

# Automation of compressor networks through a dynamic control system

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# Abstract

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**Title:** Automation of compressor networks through a dynamic control system

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**Keywords:** dynamic compressor selector, compressor automation, centrifugal compressor control, compressed air optimisation, intelligent compressor control.

Compressed air makes up an important part of South African precious metal mining processes. Rising operational costs in the struggling mining sector increased the interest of the power utility, Eskom, and mine management in achievable electrical energy savings. Demand side management initiatives, funded by Eskom, realised a significant improvement in electrical energy efficiency of compressed air networks. Supply side interventions further aided optimisation by lowering operational costs.

Previous research identified the need for integrating compressed air supply and demand side initiatives. Automated compressor control systems were needed in industry to realise missed opportunities due to human error on manual control systems. Automatic systems were found to be implemented in the industry, but missed savings opportunities were still encountered. This was due to the static nature of these control systems, requiring human intervention from skilled artisans.

A comprehensive system is required that can adjust dynamically to the ever-changing demand and other system changes. Commercially available simulation software packages have been used by various mine groups to determine an optimal control philosophy. Satisfactory results were obtained, but the simulations were still based on static control inputs. No simulation system was found that could solve and optimise a system based on real-time instrumentation feedback.

By combining simulation capabilities with dynamic control in real time, advanced optimisation could be achieved. Development was done on the theoretical design of the system, where mathematical calculations and the accuracy of the system were evaluated. This study proved that the new controller was viable and, as a result, the development of a fully dynamic control

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system incorporating the verified mathematical models followed. All of this was done following a theoretical approach.

Intricate control requirements on the supply side were evaluated to determine the impact of new intelligent compressor control strategies. It was found that improved compressor control realised an additional 6.2% electrical energy saving on top of existing savings initiatives.

Practical limitations and human perception issues were also addressed. Financial cost-benefit analyses were used to evaluate the viability of using automated compressor control. Ample maintenance data obtained from two leading mining companies was used to evaluate the impact of increased stopping and starting of compressors. Financial cost savings from electrical energy efficiency control strategies were found to considerably outweigh the minimal increase in compressor maintenance.

Savings potential on deep-level mines proved to be in the order of 5% of the baseline consumption. When these results are extrapolated to the remaining 22 South African deep-level gold and platinum mines already subjected to demand side management initiatives, potential savings of 12.67 MW can be realised. Based on the Eskom 2014/2015 Megaflex tariff structure, the financial cost saving from 12.67 MW is R61 million.

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# Contents

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<b>Acknowledgements</b> .....	<b>i</b>
<b>Abstract</b> .....	<b>ii</b>
<b>List of figures</b> .....	<b>vi</b>
<b>List of tables</b> .....	<b>ix</b>
<b>Nomenclature</b> .....	<b>xi</b>
<b>Abbreviations</b> .....	<b>xii</b>
<b>Compressor terminology</b> .....	<b>xiii</b>
<b>1 Large compressed air networks in South African mines</b> .....	<b>1</b>
1.1 Background .....	1
1.2 Compressed air usage and strategies.....	1
1.3 Previous research on dynamic compressor selection.....	11
1.4 Novel contributions of the study .....	21
<b>2 Compressor control systems</b> .....	<b>26</b>
2.1 Introduction.....	26
2.2 Compressed air application in mining .....	26
2.3 Compressor and system controllers.....	36
2.4 Compressor control in South African mines .....	62
2.5 Summary .....	68
<b>3 Designing an advanced compressor control system</b> .....	<b>69</b>
3.1 Introduction.....	69
3.2 Proposed controller.....	69
3.3 Addressing limitations .....	85
3.4 Integration and execution of control parameters .....	95
3.5 Summary .....	106

---

<b>4</b>	<b>Implementation of a dynamic control system.....</b>	<b>107</b>
4.1	Introduction.....	107
4.2	Control system set-up.....	107
4.3	Case studies.....	111
4.4	Opportunities for the South African mining industry .....	131
4.5	Maintenance versus energy cost savings.....	132
4.6	Summary .....	135
<b>5</b>	<b>Conclusion and recommendations .....</b>	<b>137</b>
5.1	Conclusion.....	137
5.2	Recommendation for future work.....	139
	<b>References.....</b>	<b>141</b>
<b>Appendix A</b>	<b>Initial compressor controller .....</b>	<b>147</b>
<b>Appendix B</b>	<b>Mine A compressed air ring set-up in software .....</b>	<b>151</b>
<b>Appendix C</b>	<b>Mine A maintenance occurrences.....</b>	<b>156</b>

---

# List of figures

---

Figure 1: Compressor characterisation curves (obtained from [3]).....	xiv
Figure 2: Breakdown of electrical energy usage in the mining industry (obtained from [11]) .....	1
Figure 3: Mine A compressor network reticulation .....	3
Figure 4: Control system identified by Booyesen (obtained from [12]) .....	6
Figure 5: Compressor control approach used by Booyesen (obtained from [12]).....	7
Figure 6: Network-solving process used by Venter (obtained from [18]) .....	15
Figure 7: Compressor selection process used by Venter (obtained from [18]) .....	15
Figure 8: Control valve set-up with electric actuators fitted .....	28
Figure 9: Pneumatic cylinder on ore chute door .....	29
Figure 10: Pneumatic actuated cylinder.....	30
Figure 11: Photos of a burst compressed air pipeline at a platinum mine .....	33
Figure 12: Existing network with 350 mm pipeline simulation .....	34
Figure 13: Proposed network with 600 mm pipeline simulation.....	34
Figure 14: Mine flow comparison.....	35
Figure 15: Shaft flow comparison .....	36
Figure 16: Typical example of a compressor characterisation map .....	38
Figure 17: Capacity control using VSD (obtained from [3]) .....	41
Figure 18: Graphical representation of VSD payback period versus required power reduction .	43
Figure 19: Ingersoll Rand ASM set-up (obtained from [56]) .....	47
Figure 20: Static priorities subjected to ordinary flow requirements .....	59
Figure 21: Pressure monitoring process .....	64
Figure 22: Network communication layout.....	71
Figure 23: Real-time flow versus filtered flow .....	71
Figure 24: Systematic approach.....	77
Figure 25: Actual, average and scaled data for future predictions .....	80
Figure 26: Superimposed profile.....	87
Figure 27: South African gold production history (obtained from [90]).....	90

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Figure 28: Pressure Node icon .....	97
Figure 29: Pressure Node Edit form .....	98
Figure 30: Air Pipe icon .....	99
Figure 31: Air Pipe Edit form .....	99
Figure 32: Node Feedback icon.....	100
Figure 33: Node Feedback Edit form.....	100
Figure 34: Air Solver Edit form.....	101
Figure 35: Compressor icon .....	102
Figure 36: Compressor Edit form.....	103
Figure 37: Compressor Controller icon .....	104
Figure 38: Compressor Controller Edit form .....	104
Figure 39: Compressor Prioritiser icon .....	105
Figure 40: Compressor Prioritiser Edit form.....	106
Figure 41: Shaft 1-A underground layout.....	113
Figure 42: Mine A layout in DCS system .....	115
Figure 43: Compressor set-up page of Mine A .....	116
Figure 44: DCS set point versus existing controller set point .....	117
Figure 45: Compressor delivery flow before DCS intervention.....	118
Figure 46: Existing compressor controller priorities .....	118
Figure 47: Priorities calculated by DCS system .....	119
Figure 48: Ideal priorities calculated by the DCS system.....	120
Figure 49: Performance assessment savings at Mine A .....	121
Figure 50: Power profile before and after test.....	122
Figure 51: Average compressor usage at Mine B before investigation .....	123
Figure 52: Mine B supply versus demand flow .....	123
Figure 53: Mine B pressure requirements.....	124
Figure 54: Simulation set-point calculation .....	126
Figure 55: DCS calculated flow ranges from simulation.....	126
Figure 56: Compressor running status during day 1 of the test.....	127

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Figure 57: Compressor running status during day 2 of the test.....	128
Figure 58: Power profile comparison for day 1 tests .....	128
Figure 59: Power profile comparison for day 2 tests .....	129
Figure 60: Calculated delivery flow using smaller compressors .....	130
Figure 61: Estimated power usage of smaller compressor combinations.....	130
Figure 62: Reduction in power usage achievable on 22 projects .....	132
Figure 63: Number of maintenance occurrences .....	135
Figure 64: Initial compressor controller at Mine A .....	147
Figure 65: Mine compressor controller for Ring A-1 indicating weekday set points and priorities	148
Figure 66: Mine compressor controller for Ring A-1 indicating Saturday set points and priorities	148
Figure 67: Mine compressor controller for Ring A-1 indicating Sunday set points and priorities	149
Figure 68: Compressor 1 to Compressor 6 surge curves and capacity control .....	149
Figure 69: Compressor 7 to Compressor 9 surge curves and capacity control .....	150
Figure 70: Compressor 1 set-up table .....	151
Figure 71: Compressor 2 set-up table .....	152
Figure 72: Compressor 3 set-up table .....	152
Figure 73: Compressor 4 set-up table .....	153
Figure 74: Compressor 5 set-up table .....	153
Figure 75: Compressor 6 set-up table .....	154
Figure 76: Compressor 7 set-up table .....	154
Figure 77: Compressor 8 set-up table .....	155
Figure 78: Compressor 9 set-up table .....	155

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# List of tables

---

Table 1: Compressor characteristics table (obtained from [18]) .....	14
Table 2: Comparison of product and existing network-simulation software pressures (obtained from [18]).....	16
Table 3: Comparison of product and existing network-simulation software flows (obtained from [18]).....	16
Table 4: Comparison of product and actual system values (obtained from [18]) .....	17
Table 5: Compressor control technology summary (obtained from [22]) .....	18
Table 6: High-pressure requiring compressed air users.....	29
Table 7: Simulation verification.....	32
Table 8: Effect of compressor location on system pressure .....	33
Table 9: Definitions of symbols for compressor characterisation .....	37
Table 10: VSD savings required to achieve payback period .....	42
Table 11: VSD payback period versus compressor power turndown .....	43
Table 12: Intelligent controller capabilities .....	50
Table 13: Definitions of symbols for force calculation .....	54
Table 14: Compressor flow characterised.....	80
Table 15: Compressor efficiency characterised .....	81
Table 16: Mine A compressor location and capacities .....	112
Table 17: Compressor capacities at Mine B .....	122
Table 18: Maintenance cost of a mine subjected to automatic control .....	133
Table 19: Maintenance occurrences at a mine with automatic compressor control.....	134
Table 20: Compressor 1 maintenance record.....	156
Table 21: Compressor 2 maintenance record.....	156
Table 22: Compressor 3 maintenance record.....	156
Table 23: Compressor 4 maintenance record.....	157
Table 24: Compressor 5 maintenance record.....	157
Table 25: Compressor 6 maintenance record.....	157

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Table 26: Compressor 7 maintenance record..... 158  
Table 27: Compressor 8 maintenance record..... 158

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# Nomenclature

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°C	:	degrees Celsius
cfm	:	cubic feet per minute
GW	:	gigawatt
GWh	:	gigawatt-hour
hr	:	hour
kg	:	kilogram
km	:	kilometre
kPa	:	kilopascal
kV	:	kilovolt
kW	:	kilowatt
lbm	:	pound-mass
Mach	:	speed of sound
m	:	metre
min	:	minute
mm	:	millimetre
MW	:	megawatt
MWh	:	megawatt-hour
n	:	adiabatic heat constant
N	:	newton
Pa	:	pascal
R	:	Gas constant
s	:	second
TWh	:	terawatt-hour
μ	:	micro (10 <sup>-6</sup> )

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# Abbreviations

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ASC	:	Air System Controller
ASM	:	Air System Manager
CAN	:	Compressed Air Network
CCC	:	Compressor Controls Corporation
CSV	:	Comma-separated Value
DCS	:	Dynamic Compressor Selector
DSM	:	Demand Side Management
ESCo	:	Energy Service Company
GPS	:	Global Positioning System
IDE	:	Integrated Development Environment
IDM	:	Integrated Demand Management
MAD	:	Measurement and Acceptance Date
OEM	:	Original Equipment Manufacturer
OPC	:	Open Platform Communication
PLC	:	Programmable Logic Controller
PSP	:	Pressure Set Point
PTFE	:	Polytetrafluoroethylene
REMS	:	Real-time Energy Management System
REMS-CM	:	REMS for Compressor Management
REMS-DCS	:	REMS for Dynamic Compressor Selector
REMS-OAN	:	REMS for Optimisation of Air Networks
SCADA	:	Supervisory Control and Data Acquisition
SQL	:	Sequel
TCP/IP	:	Transmission Control Protocol/Internet Protocol
VSD	:	Variable Speed Drive

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# Compressor terminology

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## *Blow-off valve or surge control valve*

A blow-off valve is a control valve on the delivery side of the compressor that acts as a pressure-release valve [1]. The air released through this valve is usually dumped into the atmosphere, or redirected to the compressor inlet [1]. A blow-off valve is an actuated valve capable of responding quickly in order to increase the flow through the compressor [2]. By increasing the flow through the compressor, surge can be avoided [1].

