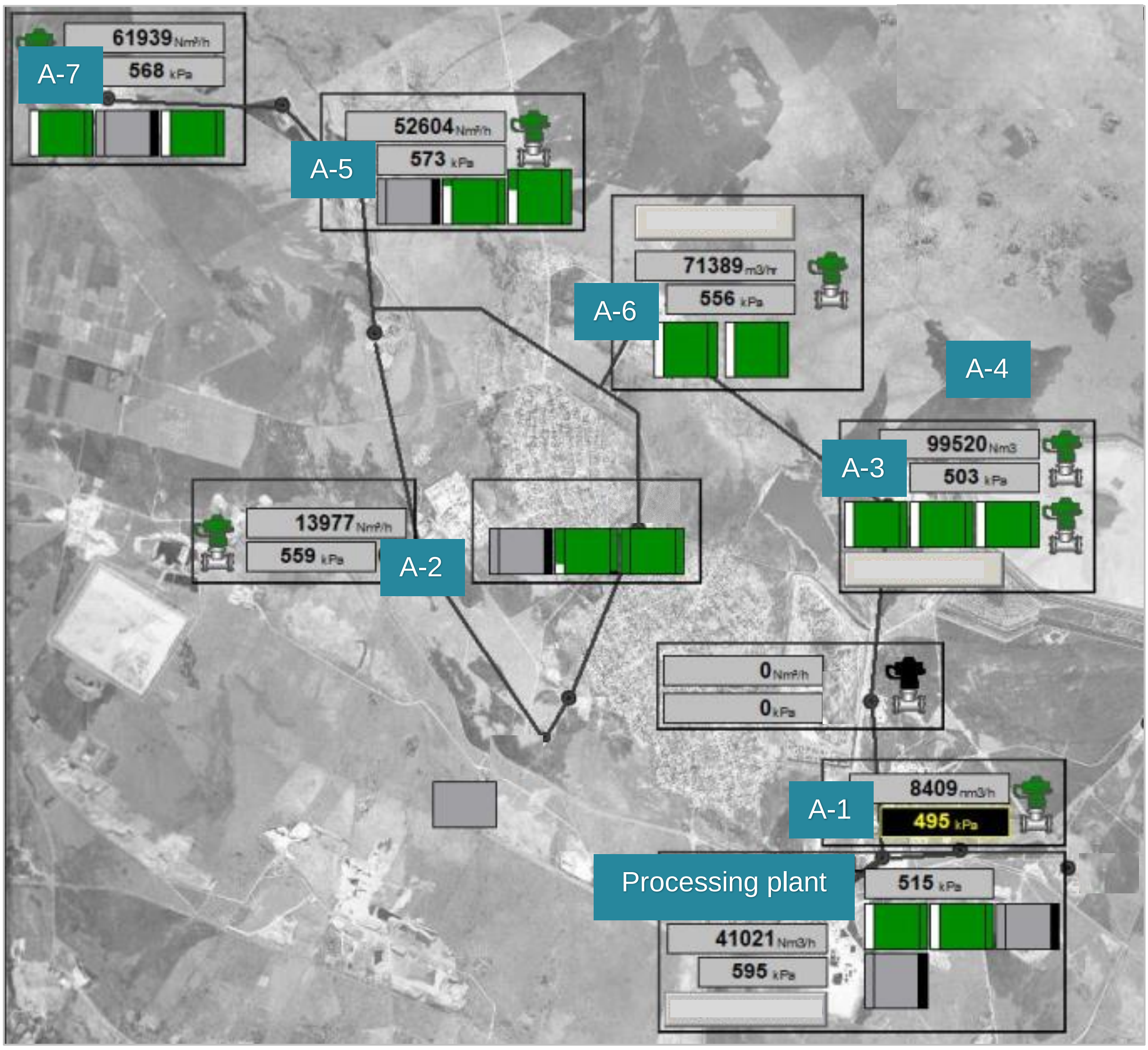

Figure C-3: System A – SCADA view

Appendix C-3 System B layout and SCADA view

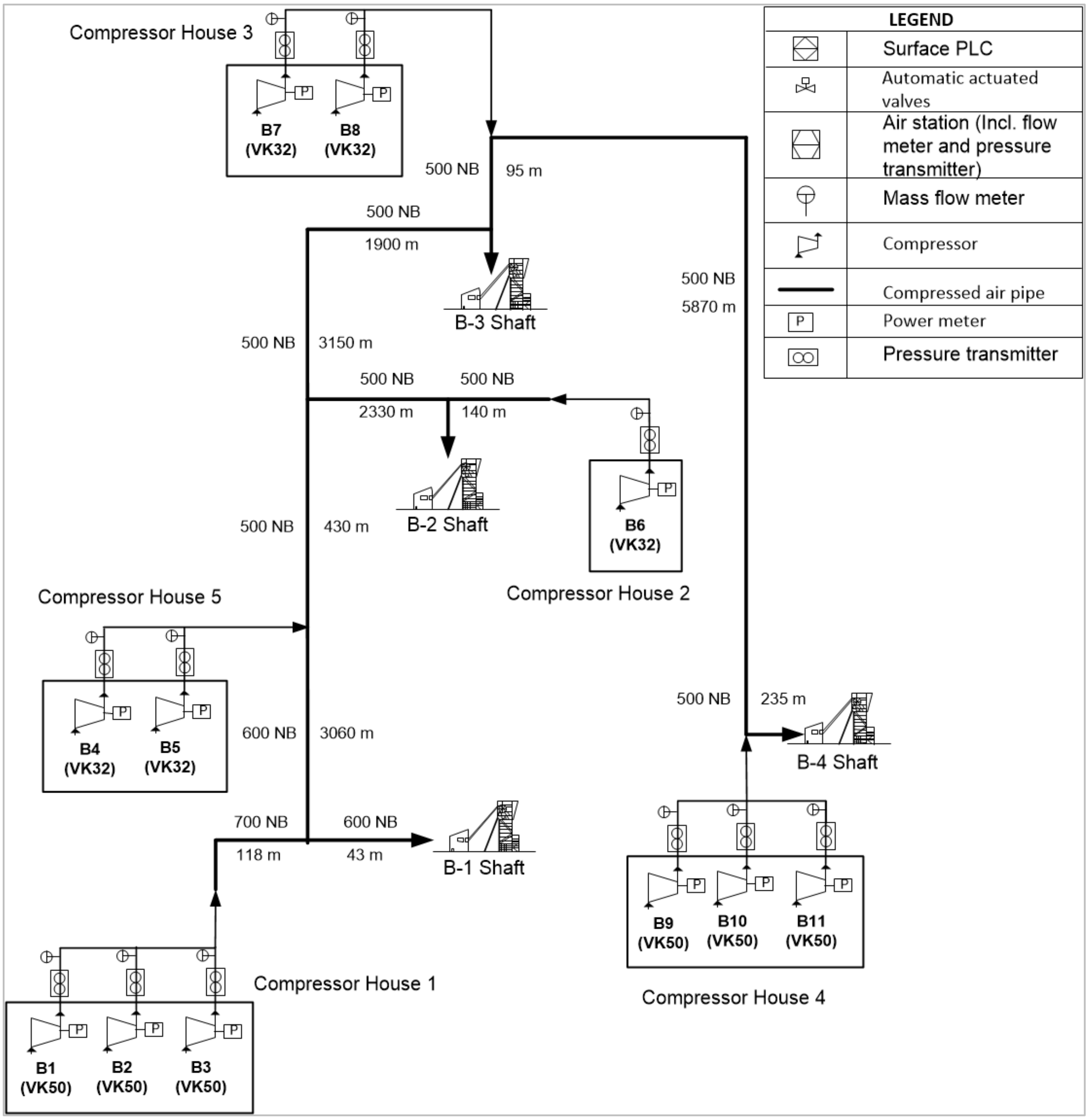

Figure C-4: System B – compressed air layout

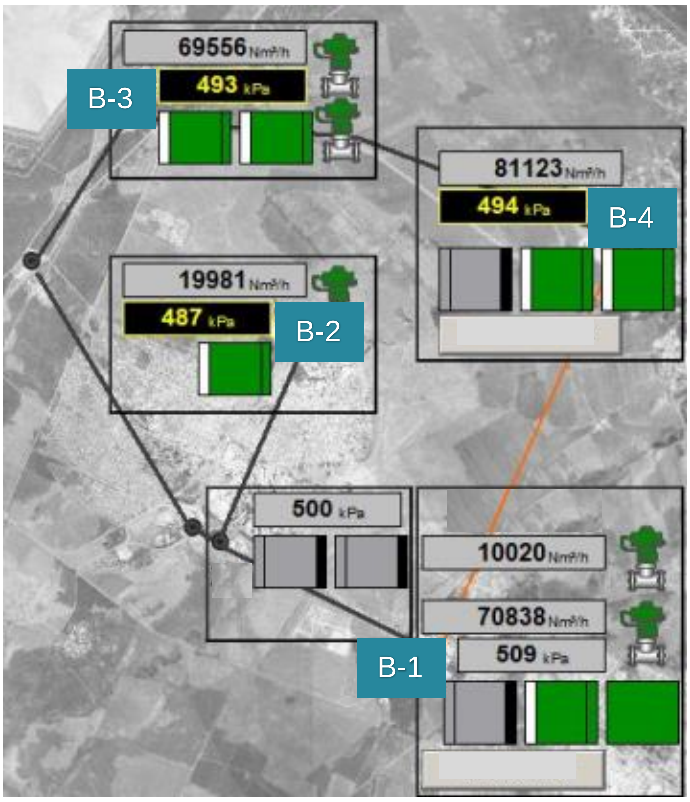

Figure C-5: System B – SCADA view

APPENDIX D SIMULATION MODELS

Appendix D-1 System A simulation model

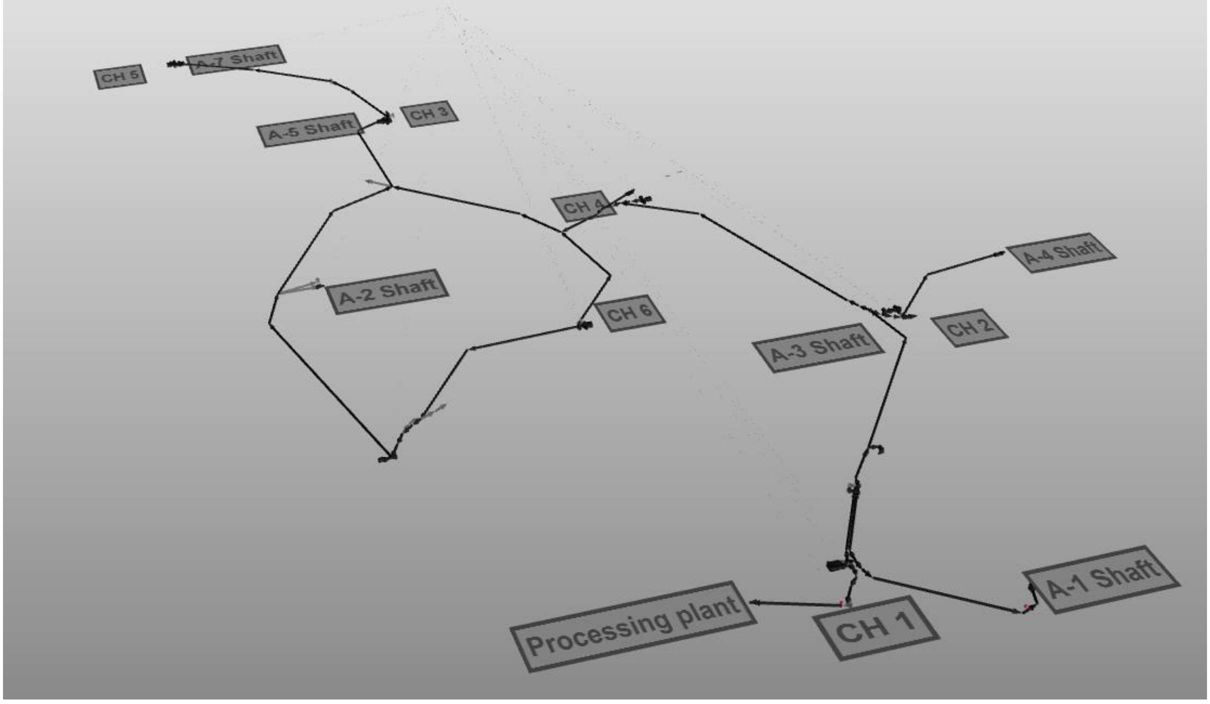

Figure D-1: System A –view of overall simulation model