## *Guide vane*

A guide vane on a compressor is a set of blades positioned on the intake of a compressor stage that rotates the air going into a compressor to manipulate the discharge flow or pressure according to the system requirements [3].

## *Suction valve*

Suction valves are control valves positioned in the inlet column of the compressor that are used for restricting airflow into a compressor. By closing the control valve the suction pressure of the compressor is lowered, resulting in reduced discharge pressure and/or flow [3]. The inverse also holds true, where compressor output is increased with the opening of the suction valve.

## *Discharge valve*

Discharge valves are control valves situated on the discharge side of the compressor [4]. The delivery pressure/flow of the compressor is then controlled by modulating the valve.

## *Surge*

Surge is the phenomenon that occurs in a compressor when the direction of the flow is reversed [5], [6]. When this happens, oscillations in flow occur that are detrimental to a compressor machine. The following effects are products of compressor surge:

- compressor vibrations [3], [4],
- radial and axial thrust on the drive shafts [7], and
- reheating of compressed air due to flow reversal [7].

### Stonewalling

Choking or stonewalling happens when the compressor reaches a point where any increase in flow is impossible. Flow velocity could reach speeds of up to Mach 1, and the efficiency of the compressor is significantly reduced [8].

### Compressor characterisation curve

A compressor characterisation curve is used to define the compressor based on flow delivery at a given pressure. This curve can be obtained for different speeds (shown on the left in Figure 1) or for different inlet guide vane positions (shown on the right in Figure 1) [3]. Each compressor has an efficient operating point situated to the right of the surge control line [9]. At this point on the compressor map, the compressor will deliver the highest amount of flow for the least amount of work. On the compressor characterisation curve the surge line is also defined, indicating the surge point at different operating conditions (indicated in red in Figure 1).

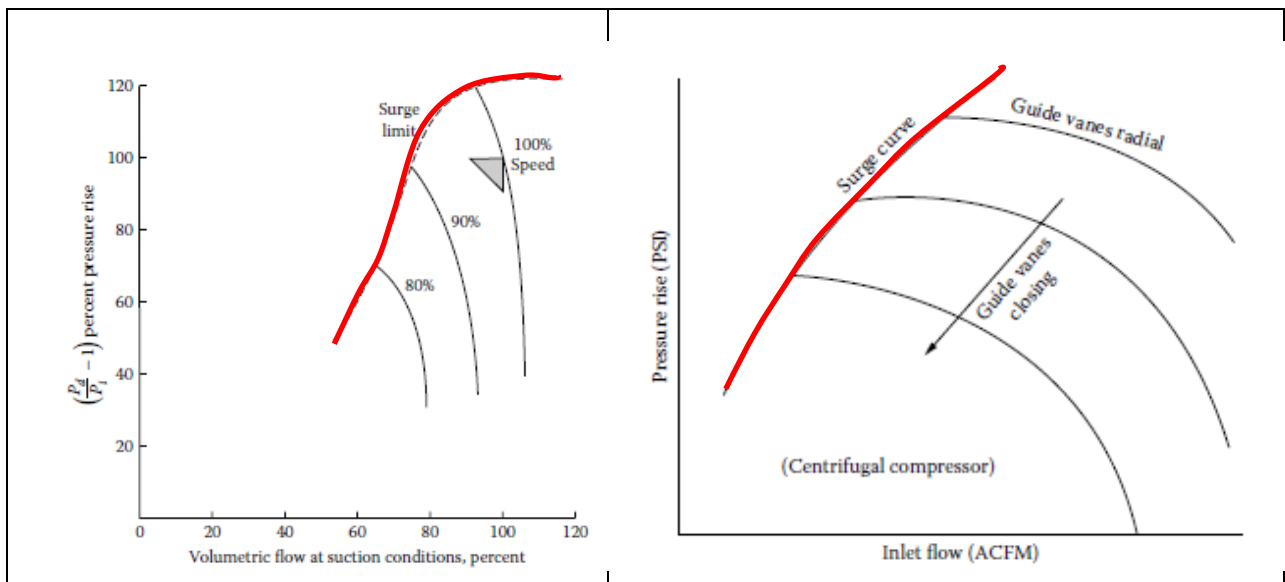


Figure 1: Compressor characterisation curves (obtained from [3])

# 1 Large compressed air networks in South African mines

## 1.1 Background

As a short-term solution to a long-term problem, the power utility Eskom successfully implemented demand side management (DSM) initiatives in the South African industry [10]. One of the focus areas of DSM is the mining sector, where an integral part of DSM success was achieved [11]. Due to the nature of mining processes, equipment with high electrical energy consumption is throughout the industry. One of these energy consumers is air compressors as found at a majority of mines. Particularly within the South African mining environment, compressed air is still used as a vital component in the process of extracting valuable ore.

The mining industry is responsible for up to 15% of the total electrical energy consumption in South Africa [11]. One of the main consumers of electrical energy on a mine is compressors, accounting for up to 17% of total electrical energy usage as seen in Figure 2 [11]. With this in mind, savings achieved on the compressed air networks (CAN) are crucial in order to reduce operational costs in a struggling sector. With electrical energy costs continuously rising, the demand for energy savings has escalated over the last couple of years.

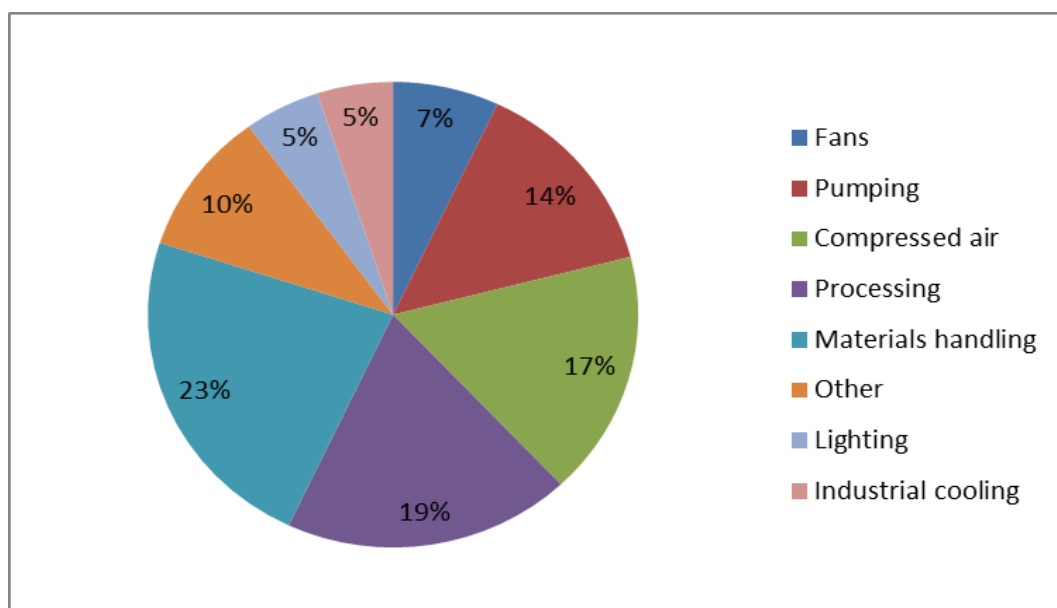


Figure 2: Breakdown of electrical energy usage in the mining industry (obtained from [11])

## 1.2 Compressed air usage and strategies

DSM on CANs entails intervention on both the supply side and the demand side of compressed air operations. Taking the condition and age of equipment found in the mining environment into

account, these interventions usually require upgrading old technology or installing new, more energy efficient equipment. Changing the equipment used has an impact on the whole mining process, whether directly or indirectly.

On the supply side interventions include: inlet guide vane control; automatic set-point scheduling or control; start/stop on demand; improved cooling and filtration systems and accurate measurement of compressor characteristics [12], [13], [14]. These interventions enable compressor systems to run more efficiently, therefore, decreasing excessive wastages on the CAN, which in turn decreases production cost. This is achieved by lowering the power consumption on the compressor, which is the main focus of the DSM program.

When the focus is shifted to the demand side, various intervention options are available. Typical interventions include:

- repairing leaks [15],
- controlling pressure according to predefined schedules [12],
- moving from pneumatic to hydraulic or mechanical equipment [14], [15], and
- setting up high- and low-pressure rings [16], and so forth.

During the project implementation phase, most of these interventions will be put into place by an energy services company (ESCO) that is contracted by Eskom to achieve a predefined energy saving. Once Eskom has approved the engineering concept, the project is awarded to the ESCo for implementation. Once implementation is completed, the project is subjected to an evaluation period known as the performance assessment phase.

During performance assessment, the project should achieve the stated target for a duration of three months. Upon successful completion of the performance assessment phase, the client signs a confirmation document known as the measurement and acceptance date (MAD) document. Upon signing the MAD document, the client accepts the stipulated target and is required to maintain the savings for three or five years, depending on the contract specifications.

Compressor systems, which are found in the precious metal mining industry of South Africa, consist of compressors with large installed capacities. The installed capacities of these compressors range between approximately 1 MW and 15 MW. Under ideal conditions compressor systems will comprise small, medium and large compressors to increase the controllability of the system.

On Mine A, for example, the compressor system consisted of eight Demag compressors with the following specifications:

- 2 × VK10 compressors (delivery 10 000m<sup>3</sup>/h, electrical installed capacity 1 MW),
- 3 × VK40 compressors (delivery 40 000m<sup>3</sup>/h, electrical installed capacity 4.8 MW), and
- 3 × VK50 compressors (delivery 50 000m<sup>3</sup>/h, electrical installed capacity 5.1 MW).

The system layout is given in Figure 3, with the locations of the compressor houses indicated. From this figure it can be seen that the network comprises various shafts and two compressor houses, interconnected through a series of piping (yellow lines). The pipelines can span several kilometres in some instances and make up an integral part of the CAN.



Figure 3: Mine A compressor network reticulation

With pipelines reaching several kilometres in length, the diameter and friction directly affect the pressure losses encountered in the system. Pressure losses affect service delivery to the shafts, which could have a negative impact on production if the pressure losses are not overcome. When only considering surface reticulation, pipelines encountered on South African mines can reach up to 75 km in length.

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Numerous compressors of different sizes and from different manufacturers are found throughout the mining sector. Some of these compressors were manufactured in the 1960s and are still operational. Due to the age of some of the equipment, stopping/starting of compressors is a major concern and it could be a limiting factor on the feasibility of compressor scheduling and prioritising. According to mine personnel, the additional mechanical and electrical stresses of stopping/starting have a detrimental effect on compressor maintenance and reliability.

The problem, however, arises after the three-month performance assessment phase discussed earlier, when the project is handed over to the client. For the purposes of this study, the client would be the relevant mine or shaft. After the performance assessment phase the client is responsible for achieving the savings obtained during the performance assessment phase. If the ESCo did not achieve the promised savings target, the client is only liable to maintain the savings as achieved during the performance assessment. However, if the savings meet or exceed the target, the client will still only be responsible to achieve the initial targeted amount.

This study will also focus on what happens to DSM projects after the performance assessment phase. Sustainability of these energy savings is still a vital part of the DSM programme, since the Eskom supply is greatly influenced by sustainable savings achieved from these projects. After the three-month performance assessment phase, the ESCo is no longer contractually bound to the project. Therefore, the full responsibility rests with the client to maintain the interventions put into place by the ESCo during the project implementation phase.

Du Plessis [13] summarised the control of compressors into three categories, namely, start/stop, load/offload and capacity control. Capacity control is the control type encountered more commonly, since the majority of compressors found in mining are equipped with some form of capacity control. Although the Air Miser<sup>TM</sup> technology identified by Du Plessis had all of the requirements to stop/start compressors on demand, it did not have mathematical network-solving capabilities.

This meant that pressure drop correction could not be made to improve service delivery to end users, and future prediction of flow requirements was not available to reduce the starting/stopping of compressors. Furthermore, the inability of Air Miser<sup>TM</sup> to interface with existing compressor programmable logic controller (PLC) equipment made it an unappealing and expensive system to implement. Due to budget constraints, solutions implemented on mining CANs were found to be more appealing when they used as much of the existing infrastructure as possible.

In the system designed by Du Plessis, the weekly system pressure profiles had to be entered manually for weekdays, Saturdays (production and non-production) and Sundays. The priorities of the compressors were entered by a compressor operator and could be adjusted as required. Time delays as used by Du Plessis proved valuable in evaluating system response to the removal of a compressor from the supply.

This study builds on the research and design as completed by Du Plessis because it uses the same controller, updated to new requirements. Changes are made to the energy management algorithm, where the schedules and set points are calculated dynamically according to system feedback. These changes remove the user-input requirement and calculate the requirements of the system in real time. It also does future predictions using mathematical modelling software.

As recommended by Du Plessis, compressor control should be incorporated with effective demand control. When this is achieved, the demand and supply side initiatives should be integrated to optimise system efficiency even further. This study will focus on integrating and matching the supply and demand side initiatives. It will also address the sustainability of compressors systems as a whole. The system should also be able to function dynamically, thus eliminating the need for compressor operators to input data on a continuous basis.

Booyesen mentions in his study [12] that compressed air supply should be adjusted to meet demand. However, Booyesen could not find proof of a successful implementation of an automated control system in the South African mining sector. The study was conducted during 2010, and further research was required to identify the control used in the mines at that time. As identified by Booyesen, the majority of South African mines use multistage centrifugal compressors in their operations, therefore, the control systems investigated specifically focused on these types of compressors.

Simulation models were briefly discussed in his study, indicating that compressors and CANs could be modelled using mathematical simulation tools. Booyesen further summarised the problems encountered with control system as:

- human control – errors made by operators due to lack of knowledge,
- lack of real-time information – insufficient instrumentation,
- pressure set points (PSP) that are higher than required – lack of PSP control based on end-user requirement,
- excessive compressor blow-off – manual operation prevented compressor shutdown, and

- inefficient compressor selection – lack of system information in compressor prioritising.

Figure 4 summarises the control philosophy of the system developed by Booyesen. This required automating the inlet guide vanes of compressors, automating remote stopping/starting compressors, and installing sufficient instrumentation throughout the system.

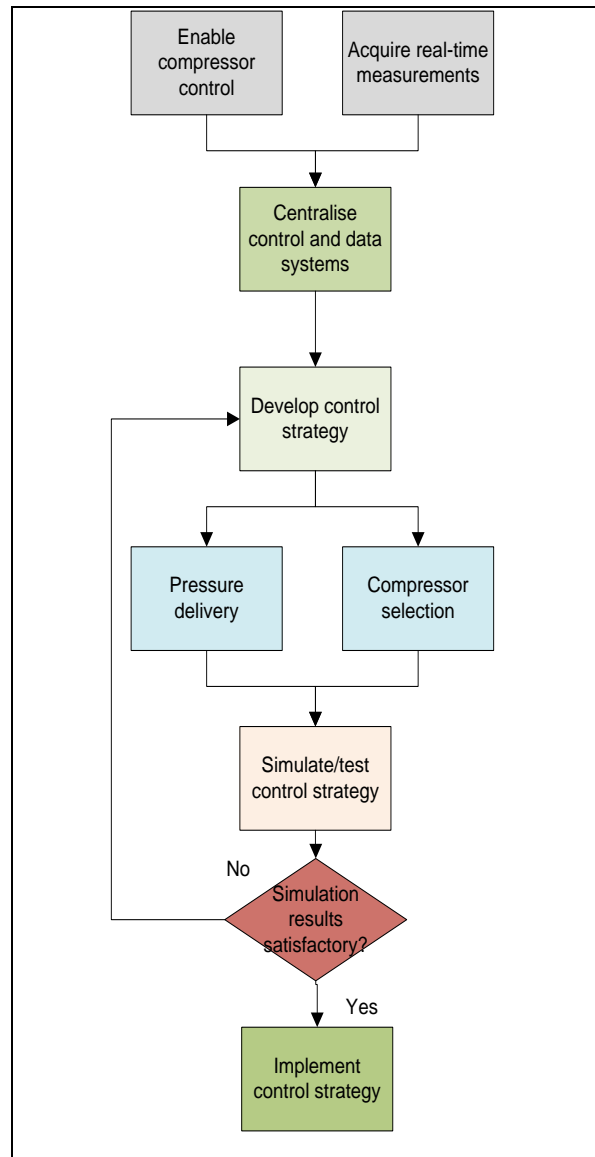


Figure 4: Control system identified by Booyesen (obtained from [12])

The inlet guide vanes and blow-off valves of the compressors did capacity control to match the system demand. The control system is explained in the flow chart given in Figure 5.

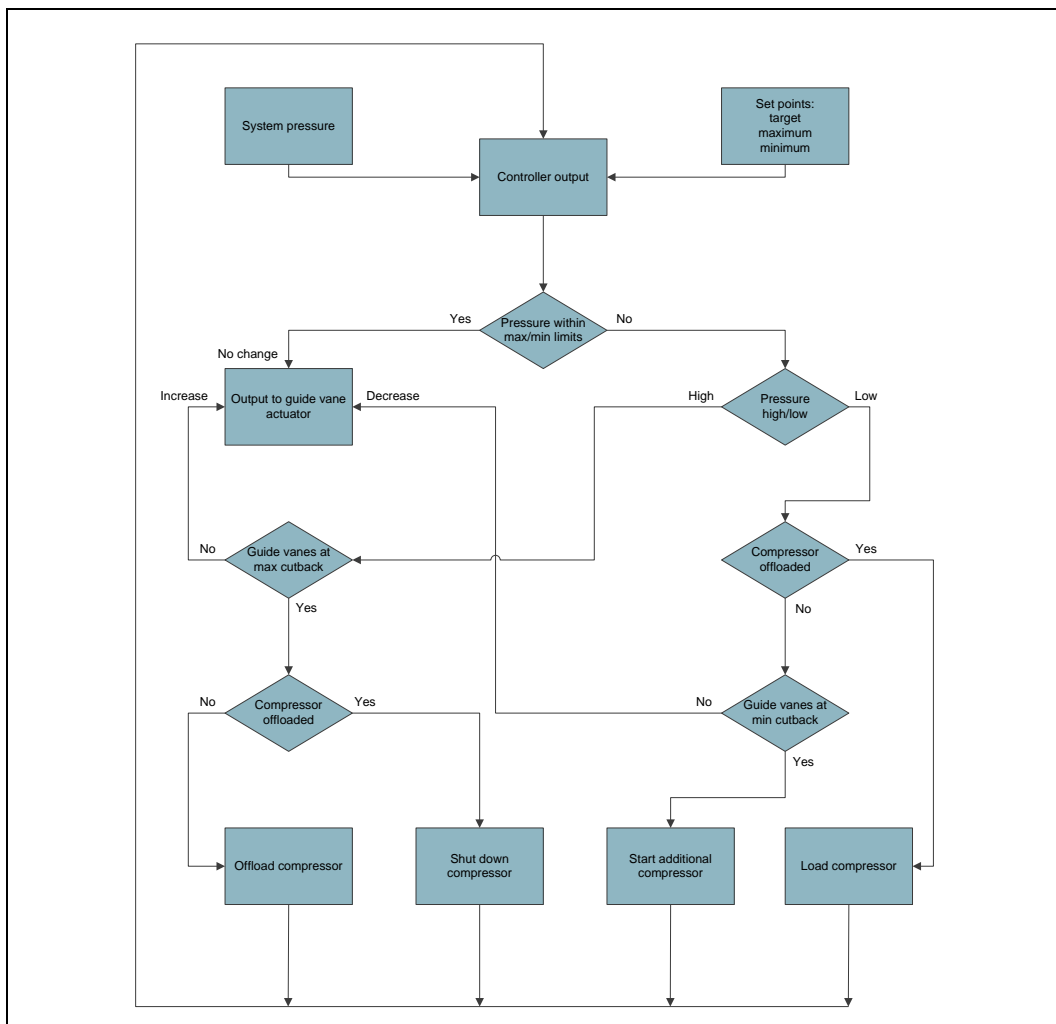


Figure 5: Compressor control approach used by Booyesen (obtained from [12])

The flow chart presented in Figure 5 can be explained by the following steps:

1. The set points of the system are entered in the form of a 24-hour profile. From this profile, the maximum variance is added to achieve the maximum and minimum limits (pressure will be regulated within this range).
2. Capacity control of the trimming compressor will be done using inlet guide vane control. When the pressure is below the specified minimum, the guide vane angle of the trim compressor will be opened to increase delivery of the trim compressor. When the system pressure is above the maximum pressure, the guide vanes will close and effectively reduce the trim compressor output delivery.
3. When the flow requirement drops to below the level where capacity control through inlet guide vanes cannot be successfully reduced, the trimming compressor will offload.

4. The offloaded compressor will operate in the offloaded state to allow the system to respond to the removal of the compressor. If there is a sudden drop in pressure, the compressor will be loaded again to deliver flow to the system. If the system pressure remains within the specified range until the timeout has lapsed, the compressor will be stopped.
5. When the system pressure drops below the minimum specified pressure and the guide vanes of the trim compressor are fully open, an additional compressor will be started according to the static priority list defined in the controller.

A 24-hour system set-point pressure was calculated using the air requirement of equipment throughout a typical production day. The problem, however, was that the set-point profile was static and had to be updated by an operator when required. The operator had to have a working knowledge of the system in order to avoid incorrect pressure delivery. Incorrect pressure settings could lead to a loss in production.

Compressors were prioritised so that the most efficient compressors were run as baseload compressors, and the less efficient compressors were run as trimming compressors. The compressors were prioritised once based on the flow requirements during a typical production day, and the priorities were entered into the controller. The trimming compressor was selected to operate between 60% and 100% guide vane opening to allow the system to respond to small changes in demand.

If the efficiencies of the compressors changed, the priorities would have to be changed manually by an experienced operator with working knowledge of the system. The static nature of the system was not identified as a problem by Booyesen in his study. System changes were made manually, thus simulating the new proposed control philosophy to evaluate the effect on the system, taking compressor airflow delivery into account. The effect on the power consumption was calculated using the estimation made by Marais [17] that a 14 kPa pressure reduction would result in a 1% power reduction.

Practical challenges were encountered by Booyesen [12] that resulted in compressor cycling (increased stopping/starting of compressors). This was due to the incorrect sizing of compressors that led to two compressors being insufficient to match the demand, but three compressors delivered too much flow. The third compressor would then stop and start to try and maintain the system pressure at required operating points. Booyesen mitigated the problem by increasing the time a compressor was left to run in the offloaded condition.

The final case study presented by Booyesen indicated the importance of compressor location and prioritising. Although compressor prioritising was static based on a typical consumption day, the effect of efficient prioritising was evident in the results. By dynamically assigning priorities to the compressors, the system could be fully automated without the constant need of human interaction.

The important conclusion drawn from Booyesen's study was that fully automated capacity control – in the form of guide vane and blow-off valve control – was the most effective way to control compressor output. This then had to be incorporated into a fully instrumented and controlled system to limit the demand in off-peak periods. From there, the most efficient compressors had to be selected based on delivery size, delivery volume to power consumption efficiency, location and other site-specific requirements.

In Booyesen's study, the control was based on static inputs, but this was not identified as a limiting or problematic factor to achieve the required results. Compressor blow-off needed to be reduced through efficient scheduling of compressors according to demand, meaning that unrealistically high demand set-point requirements needed to be identified and reduced or removed. Compressors had to be scheduled efficiently using the relevant system information (for example, flow, pressure, location and energy efficiency).

Booyesen suggested that future work to be investigated should include the influence of pipe resistance and pressure drop in compressor control systems. The effect of compressor control on compressor maintenance should also be considered when controlling compressors. The effective control and instrumentation of end users should be investigated, together with some sort of intelligent control capable of predicting system demand.

The integrated approach described by Marais [14] focused primarily on demand side strategies to reduce compressed air usage on South African mines. The aim of his study was to simplify the approach to identify energy savings potential on a site. The following section will summarise his findings, which will be incorporated into the design of a comprehensive system approach.

By using actual system data obtained from 22 sites, Marais concluded that a 10% reduction in pressure would result in a power reduction of 16–18% [14]. Although this was a calculated estimate, it seemed to hold true for the majority of South African mines. This factor was subject to the system pressure remaining between 300–700 kPa, which is generally the case in the gold and platinum industries.

This factor may be inaccurate when changes are made to compressor efficiencies through a reduction in cooling water temperatures, replacement filter systems, inlet pressure temperature and pressure, and so forth. Pressure reduction and flow reduction as a result of demand side initiatives resulted in savings as calculated by the factor.