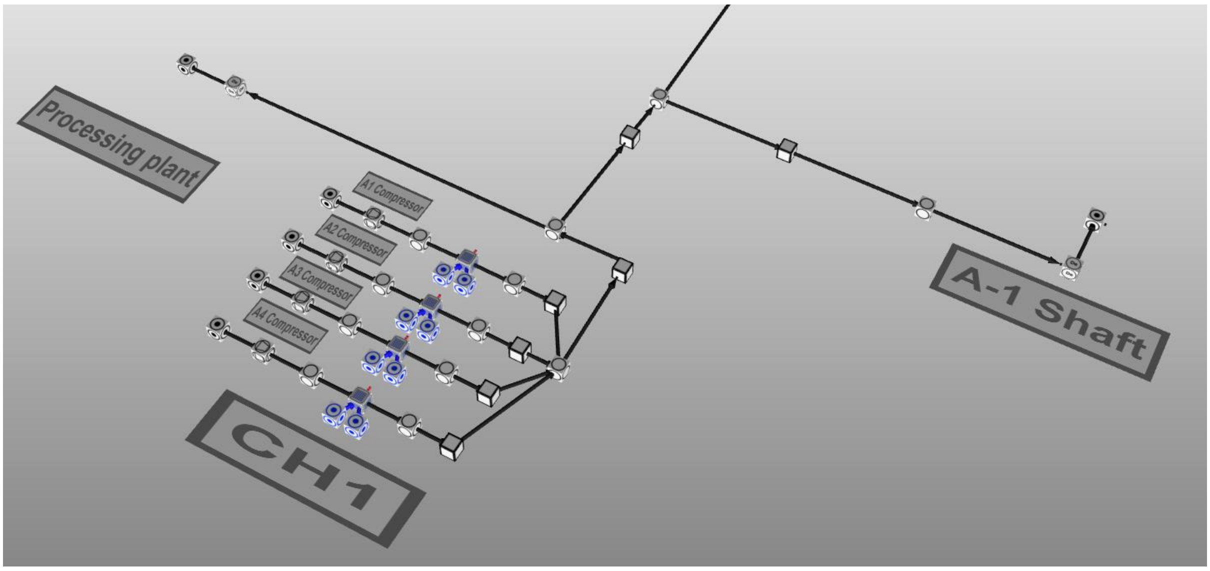

Figure D-2: System A – detailed view of simulation model

Appendix D-2 System B simulation model

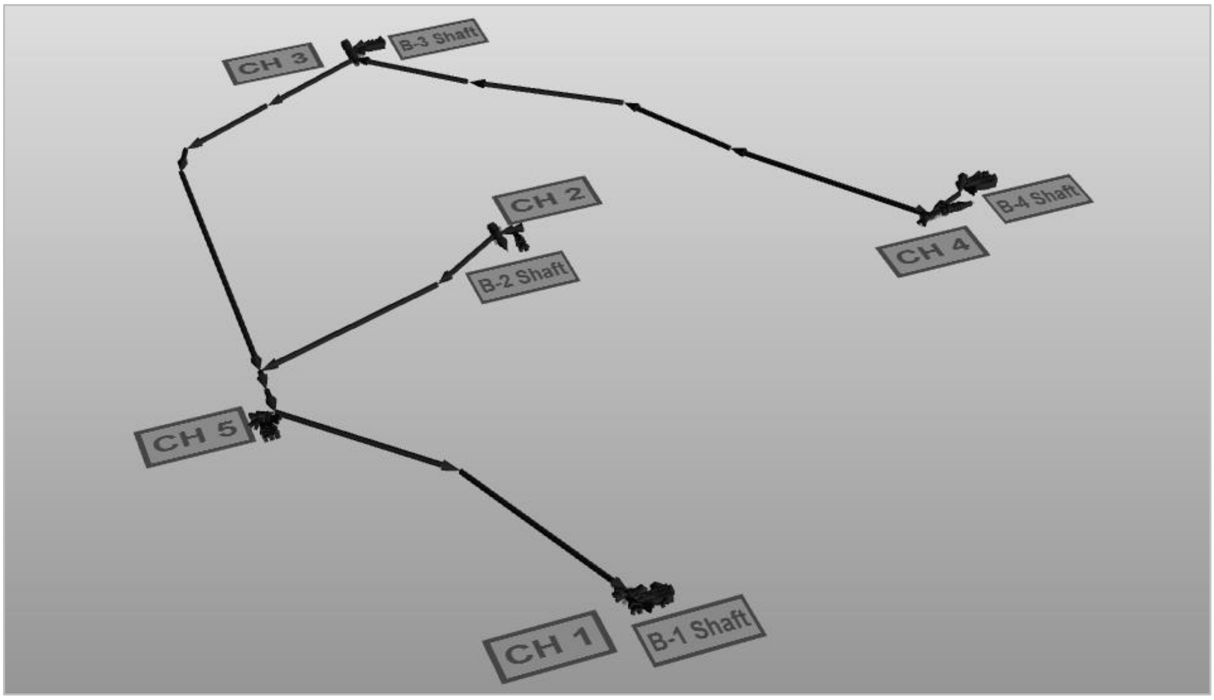

Figure D-3: System B –view of overall simulation model

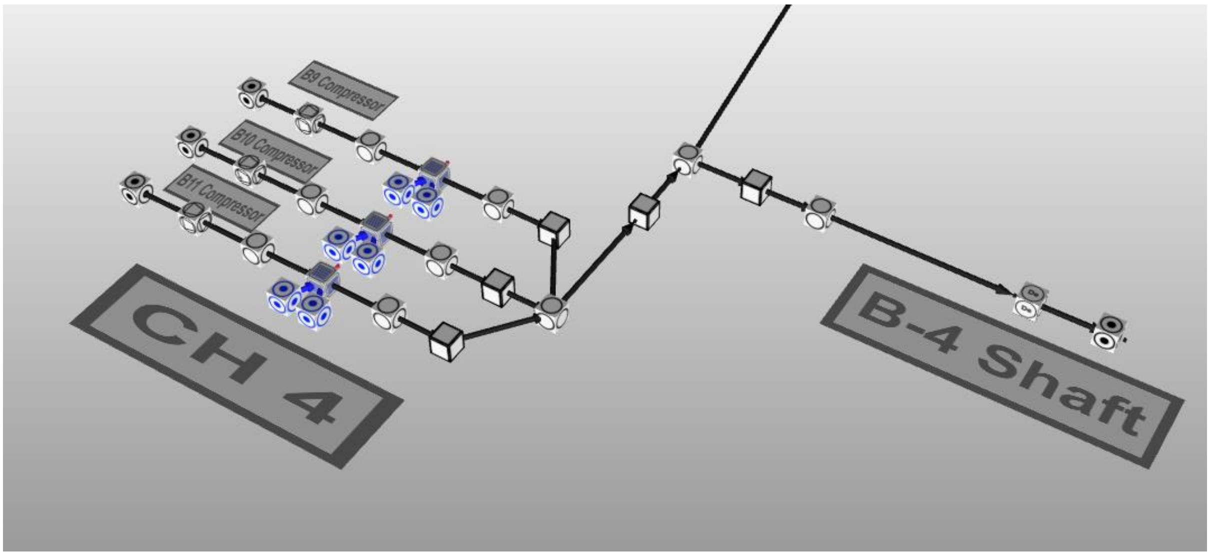

Figure D-4: System B –detailed view of simulation model

APPENDIX E VERIFICATION OF SIMULATION MODELS