In his study [14], Marais categorised the demand of a system into productive and non-productive leaks. He further stated that a system could be optimised by optimising the supply or the demand side of the system. Fixing leaks was considered to be the first solution to reduce demand, as leaks are classified as non-productive. However, Marais identified that the fixing of leaks had to be accompanied by a reduction in supply to the system in order to achieve energy savings.

Although he mainly addressed demand side initiatives, Marais had case studies stating the importance of supply side optimisation as well. He found that significant savings could be achieved through the effective scheduling of compressors, and other optimising techniques not given in his study. For example, more efficient compressors resulted in an electrical energy reduction of 47% on one of the mines in his study. On another site, the proper configuration of compressors resulted in a 35% reduction in power consumption.

Marais stated the importance of adjusting the supply of the compressor system to meet the reduced demand. He gave solutions to isolate high-pressure users by retrofitting them with smaller compressors. He also suggested that if a compressor system did not have small trimming compressors, smaller compressors could be added to serve as trimming compressors to meet varying demand. He did not state how the supply should be adjusted, but he did suggest that compressors should be scheduled to run during higher demand periods.

In his study, he based the scheduling on the delivery capacity of the compressor; taken as a static quantity. Here he stated that when flows were not known, spot checks could be done to determine the compressors' supply ranges. This indicated a static control philosophy, which can only be updated when another spot check was done.

Various strategies were implemented throughout his case studies to reduce pressure demand and required end user flow. This was further assisted by installing surface control valves that regulated downstream pressure, both on surface and on a per-level basis. The supply was then adjusted to the required pressure. It was, however, not indicated whether the system would automatically update when these set points were adjusted on the control valves.

The integrated approach was summarised by Marais as a continuous process of reducing demand and adjusting the supply accordingly. Although this approach was the best to achieve optimum efficiency, it was not evident from the case study if it was the approach that was followed. In his study, Marais followed the optimisation iterative procedure he described a few times to achieve the savings required from the project. This approach was, however, continuous, but no evidence was found in his study that the process was implemented as such.

Throughout the studies the demand side was optimised, and the supply was matched to the newly reduced demand. PSPs were given to control valve set-ups and compressor delivery set points were adjusted accordingly. It was unclear how the supply had to be adjusted and what input parameters were required. The frequency of possible re-evaluation of the system was also unknown.

Marais also noted that simulation software existed to model the system, but inputs were required that were not always readily available. He further stated that this approach was time-consuming and not always viable during the investigation phase of projects to determine approximate savings. Due to the complexity of the systems, the simulation software did aid to calculate the system response under specified conditions.

Further study areas identified by Marais included the following [14]:

- the effect of autocompression and line friction losses,
- efficiency improvements of compressors and the effect thereof on the system,
- development of a reliable compressor control system,
- the effect of the stopping and starting compressors on maintenance costs, and
- solutions to remove constant flow requirements from the system.

### **1.3 Previous research on dynamic compressor selection**

Venter did the mathematical modelling and theoretical design of a compressor controller focussing on the problem areas identified [18]:

- CAN solving,
- compressor control,
- compressor control room operator,
- communication network, and
- quantifying pressure loss components.

The aim of his study was to incorporate compressed air simulation software into a real-time energy management system. The existing mathematical modelling used by the software for solving airflow in a CAN would be done dynamically using the actual system inputs. The outputs would then be used to determine compressor demand, both at present and future network states.

Venter stated that pressure losses encountered in the system could not be assumed due to the complexity of the system. Therefore, the controller to be designed should calculate the actual pressure loss. The system would then be able to compensate for the losses in order to supply the correct required pressure.

Scheduling the compressors according to theoretical calculated demand would then result in eliminating unnecessary stopping and starting of compressors. This would be done automatically and dynamically, as it required complex mathematical calculations that could not be performed by a compressor operator on a continuous basis. Control room operators also did not have to monitor the system 24 hours a day.

Strict mine information technology standards and protocols have to be adhered to at all times, and the controller should be able to interface with existing hardware. Supervisory control and data acquisition (SCADA) systems and PLCs have to be used to add redundancy to the system. Although the default control and safety will reside in the PLCs and the SCADA, the fluid dynamic calculations can be programmed into this equipment. A stand-alone controller will, therefore, be developed to address the need.

Venter's model addressed the issue of compressors not being able to gauge the shaft's pressure demand, sometimes resulting in excess pressure supplied to the end users [18]. The cycling of compressors due to a drop in system pressure was also discussed by Venter. The solution would be to anticipate the changes and perform control accordingly. Guide vane control would also be reduced to one compressor according to the compressor's assigned priority.

By knowing the actual demand of end users at a specific time and a fixed period in advance, the compressors could be scheduled according to the actual need. Thus, the unnecessary usage of larger compressors would be reduced. Compressors could be prioritised and sized correctly, removing unnecessary compressor blow-off, therefore, increasing system efficiency. PSPs would also be optimised according to actual end-user pressure requirements. Venter stated that compressors would require less energy to operate at the reduced PSP (reduced losses); this was confirmed by Marais [14].

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Assumptions made by Venter while developing the mathematical model were [18]:

- isothermal flow [19], [20],
- average temperature of 43 °C,
- pressure transmitters were accurate within 0.15% [21],
- adiabatic heat constant ( $n$ ) of 1.4,
- gas constant ( $R$ ) of 287 J/kg-K,
- air density varied by up to 40% in required pressure range and was, therefore, calculated at each iteration,
- average viscosity of  $3,0134 \times 10^{-5}$  kg/m-s (chosen at a 300–700 kPa pressure range),
- Reynolds number was calculated with each iteration to determine pipe friction loss factor,
- constant height was used (change in altitude < 1% ),
- incompressible flow was assumed (flow < Mach 0.3),
- losses due to leaks in a node were assumed to be negligible,
- flow meter readings were used to calculate mass flow (error of 0.1–0.5%),
- fluid velocity was calculated from airflow measurement,
- distances measured using Google Earth™ were found to be sufficient (error less than 0.32% at a distance of 2 879.72 m when compared with GPS coordinates),
- pipe roughness of 45  $\mu\text{m}$ ,
- K-loss value determined using historical system measurements (flow and pressure), and
- pipelines used in the model were only surface reticulation pipelines.

The network was broken down into various nodes, and these nodes were then solved using conservation of mass and node-and-loop equations derived from fluid dynamic calculation methods. The description of the mathematical model and fluid dynamic calculation methods used are outside the scope of this study. A detailed description can be obtained from Venter's work [18]. The network was solved to determine flow rates and pressures of the CAN at various points in time, including present and future values.

In Venter's study, the compressor deliveries were characterised using historical data. By defining the characteristics of the compressors, the delivery capacity of the compressor could be known at different pressures during the day. By determining the demand of the system, Venter stated that the supply could then be compiled from the historical information contained in the individual compressor characteristics.

The system controller defined by Venter could now determine the minimum number of compressors needed to satisfy the demand. Venter's approach was to stack the compressors using their maximum deliverable flow, with the last prioritised compressor selected at 50% of its rated capacity. This would ensure that there was sufficient capacity to absorb small changes in demand without having to cycle compressors.

To better illustrate the selection principle, Venter gave the following example [18]: a CAN required 25 kg/s flow and had the compressors as listed in Table 1. The compressor selector prioritised Compressor 2 and Compressor 5 based on their delivery capacities. Because combined they were only able to supply 22 kg/s, these two compressors had to be supplemented by a third compressor. To cater for small changes in demand, the compressor selector would select Compressor 4 instead of Compressor 3 to supplement the system. If Compressor 1 was added, all three compressors would be required to do capacity control using guide vanes and blow-off valves, thus reducing the system efficiency.

Table 1: Compressor characteristics table (obtained from [18])

Compressor	Flow range (kg/s)
Compressor 1	7–9
Compressor 2	9–11
Compressor 3	2–3
Compressor 4	2.5–3.5
Compressor 5	9–11

The system researched by Venter incorporated system solving and compressor selection control into one solution. Figure 6 and Figure 7 give the processes followed by Venter in the design of his control solution. The solution required the shaft set points on the surface control valves, and from there the demand would be calculated using network-solving calculations. The results would be used to select the optimal compressors for the system at its state at a specific time.

According to Venter, by updating the priorities manually in the master control of the compressor, system stability could be maintained in the event of communication failure. Venter further mentioned that the redundancy would also ensure that the system could revert back to normal when the controller was removed from the system.

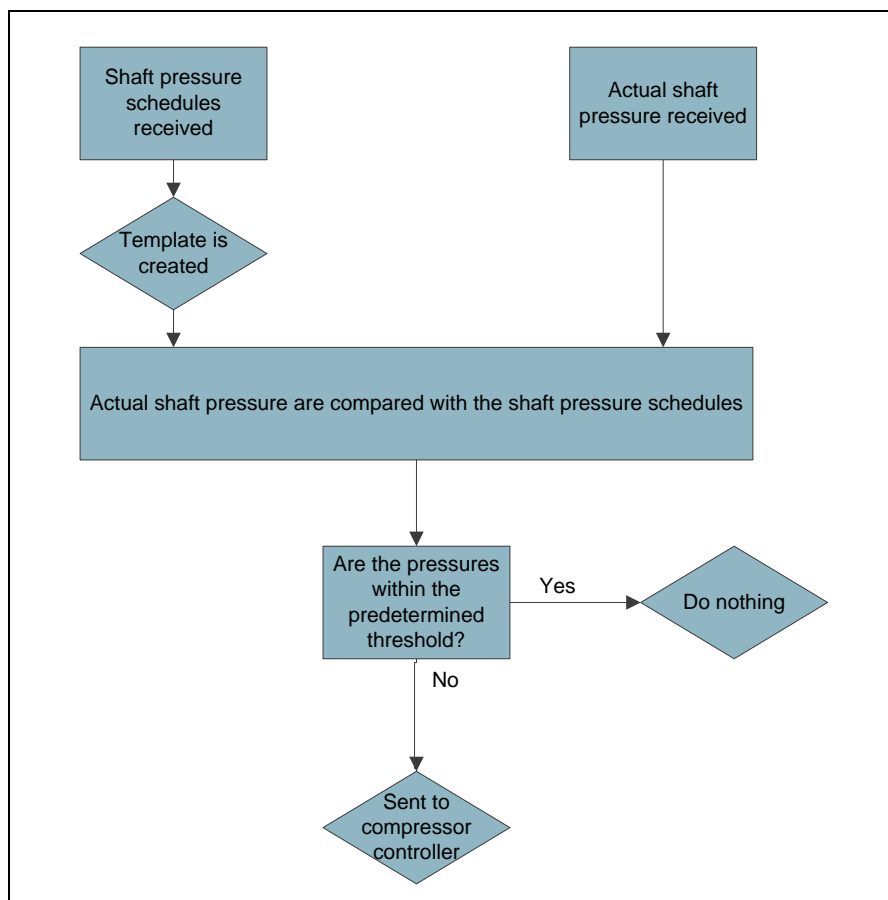


Figure 6: Network-solving process used by Venter (obtained from [18])

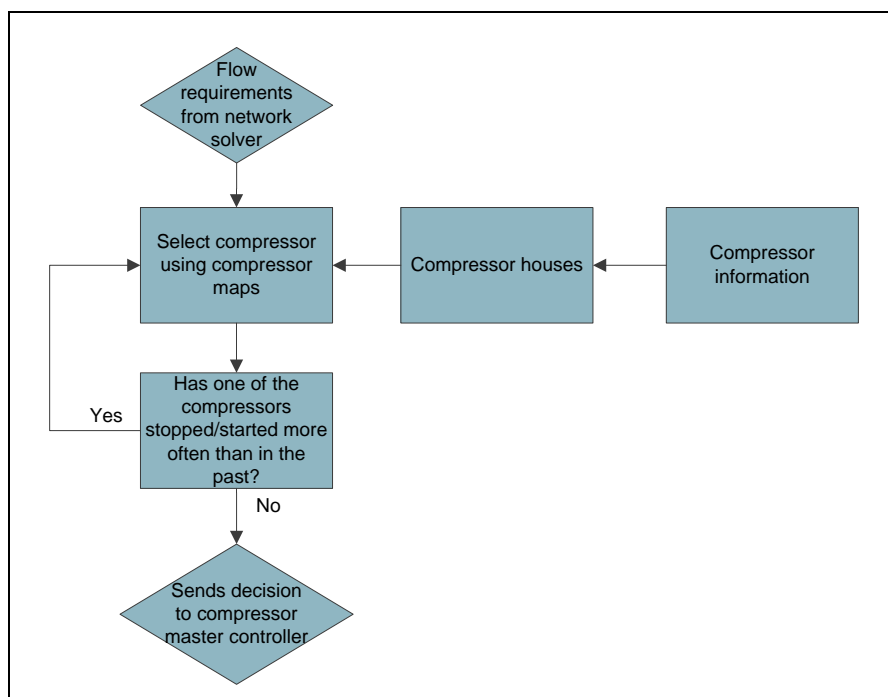


Figure 7: Compressor selection process used by Venter (obtained from [18])

The design of the system was done assuming that accuracy within 10% of actual values was sufficient. Using historical data, the model's validity was tested theoretically. When comparing the system calculations with the existing network-simulation software<sup>1</sup>, the developed model correlated closely with the existing software. The biggest deviation was roughly 3%, as can be seen from the values tabulated by Venter in Table 2 and Table 3.

Table 2: Comparison of product and existing network-simulation software pressures (obtained from [18])

Flow node	KYPipe (kPa)	DCS (kPa)	Correlation (%)
$P_{t1}$	620.90	619.90	99.84
$P_{t2}$	566.40	566.30	99.98
$P_{t3}$	566.80	566.50	99.95
$P_{t4}$	632.40	632.30	99.98
$P_{t5}$	567.00	567.00	100.00
$P_{t6}$	567.40	566.90	99.91
$P_{t7}$	621.80	621.90	99.98
$P_{t8}$	659.30	659.10	99.97
$P_{t9}$	664.70	664.40	99.95

Table 3: Comparison of product and existing network-simulation software flows (obtained from [18])

Pressure node	KYPipe (kg/s)	DCS (kg/s)	Correlation (%)
$\dot{m}_{t1}$	85.20	86.70	98.27
$\dot{m}_{t2}$	79.10	80.30	98.51
$\dot{m}_{t3}$	57.60	58.00	99.31
$\dot{m}_{t4}$	3.00	3.12	96.15
$\dot{m}_{t5}$	54.50	55.00	99.09
$\dot{m}_{t6}$	57.70	58.20	99.14
$\dot{m}_{t7}$	60.80	61.40	99.02
$\dot{m}_{t8}$	81.20	82.20	98.78
$\dot{m}_{t9}$	60.40	61.10	98.85
$\dot{m}_{t10}$	57.80	58.40	98.97
$\dot{m}_{t11}$	2.60	2.60	100.00
$\dot{m}_{t12}$	58.00	58.30	99.49
$\dot{m}_{t13}$	55.40	55.80	99.28
$\dot{m}_{t14}$	37.20	38.10	97.64
$\dot{m}_{t15}$	79.70	81.10	98.27

<sup>1</sup> Flownex and KYPipe available at <http://www.flownex.com/> and <http://www.kypipe.com/> respectively.

$\dot{m}_{t16}$	48.40	48.80	99.18
$\dot{m}_{t17}$	40.00	40.40	99.01
$\dot{m}_{t18}$	70.60	71.20	99.16
$\dot{m}_{t19}$	17.80	17.90	99.44
$\dot{m}_{t20}$	50.30	51.00	98.63
$\dot{m}_{t21}$	68.20	68.80	99.13

When the system was compared with the actual pressure data obtained from a specific site, the accuracy of the system was even higher as can be seen in Table 4. Scheduling of compressors using Venter's model resulted in fewer compressor stop/starts and reduced network power consumption. Pressure losses were calculated in the pipeline to ensure that all end users were supplied with their required pressures.

Table 4: Comparison of product and actual system values (obtained from [18])

	Shaft 1	Shaft 2	Shaft 3	Shaft 4
<b>Measured pressure (kPa)</b>	688.20	688.10	680.10	635.90
<b>Calculated pressure (kPa)</b>	689.00	683.80	683.70	641.70
<b>Accuracy (%)</b>	99.88	99.46	99.47	99.09

The model used to solve the CAN was converted to a user-friendly interface by a software development team. Venter did not mention that any testing was done to verify the conversion of the system to the new interface. The system was also only tested theoretically and against actual data using the model. Venter did recommend that the system be tested on the actual system to verify the results. The system implementation into a new interface also needed to be tested to ensure the model was correctly transferred from Visual Basic.NET to the Delphi programming language.

Although the model used had been verified, the practical implementation results could vary significantly. A problem was also identified with the static compressor characterising done using historical values. Due to the dynamic nature of the system, any static components could limit the dynamic capability of the system. Control room operators were also required to update the default priorities of the compressors manually, adding a static component to the dynamic solution. Default priorities were used as fall-back values when there was an interruption in the normal modus operandi.

Furthermore, Venter did not mention all of the instrumentation requirements of the system or the operational difficulties of the system. The implementation of the system did pose a few hurdles along the way as there were numerous untested obstacles that had yet to be identified. There could have been a significant difference between theoretical tested results and practical implementation. Although the model proved to be accurate, practical testing needed to be done to verify the system and the newly developed interface.

Van Heerden [22] proposed a compressor controller to address the need for an integrated CAN controller. The capability of the newly developed system was compared with other technologies available on the market (Table 5). The suggested solution would incorporate valve control with automatic prioritising of compressors.

Table 5: Compressor control technology summary (obtained from [22])

Name of controller	Incorporated valve control	Automated control	Manual override functionality	Manual priorities	Automated priority handling	Number of controllable compressors	Integrated control	Historical data availability	Monitoring
REMS-CM	–	X	X	X	–	∞	–	X	X
REMS-OAN	X	X	X	X	–	∞	–	X	X
PL4000	–	X	–	–	X	∞	–	X	X
AIRtelligence PROVIS 2.0	–	X	–	–	X	16	–	X	X
Hiprom Lonmin controller	–	X	X	X	–	∞	X	–	X
REMS-DCS	X	X	X	X	X	∞	–	X	X
<b>Legend:</b>	<b>X : contains the mentioned feature,</b> <b>– : feature not available in controller, and</b> <b>∞ : infinite number.</b>								

The controller would address the dynamic nature of CANs encountered in the mining industry. Van Heerden would achieve this through assigning priorities dynamically to individual compressors according to the system demand as retrieved from the incorporated valve control. Building on the research done by Venter, Van Heerden developed the controller using all of the assumptions and calculations as given by Venter. Using the numerical approach, both Venter

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and Van Heerden agreed that a 10% error in calculated values would be adequate due to the assumptions that needed to be made.

Van Heerden designed the system to [22]:

- prioritise compressors dynamically,
- calculate compressor set points dynamically,
- start and stop compressors automatically,
- simulate an air network,
- estimate the future state of an air network,
- log all data,
- control user access,
- gather data from a SCADA,
- feature an open platform communication (OPC) connection, and
- have a graphical user interface to display feedback.

According to Van Heerden, the system would be able to give an estimation of the future flow using the predetermined set points at the various end users to calculate their demand. For the real-time calculation, the flow meter readings were used to solve the actual pressure delivered to the end users. This was used to ensure that the end users received their desired pressures as given by the required PSPs. The future flow and existing flow were used to determine the priorities of the compressors, with the higher value of the two used to reduce compressor cycling.

The system design was component-based, thus allowing for future expansion of the CAN. Different components were used to characterise the system according to site-specific details. Pipeline friction and K-loss factors, diameters and lengths were used to define network reticulation. End users and compressors were also added, each with its own characteristic data embedded into the components.

With all of the inputs defined throughout the components, the system could calculate all of the unknown variables in order to dynamically prioritise the system based on actual system data. PSPs of the compressors and priorities of the individual compressors were calculated dynamically based on system demand. The starting and stopping of compressors were based on the controller designed by Du Plessis [13] that Van Heerden updated to work with the new control system.

Van Heerden's study entailed the programming of Venter's design into a user-friendly interface to be used at the mines. Van Heerden developed the system based on Real-time Energy Management System (REMS) technology as created in-house by TEMM International. The controller was the third product developed to optimise CANs, building forth on REMS-CM (Compressor Manager) and REMS-OAN (Optimisation of Air Networks). This was done in the Delphi 6 Integrated Development Environment (IDE).

The system calculations were compared with KYPipe calculations, as was the case with the original design done by Venter. The outcome was similar to that of Venter's study, with system accuracy in the region of 97–99% in most cases for both pressure and flow calculations when compared with KYPipe calculations.

The system was then tested using theoretical values, which were also satisfactory. Both the set-point and priority controllers proved their functionality during theoretical testing. After the successful testing of the software using theoretical scenarios, the system was implemented on a platinum mine.

Although the system could calculate the PSPs and priorities dynamically, stability issues resulted in the system not being able to run in full automatic control. The stability of the system was addressed, and the system was tested for extensive periods of time. The system was not subjected to abnormal conditions, such as strikes and compressor trips, to verify the control under these conditions. Other factors that could influence the system were not investigated as part of Van Heerden's study.

No indication is given as to why these stability issues occurred, and this still had to be investigated. The system needed to be tested as a stand-alone system as well, as Van Heerden's tests were only done with the developed system as an advisory system. The system should also be able to recover from erroneous inputs, a problem that was not addressed in Van Heerden's study. This could pose serious problems if the system was left to automatically control a compressor system on a mine.

Van Heerden also identified that the compressor location needed to be incorporated when calculating the compressor priorities. In larger systems, the placement of a compressor could be a valuable factor when prioritising the most efficient compressor. At that time, the efficiency prediction of the system was based on the sheer volume of the compressor. The assumption was made that the larger compressor would be the most efficient compressor. Further studies

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needed to be completed to incorporate actual power consumption of the compressor with the real-time delivery volume.

No information was given as to how the compressor characterisation was done. The compressor characterisation might as well have been a static range of delivery entered by the user, as described by Venter. If this was the case, the system had a static limitation which needed to be addressed. The system should have been able to function as a complete dynamic solution, which was not evident at that stage. The system needed to be subjected to different system configurations to test the adaptability to different compressors and network set-ups.

### *Limitations of existing compressor control systems*

Compressor control found in the South African mining industry ranges from simple non-automated control to fully automated static control. The different controls found throughout various mines that were investigated are explained in the following paragraphs. With the availability of technology on the control system increasing, control philosophies have developed and improved over time. Initially, control was simple when energy costs and carbon dioxide offset were of minor concern.

With energy cost rising, the need to match demand and supply more closely increased. As a result, the control system complexity increased as well. Although ample initiatives were deployed on the demand side to optimise the consumption, the integrated control side (supply and demand matching) developed considerably slower.

Due to the installed capacity of the compressors and the importance of compressed air on production, resistance to change on the control of compressors limited rapid development of these technologies. Although progress has been dampened, improvements have still been made. The following section indicates the new development and goal of this study.

## **1.4 Novel contributions of the study**

### *Dynamic scheduling and control of centrifugal compressors through a novel integrated approach*

During research, the following problems have been identified:

- There are only a few experienced compressor system operators in the mining sector.
- The majority of these operators are underskilled without understanding detailed system operations. Their focus is on production and not minimum energy consumption.
- Control rooms are not manned 24/7 to react to system changes timeously.

- When system operations deviate from the norm, operators are unable to respond to changes efficiently.
- Although automated compressor controllers exist, they are static in nature and incapable of adapting to changing demand without human intervention.

This study aims to resolve these problems by implementing an intelligent controller capable of operating and adapting to system changes without requiring human intervention.

#### *Combining best practice models into a new comprehensive control solution for centrifugal compressors*

During research, the following problems have been identified:

- Practical experience in system operations by technical competent personnel resulted in many instances of 'best practices' developed throughout industry.
- Some of these practices incorporated energy efficiency strategies for their specific systems.
- Knowledge is limited to the specific mines and not distributed throughout the industry.
- Previous energy efficiency initiatives implemented throughout industry proved the feasibility of these practices, but they were static and incomplete.

The aim of this study is to combine various best practices into a comprehensive automated solution that will improve system reliability and acceptance in industry.

#### *Creating a unique dynamic compressor selection model*

During research, the following problems have been identified:

- Energy efficiency projects being implemented rely on automatic reduction in supply of compressed air to maximise energy savings.
- Compressed air demand fluctuates constantly and existing control systems encountered throughout South African deep-level mines are not able to adjust accordingly.
- Compressor selection on a compressed air network is done predominantly through operator judgement based on practical experience, and not on efficiency criteria.
- Limited automatic control of compressors is done statically, and needs constant manual revision. Static control limits system efficiency as the best-fit solution is not constantly implemented due to system demand fluctuations.