Appendix E-1 Case Study A verification

Table E-1 gives the percentage errors of the pressure, flow and power of each compressor on System A, as well as the coefficients of determination for the power and flow of each compressor. As shown, the percentage errors of the three parameters (pressure, flow and power) were lower than 5%, whilst the coefficients of determination of the flow and power for each compressor were greater than 0.9. Therefore, as per Section 2.4.3, all the compressors were deemed to be calibrated accurately.

Table E-1: System A – compressor verification

Compressor	Pressure $Error\%$	Flow $Error\%$	Power $Error\%$	Flow r^2	Power r^2
A-1 VK32	3.3%	1.7%	2.5%	1.00	0.99
A-2 VK32	3.2%	1.5%	2.1%	1.00	0.99
A-3 VK32	4.2%	1.7%	1.7%	N/A	N/A
A-4 VK50	4.6%	4.2%	4.5%	0.97	0.99
A-5 VK32	3.7%	4.2%	2.4%	N/A	N/A
A-6 VK32	4.1%	3.6%	2.3%	N/A	N/A
A-7 VK32	2.0%	3.5%	3.1%	0.99	0.99
A-8 VK32	3.3%	2.1%	2.8%	0.99	0.99
A-9 VK32	2.9%	2.2%	1.8%	N/A	N/A
A-10 VK50	N/A	3.9%	4.9%	0.99	0.99
A-11 VK50	N/A	3.2%	2.1%	0.99	0.99
A-12 VK50	N/A	3.7%	3.2%	N/A	N/A
A-13 VK32	N/A	2.7%	1.5%	1.00	1.00
A-14 VK32	3.0%	1.7%	2.0%	1.00	1.00
A-15 VK32	3.7%	3.4%	1.7%	0.97	1.00
A-16 VK32	3.5%	2.4%	2.4%	0.93	0.99
A-17 VK32	3.8%	2.3%	2.2%	0.99	0.99
A-18 VK32	4.8%	1.5%	1.8%	0.98	1.00
A-19 VK32	4.7%	2.2%	2.3%	1.00	0.99