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This study devises a strategy to enable dynamic compressor prioritising by evaluating actual real-time system performance data. Data is then processed to effectively schedule compressors to match a fluctuating demand.

*Embedding dynamic selection criteria to determine the most efficient compressor combinations into a compressor controller*

During research, the following problems have been identified:

- Numerous systems are encountered throughout industry, each with its own requirements and operational specifications.
- Simulation packages can aid in the selection criteria, but it is a static approach with thousands of different scenarios required to be simulated and preprogrammed.
- Actual impact and updated information such as compressor placement, delivery range, efficiency (kWh/m<sup>3</sup>) and installed capacity are required in real time for optimal scheduling to improve system efficiency.

This study aims to embed the dynamic selection model (developed during this study) into an adaptable compressor controller to improve system efficiency by enhancing system controllability.

*Evaluating unique dynamic selection models practically*

Prior to this study, the following have been achieved:

- Dynamic compressor selection models were investigated based on a mathematical approach.
- A mathematical model was developed and the concept theoretically proven, but it was incomplete for practical implementation.
- The model did not make use of real-time data for evaluation purposes and was based on historical average data.

During this study, a new model is developed and implemented into the control system. Practical implementation and evaluation of the novel dynamic selection model is done on deep-level mines in South Africa. Real-time instrument data is used and the results are evaluated.

*Developing an innovative simulation component model to simulate the effect of dynamic compressor prioritising*

During research, the following problems have been identified:

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- Simulation model exists that can evaluate system demand and the required supply will be calculated based on static inputs for a specific situation in time.
  - These models proved valuable in project investigation to determine energy saving potential.
  - All changes in system characteristics, supply and demand values require resimulations, which are time-consuming.
  - Real-time evaluation capability is required with the existing system to evaluate system performance using actual system data.

During this study, a novel integrated simulation model is developed and utilised to determine project feasibility and propose an energy efficient control philosophy.

*Following a fresh approach in analysing the impact of automatic control on centrifugal compressors*

During research, the following problems have been identified:

- Automatic compressor stop/starts are believed by some mining personnel to increase maintenance costs through additional wear and tear. This impedes compressor control automation, which in turn negatively impacts energy efficiency projects.
- These are perceived claims that are not based on practical case studies of automated compressor systems.

By evaluating the actual impact on operational cost, and cost benefit through automatic control, mining personnel can be convinced to upgrade from manual to automatic control to improve energy efficiency of other compressed air demand side initiatives.

This study evaluates and proves the financial viability of automatic compressor control using actual system maintenance and financial data.

*Developing a new systematic model to investigate and evaluate true energy savings potential when implementing dynamic compressor selection technology on a compressed air network*

During research, the following problems have been identified:

- Due to the dynamic nature of compressor systems, project investigations can be time-consuming due to numerous different scenarios that have to be simulated for the investigation.
- Oversights in scenarios tested can result in incorrect and costly errors usually only realised during the project implementation phase.

This study develops a new systematic model:

- By using the dynamic compressor selector in parallel with the existing system, simulations can be done using real-time system data in analysing true potential savings.
- By analysing project financial viability based on actual, real-time system operational constraints.

This study will use the DCS system to investigate, adjust and manually test proposed network configurations before actual project implementation. This model will reduce investigation cost and time and minimise human oversights.

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## 2 Compressor control systems

### 2.1 Introduction

Due to the vast number of CANs that exists throughout the industrial sector, compressor control is not a new phenomenon. Compressor capacity control and system controllers have been developed and implemented throughout the world, and the mining industry is no exception. The main focus over the years has been on capacity control and surge control, which left a gap in CAN system controller development. This chapter does a detailed investigation into existing technologies that exist throughout industry, with a special focus on the systems encountered in the South African mining sector.

In order to understand a CAN completely, one must identify all of the end user equipment that uses compressed air. This equipment has to be specified according to their flow and pressure requirements. In a typical mine, the system can be divided into surface and underground sections, both which have their own list of requirements.

### 2.2 Compressed air application in mining

#### 2.2.1 Surface compressed air application

On surface, compressed air is conveyed to the various end users using an extensive network of pipelines. Although the production operations are predominantly underground, some compressed air is required on the surface as well. Users situated on the surface include processing plants, workshops, agitation dams and pneumatic control equipment.

The plants use compressed air for the following processes:

- agitation,
- leaching,
- control equipment such as pneumatic valves and cylinders,
- flotation, and
- pneumatic tools.

Usually, the restrictive requirements are agitation and floatation; these equipment require high volumes of air. Although the typical equipment such as cylinders and valves require high pressure, they only require a low flow. When pressure is reduced to below the equipment's minimum pressure requirements, cylinders and valves may fail resulting in costly process interruptions.

Depending on the workshop, different compressed air users can be encountered. A blacksmith workshop, for example, uses air hammers to reshape iron (used in the reconditioning of used drill tips). Mechanical workshops use pneumatic tools, tyre inflators and other low-flow, high-pressure tools. Although these users require pressures in excess of 400 kPa, they are primarily operated in conjunction with the production shifts and high pressures are usually available.

Some cases were encountered where the workshops required an additional compressor to sustain the high pressure required<sup>2</sup>. In this case, stand-alone compressors with adequate receivers (pressure vessels for compressed air storage) were installed. With the use of receivers, the fluctuating demand could be met using much smaller compressors. Mechanical, boilermaker and rock-drill workshops were all supplied using the same compressors.

At the shafts, compressed air is used for surface operations in numerous ways. High pressure (in excess of 400 kPa) is usually required to operate loading boxes and ore pass chutes fitted with pneumatic cylinders. This pressure requirement is easily met since the surface pressure seldom drops to below this level. Low flow is required to operate these loading boxes and chutes, but pressure is vital to prevent ore spillages.

Pneumatic control valve stations are used to control the pressure supplied to the shaft. A typical valve set-up is given in Figure 8, and comprises a main line and a bypass control valve (electric actuators fitted). The operating pressure of a typical pneumatic valve is above 400 kPa [23], [24]. The pressure upstream of the valve (higher pressure side) is normally sufficient for safe and effective operation. Pneumatic actuators are also used on other valve applications such as water supply control valves.

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<sup>2</sup> As encountered at a platinum mine in the North West Province during DSM project implementation.

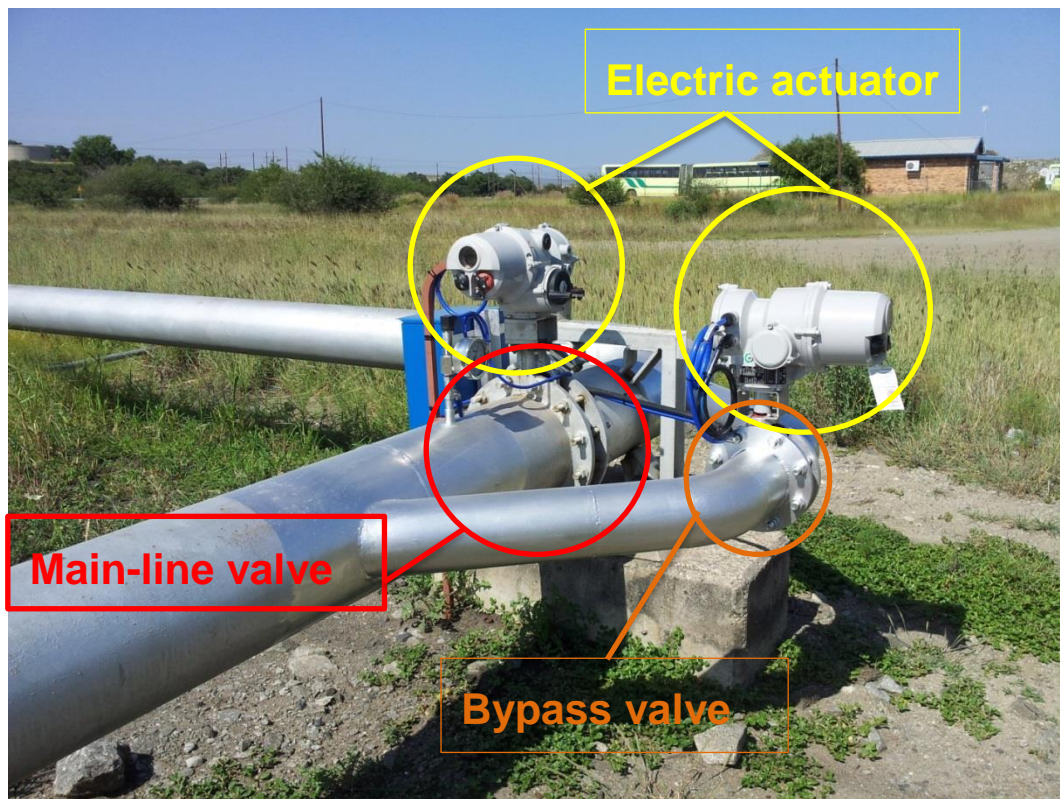


Figure 8: Control valve set-up with electric actuators fitted

At some of the bigger mine set-ups, railway systems are used to transport ore from the shafts to the processing plants. At the shafts, the trains (or hoppers) are loaded using pneumatic silo chutes. When the train arrives at the plant, it is connected to the CAN from where pneumatic cylinders (Figure 9) actuate the hopper doors to tip the ore into the catchment area. Here, as is the case with many other cylinders, a pressure in excess of 400 kPa is required to operate the hopper doors effectively.

One of the often overlooked surface consumers is the distribution network. Due to the size of the network, leakages are often left undetected for extended periods of times, thus contributing to compressed air consumption. Even when leaks are excluded, the extended network reticulation generates a loss component in the network due to friction losses. Inadequate sized columns can result in excessive pressure drops in high-flow scenarios.

Other equipment exist that is not mentioned in this section but that also contribute to compressed air consumption. The specific equipment covered in this section were discussed because they contributed the most to the surface restraints in the energy efficiency projects encountered during the research. Due to energy efficiency projects following a systematic

approach, additional equipment may be encountered that will create the next limitation to further reduce compressed air usage.

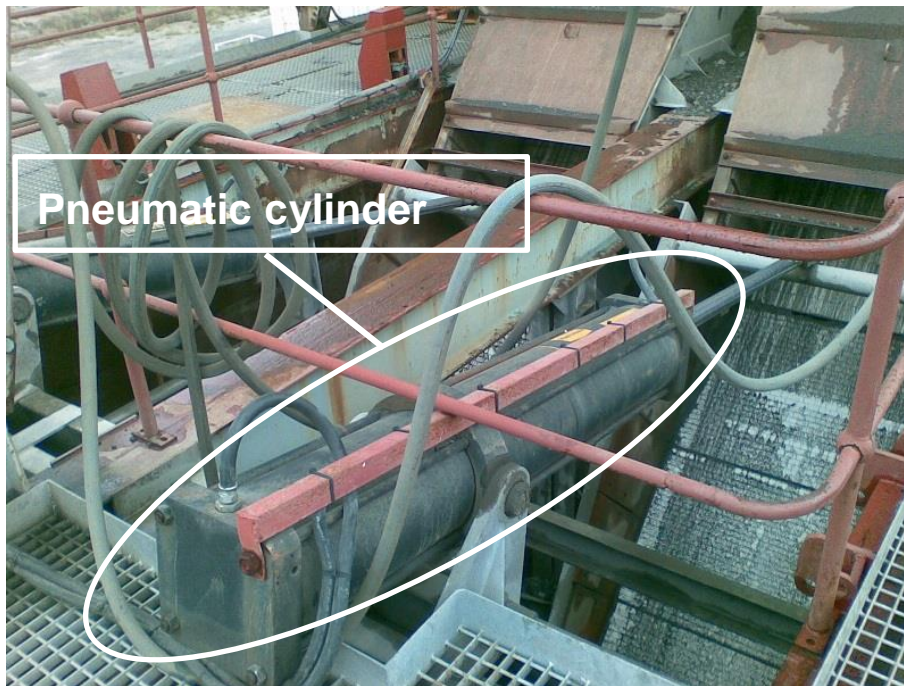


Figure 9: Pneumatic cylinder on ore chute door

### 2.2.2 Underground compressed air application

Traditionally, most hard-rock mining operations use pneumatic drilling when extracting precious ore. Although electric drills have been implemented in some mining shafts [25], they are only used to a minor extent. Table 6 gives a short summary of compressed air users encountered in typical underground mining operations requiring high pressures. Rock loaders found in mines can be electric, hydraulic or pneumatic. Although electric and hydraulic loaders are being implemented more frequently due to energy efficiency improvements [26], pneumatic loaders still dominate the South African mining industry [27].

Table 6: High-pressure requiring compressed air users

Equipment	Air requirement
<b>Pneumatic rock drill</b>	350–500 kPa [28], [29]
<b>Rock loaders</b>	10–15 m <sup>3</sup> /min at 450–750 kPa [27], [30]
<b>Air hoists</b>	400 kPa [31]
<b>Pneumatic winches</b>	Specification: 600–630 kPa [32], [33] Actual: 400–700 kPa [34]

Equipment	Air requirement
<b>Pneumatic control valves</b>	>400 kPa [23], [24]
<b>Pneumatic actuators on chute doors</b>	400–450 kPa <sup>3</sup>

Compressed air control valves are furthermore installed underground to add controllability to the system. In some instances, when supply is limited (due to compressor failure) air is only directed to the most productive levels to minimise production losses<sup>4</sup>. On the ore transportation system, pneumatic chute doors, loading boxes, bin doors and so forth, are all actuated using pneumatic cylinders. An example of one of these cylinders is shown in Figure 10. These cylinders are critical components in the production cycle, and failure due to insufficient pressure may lead to production losses.



Figure 10: Pneumatic actuated cylinder<sup>5</sup>

<sup>3</sup> Based on practical implementation results of DSM projects.

<sup>4</sup> Level valves were closed on all levels on a main production shaft to allow system pressure to rise and stabilise. Valves were opened systematically as workers reached the drilling areas. This allowed the mine ample time to start additional compressors as the load gradually increased.

<sup>5</sup> Photograph taken during a site visit to a mine situated in the North West Province.

Other equipment, which will not be discussed here, that also requires compressed air includes, for example, pneumatic tools, pneumatic pumps and the blowers used in agitation of underground dams.

Compressed air is commonly wasted when ventilation requirements are met by using this expensive service. Although this is bad practice, it is allowed in some mines<sup>6</sup> when problems are experienced with the ventilation system and underground temperatures become dangerously high.

### 2.2.3 Other consumers in a compressed air application

Other factors in a CAN that could also be classified as ‘consumers’ of compressed air are line losses and leaks that result in pressure losses. Compressors are commonly operated at higher pressures to overcome this added constraint on the network. Higher pressures require increased energy consumption, which in turn reduces the system efficiency. Higher pressures also increase the volume of compressed air lost through leaks, which further reduces the energy efficiency of the system.

Network layout and compressor placement also contribute to system efficiency. Pipelines conveying compressed air to the various end users should be as straight as possible. Furthermore, pipe diameters should be correctly sized for the flow requirement of the various consumers. Various project investigations done during the course of this study found that optimal compressor placement could result in improved system efficiency.

One of the biggest platinum producers in South Africa required a detailed investigation to determine the optimal placement of a new compressor at one of their operations. The compressor to be placed within their vast compressor network had an installed capacity of 4.8 MW, delivering 40 000 m<sup>3</sup>/h of compressed air at rated conditions. The mine had one of three possible positions where the compressor could be located.

The optimum placement of the compressor would result in a higher average ring pressure. The system was simulated by entering all of the network characteristics and data available in fluid dynamic simulation software. Piping configurations were available, together with the GPS coordinates of the entire network. The simulation model was verified using historical data

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<sup>6</sup> A ventilation shaft at a mine in Welkom had a rockfall that blocked ventilation passages. Compressed air was used as a short-term solution to provide ventilation.

available for low-, medium- and high-flow conditions at the end users, with an average accuracy of 96%. The verification data is given in Table 7.

Table 7: Simulation verification

Simulation results using historical data			
High-flow scenario			
Shaft	Actual pressure [kPa]	Simulated pressure [kPa]	Error [%]
Shaft A	499	530	6
Shaft B	468	482	3
Shaft C	474	467	2
Shaft D	480	520	8
Shaft E	546	532	3
Shaft F	484	517	6
Medium-flow scenario			
Shaft	Actual pressure [kPa]	Simulated pressure [kPa]	Error [%]
Shaft A	554	526	5
Shaft B	486	472	3
Shaft C	503	468	7
Shaft D	522	527	1
Shaft E	568	545	4
Shaft F	524	500	5
Low-flow scenario			
Shaft	Actual pressure [kPa]	Simulated pressure [kPa]	Error [%]
Shaft A	497	496	0
Shaft B	453	462	2
Shaft C	460	460	0
Shaft D	474	518	8
Shaft E	554	518	6
Shaft F	475	481	1

The compressor was then simulated at each of the three identified locations, and the average pressures at the end users were recorded. In Table 8 it can be seen that the placement of the compressor at Shaft D increased the average pressure the most, followed by Shaft C and then Shaft F. Part of the investigation was simulating the removal of four compressors from the network which were inefficient and far away from operations. The network constraints resulted in excessive pressure drops and the bursting of surface piping (Figure 11) when compressor set points were above 550 kPa.

Table 8: Effect of compressor location on system pressure

Compressor pressure at specific locations			
Shaft	Shaft C (kPa)	Shaft D (kPa)	Shaft F (kPa)
Shaft A pressure	520	520	520
Shaft B pressure	532	532	532
Shaft C pressure	480	478	425
Shaft D pressure	466	479	411
Shaft E pressure	529	529	528
Shaft F pressure	516	516	521
Average pressure	507	509	489

From the simulation results it was found that the pressure drop of the existing system was much higher than it should have been. If the pressure drop was resolved, it would not be necessary to add compressors to the network. The outcome of the investigation was that the network had to be inspected before the additional compressor was sourced. The pressure drop could be attributed to blockages or leakages in the pipeline. The pipeline was later upgraded to reduce the pressure drop and no additional compressor was installed.



Figure 11: Photos of a burst compressed air pipeline at a platinum mine

Another investigation was conducted at a platinum mine where a compressor's blow-off dumped air excessively to the atmosphere to prevent compressor surge. Air could not be exported to the rest of the CAN due to network piping restrictions. As can be seen in Figure 12, the compressor was situated at a low-flow consumer shaft (Point A) and connected to the network piping with an old 350 mm column (Point B). The compressor had an installed capacity of approximately



Various other investigations into correct sizing of air columns have been conducted at clients in the mining industry. These investigations indicate that the need exists to investigate and optimise CAN reticulation and infrastructure. As indicated, in some instances compressors could be stopped if pipelines were upgraded to the appropriate sizes. Due to the financial impact of these infrastructure upgrades, lack of software, equipment and time, clients do not always implement these changes.

#### 2.2.4 Usage patterns of compressed air equipment

When all of the equipment that were discussed in the previous three sections are considered, a typical usage pattern can be constructed for a typical mine. Although the majority of mines follow a drilling, blasting and cleaning shift operational schedule, not all mines are the same. Figure 14 shows the compressed air requirements of two neighbouring platinum mines (Mine A and Mine B) of two of the leading platinum producers, as well as the consumption of one of the leading gold mines (Mine C).

When the consumption of the platinum mines are compared with the consumption of the gold mines, some differences and similarities can be seen. This indicates the major differences from mine to mine, as well as from industry to industry. Mine A and Mine B has a proper bell-shaped curve where compressed air generation was reduced significantly during non-production times. In comparison, Mine C operated almost constantly at maximum delivery during the shifts requiring compressed air.

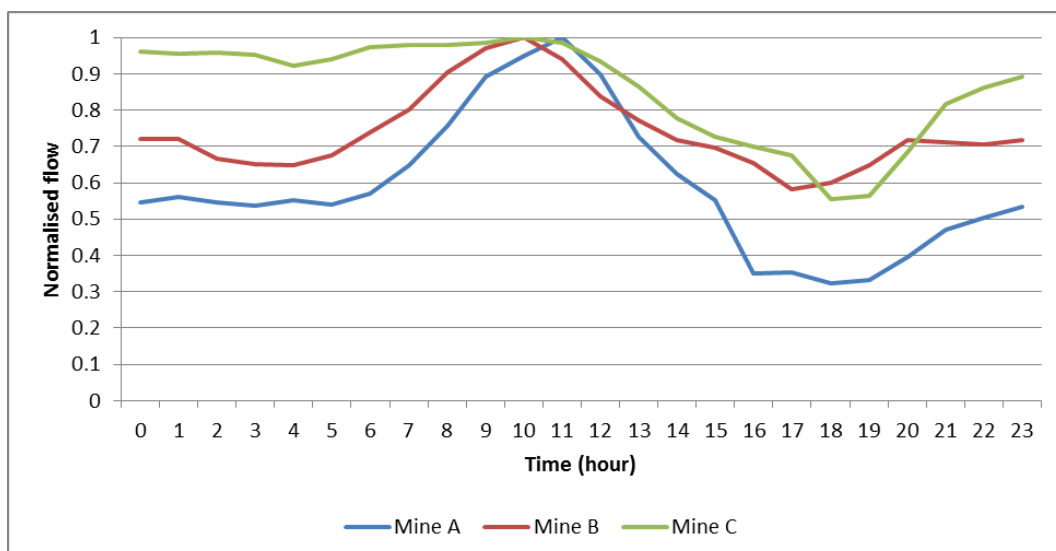


Figure 14: Mine flow comparison

Compressed air usage varied from day-to-day on the same shaft as can be seen in Figure 15. Air usage patterns differed for the same weekday week-on-week as can be seen on 5 April, 12 April and 19 April. An adaptable controller that could cater for all of the different scenarios, as well as for the varying demand, could benefit the mining industry significantly by improving CAN efficiency.

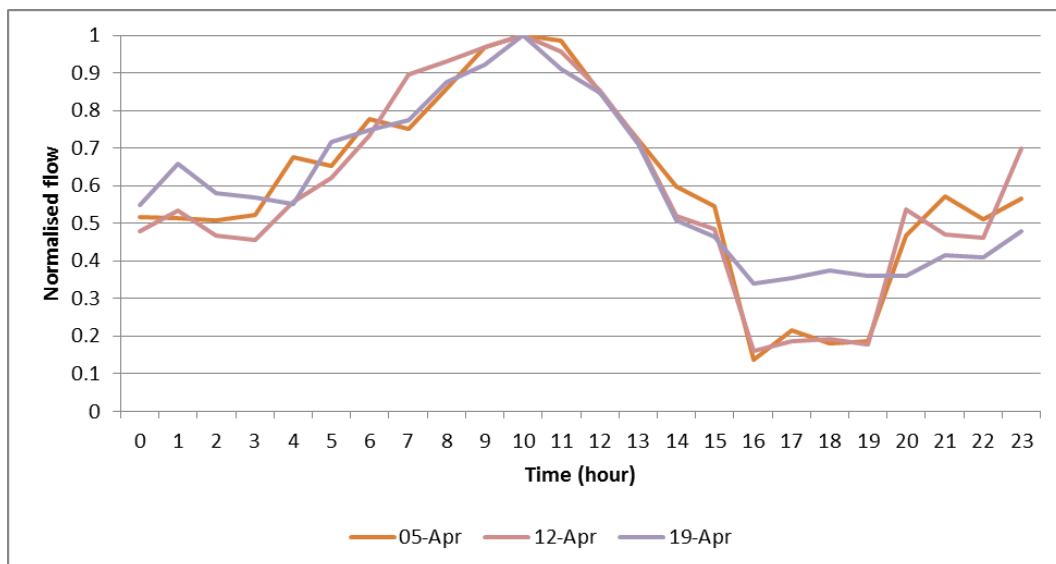


Figure 15: Shaft flow comparison

## 2.3 Compressor and system controllers

### 2.3.1 Basic compressor capacity controllers

Capacity control in this document refers to controlling the delivery capacity of a compressor in terms of kg/s or m<sup>3</sup>/hr to match the required demand. This section will investigate the more common capacity control methods, discussing their advantages and disadvantages. Compressor capacity can be controlled by the following methods [3], [35]:

- starting and stopping the compressor,
- limiting the air into the compressor (suction throttling),
- limiting the air delivered by the compressor (discharge throttling),
- loading and offloading the compressor,
- changing the angle of the intake air (guide vane modulation),
- bleeding delivery into atmosphere (through blow-off valve), and
- using variable speed control.

According to Horowitz et al. [3], the most efficient method to control supply capacity is by using speed control, followed by guide vane modulation, suction throttling and then discharge throttling. No mention is made of using blow-off valves as a form of capacity control, however, Hanlon [4] regards bypass control as very inefficient. Loading and offloading of compressors causes other problems such as surge and a reduction in efficiency, and it is not regarded as good practice [4].