Table E-2 gives the percentage errors of the pressure and flow of all the compressed air end users on System A, as well as the coefficient of determination for every end user's flow. As can be seen, the percentage errors were less than 5% for each user's pressure and flow, and the coefficients of determination were greater than 0.9 for each shaft's flow. Therefore, the simulation models for each shaft and the processing plant were deemed to be accurate. The processing plant's coefficient of determination was excluded (as discussed in Section 2.4.2), since it had no distinct profile because it was operational for the entire day.

Table E-2: System A – compressed air end user verification

End user	**Pressure** $Error\%$	**Flow** $Error\%$	**Flow** r^2
A-1 Shaft	0.8%	0.6%	1.00
A-2 Shaft	3.4%	4.3%	0.99
A-3 Shaft	2.9%	4.9%	0.97
A-4 Shaft	3.7%	4.1%	0.98
A-5 Shaft	2.8%	4.8%	0.97
A-6 Shaft	3.0%	2.9%	0.98
A-7 Shaft	4.2%	4.4%	1.00
Processing Plant	4.16%	4.3%	N/A

As the accuracy of the simulation model has been verified (as discussed in Section 2.4.3) for all components (compressors and shafts), the simulation model of System A was therefore verified.

Appendix E-2 Case Study B verification

Table E-3 gives the percentage error of the pressure, flow and power for each compressor on System B. The table further lists each compressor's coefficient of determination for the flow and power. From this table, it is apparent that all the percentage errors are equal to or less than 5%. Furthermore, the coefficient of determination is greater than 0.9 for every compressor's flow and power, barring compressor B-8 VK32, which was excluded. Consequently, the simulation model is verified for all of System B's compressors.

Table E-3: System B – compressor verification

Compressor	**Pressure** $Error\%$	**Flow** $Error\%$	**Power** $Error\%$	**Flow** r^2	**Power** r^2
B-1 VK50	4.0%	3.0%	2.8%	0.93	0.99
B-2 VK50	3.6%	3.1%	1.8%	0.99	1.00
B-3 VK50	3.9%	5.4%	3.3%	0.91	0.99
B-4 VK32	2.5%	2.3%	4.2%	0.92	0.99
B-5 VK32	2.2%	1.6%	4.0%	1.00	0.99
B-6 VK32	3.5%	2.3%	3.9%	1.00	0.98
B-7 VK32	5.0%	2.6%	2.9%	1.00	0.99
B-8 VK32	5.0%	2.0%	1.8%	N/A	N/A
B-9 VK50	3.7%	3.0%	1.6%	1.00	1.00
B-10 VK50	4.1%	3.4%	2.7%	0.98	1.00
B-11 VK50	4.1%	1.8%	2.2%	1.00	1.00

The reason for the omission of compressor B-8 VK32's coefficient of determination is that this compressor was operational for the entirety of the day. As discussed in Section 2.4.2, if a compressor does not have a distinct profile (i.e. is running continuously), its coefficient of determination for power and flow will be disregarded.

Table E-4 gives the percentage errors for the flows and pressures of all the shafts on System B, as well as the coefficients of determination for each shaft's flow. It is apparent from the table that all the percentage errors are less than 5% and that every shaft's coefficient of determination for the flow is more than 0.9. For this reason, all the shafts in the simulation model are verified.

Table E-4: System B – shaft verification

Shaft	**Pressure** $Error\%$	**Flow** $Error\%$	**Flow** r^2
B-1 Shaft	2.7%	4.2%	0.99
B-2 Shaft	2.0%	3.3%	1.00
B-3 Shaft	2.4%	4.0%	1.00
B-4 Shaft	2.9%	2.2%	0.99

The simulation model for System B is therefore deemed to be verified and that the percentage error and coefficient of determination for each component (compressors and shafts alike) are calibrated within the constraints set apart in Section 2.4.3.