Starting and stopping of compressors may also lead to excessive heat build-up in alternating current electric motors [35]. This heat build-up may in turn result in motor failure and increased maintenance costs. Care should be taken when automated control is done on compressors to limit the number of stop/starts within a specific time window. Capacity control limits the flow supplied by a given compressor by using different techniques. It is, however, important to have active surge control on these compressors to avoid severe damage to the compressors [6]. In order to do this, the compressor needs to be characterised using a compressor characteristic curve.

### Compressor characteristic curves

A centrifugal compressor can be characterised by the following equation [3]:

$$H = \frac{\tau\omega}{W} = \frac{n}{n-1} ZRT_{inlet} \cdot \left[ \left( \frac{P_{Discharge}}{P_{Inlet}} \right)^{\frac{n}{n-1}} - 1 \right] \quad (1)$$

Where

Table 9: Definitions of symbols for compressor characterisation

Symbol	Description	Unit
$H$	Polytropic compressor head	m
$\tau$	Motor torque	J
$\omega$	Angular velocity of shaft	Radians/hr
$W$	Mass flow through compressor	kg/hr
$N$	Polytropic coefficient	–
$Z$	Gas compressibility factor	–
$R$	Gas constant	–
$T_{inlet}$	Inlet temperature	K
$P_{Discharge}$	Discharge pressure	Pa
$P_{Inlet}$	Inlet pressure	Pa

By plotting the equation above, a compressor characterisation curve is obtained as given in Figure 16. This indicates the critical operation point of the compressor as designed by the original equipment manufacturer (OEM). Although this curve can be constructed for all system pressures and flows, it is usually limited by the surge and stonewall lines.

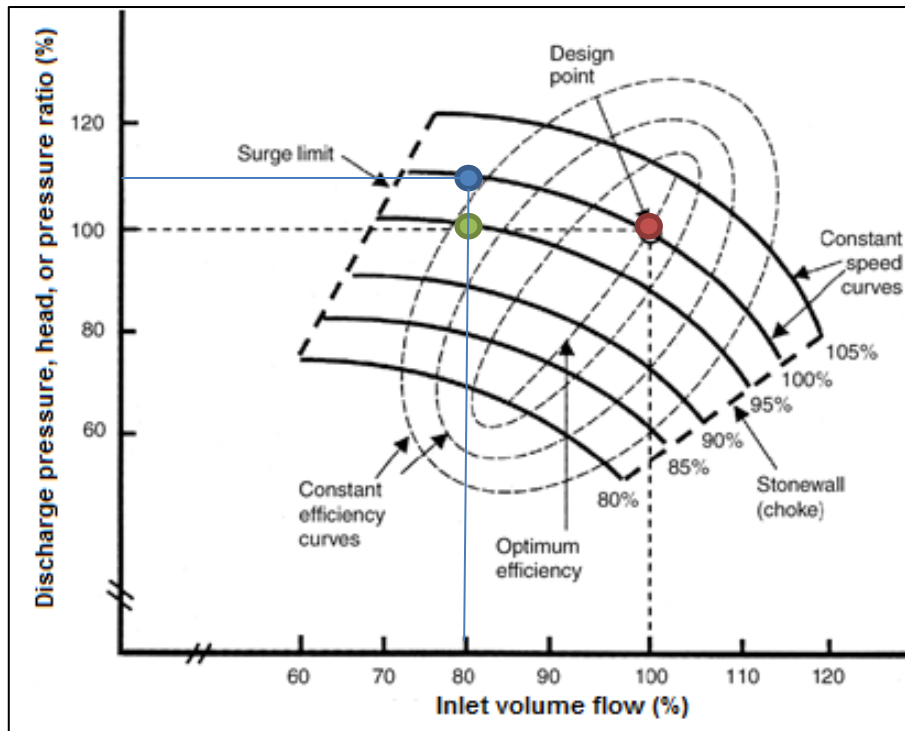


Figure 16: Typical example of a compressor characterisation map<sup>7</sup>

### Discharge throttling

Discharge throttling is when the delivery of a compressor is limited by using a control valve on the output of the compressor. Due to the control being done on the high-pressure end, the pressure drop across the control valve is large. This results in a significant reduction in compressor efficiency.

Discharge throttling is the least efficient capacity control method [36], [37]. The turndown (or capacity reduction) on the delivery flow should, however, be limited as turndown may lead to compressor surge [36]. Discharge throttling does not reduce the delivery capacity of a compressor [38].

<sup>7</sup> Source: [http://petrowiki.org/images/e/e6/Vol3\\_Page\\_279\\_Image\\_0001.png](http://petrowiki.org/images/e/e6/Vol3_Page_279_Image_0001.png)

To better illustrate the effect of discharge throttling, consider the compressor map given in Figure 16. In order to reduce the delivery flow from 100% rated flow (indicated by the red dot), to 80% flow (indicated by the blue dot), the differential pressure in the compressor must be increased by 10%.

With a differential pressure increase of 10%, the compressor will have to work harder to achieve the system requirements, thus reducing energy efficiency. Surge control is also significantly more difficult to achieve with discharge throttling [6].

### *Suction throttling*

Suction throttling of a compressor entails limiting the air in the suction column of a compressor through the use of a modulating control valve. This control valve effectively lowers the suction pressure of the compressor, which in turn reduces the discharge volume. The inlet gas density is also reduced, resulting in the compressor power consumption being reduced [36], [37].

Suction throttling is more efficient than discharge throttling due to the significant lower pressure drop across the control valve [36]. The capacity of the compressor can be turned down by 53.7% using suction throttling [38]. Although suction throttling is not the most efficient capacity control technique, it is still a very effective method [39] used on some of the compressors encountered in the mining sector. Some compressors are not retrofitted with inlet guide vanes or variable speed drives (VSDs) and suction throttling is used<sup>8</sup>. Care should be taken to avoid closing the throttling valves in both suction and discharge throttling. As with discharge throttling, surge avoidance control is complicated as the operating point can shift drastically on the compressor curve with suction control valve modulation [36]. Positive flow is required through the compressor at all times to avoid surging and overheating of the compressor [7]. A minimum valve position is usually programmed into the controller to avoid this from happening.

### *Inlet guide vane modulation*

Inlet guide vane control on a compressor is the most common capacity control encountered in the South African mining industry. By prerotating the air going into the compressor, the capacity is reduced through reduction in the compression head [40]. Not only is the capacity reduced, but the energy usage of the compressor is also reduced much more than when throttling techniques are used [40].

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<sup>8</sup> Encountered at various mines during the implementation of DSM projects.

Inlet guide vane control is optimal when combined with a proper surge avoidance controller. By having active surge control, the flow boundaries of the compressor are known based on the characteristic curve of the compressor. This enables the flow reduction to be turned down to the absolute minimum while mitigating the risk of surge. Typical turndown using inlet guide vane control is 62.3% [38].

Inlet guide vane control is done in conjunction with surge avoidance using the same controller. PLCs are used increasingly in modern control strategies, together with high reaction speed actuators on the inlet guide vanes. Increased compressor safety and reaction times are an additional benefit using modern equipment to do inlet guide vane control. Inlet guide vane control does not result in a sudden increase or decrease of suction or delivery pressures, and is, therefore, a safer control method than throttling [36]. This enables the controller to operate the compressor much closer to the surge line, increasing efficiency without compromising the reliability of the compressor.

### *Loading and offloading*

Loading and offloading of compressors is done by controlling the suction valves, inlet guide vanes and blow-off valves of the compressor. A previously defined minimum suction valve opening, or guide vane opening, is used and the blow-off valve is opened fully. Due to the delivery being dumped to atmosphere, the compressor no longer contributes to the system and is, therefore, seen as offloaded. A non-return valve prevents system air from reversing through the compressor. In the offloaded position, a compressor can reduce its power consumption by up to 71% [41].

By loading the compressor, the process explained above is reversed to allow the compressor to contribute to the system. The blow-off valve is slowly closed and the suction throttle or guide vanes are slowly opened to increase delivery of the compressor. Loading and offloading of the compressor is an alternative to stopping and starting the compressor. This can be done effectively if sufficient compressed air storage capacity is available [35].

This is helpful in cases where outdated switchgear prevents the stopping and starting of compressors<sup>9</sup>. By offloading a compressor, all delivery of a compressor is removed from the system. On some of the mines, loading and offloading of older compressors is prohibited due to concerns of motor temperature and vibrations that may lead to compressor trips.

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<sup>9</sup> Technique used to perform peak clipping project at a gold mine in the Randfontein region.

### Variable speed drives

VSDs can be applied to limit the compressor delivery by reducing the rotational speed of the compressor [42]. McIn [6] believes that VSD capacity control is the most efficient method to control the capacity of a compressor. Active surge control has also been developed using VSDs and simulations confirmed the concept [43].

For a constant system pressure as indicated in Figure 17, a 20% reduction in speed resulted in a flow reduction of almost 6 000 lbm/h (0.76 kg/s) [3], [44]. At Point 1 (indicated in red) on the compressor characteristic map, the speed is 100% and the delivery of the compressor is roughly 9 800 lbm/h (1.23 kg/s). By reducing the speed to 80%, the flow is reduced to 3 700 lbm/h (0.47 kg/s) at Point 3 (indicated in blue). Therefore, a 20% speed reduction resulted in a 62% decrease in flow delivery.

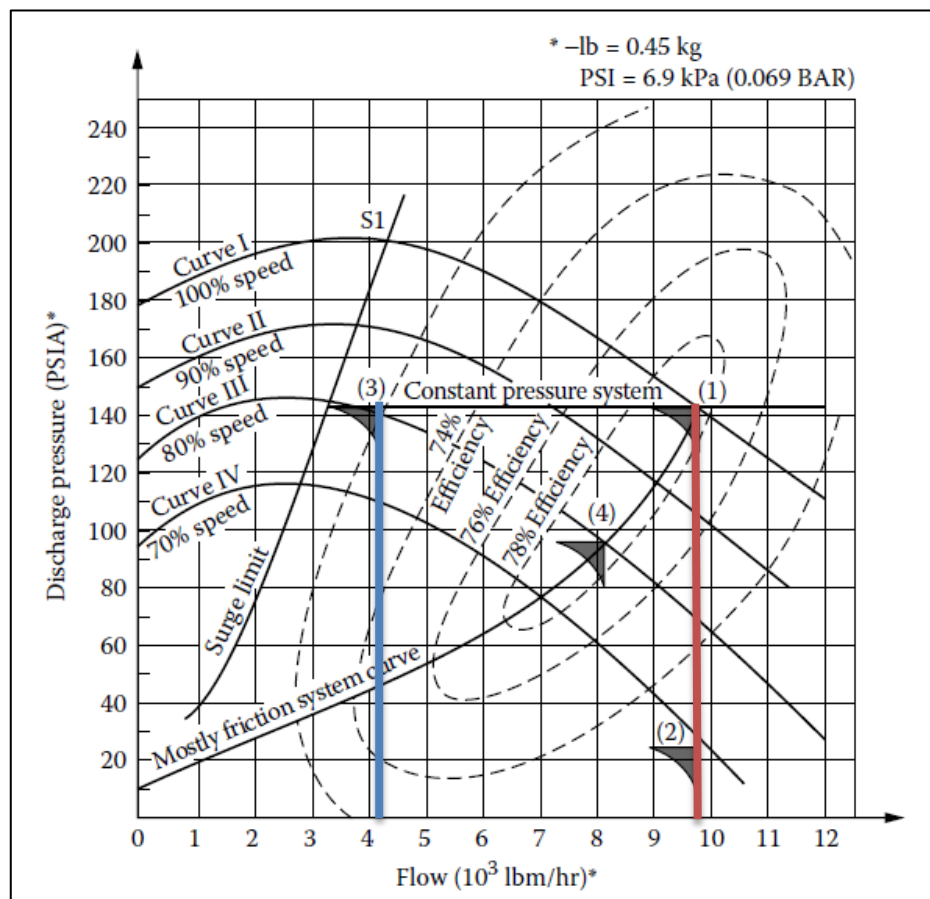


Figure 17: Capacity control using VSD (obtained from [3])

With the reduction in speed and flow, the energy consumption of the compressor also decreased accordingly [45]. In the South African mining industry, VSDs with a typical rated

capacity of 4–15 MW are required. These compressors are usually supplied from 6.6 kV and 11 kV incomers<sup>10</sup>.

Drawbacks of VSDs include high capital cost and limited proof of concept on larger centrifugal compressor machines [35], [46]. This delayed the implementation of VSD technology on compressors larger than 1 MW in the mining industry (as no records could be found of such installations<sup>11</sup>). Typical VSD costs could be anywhere in the region of (R2 200) per kilowatt installed capacity [47]. A VSD for a 4.8 MW compressor would, therefore, be close to R11 million.

When taking the cost of these VSDs and the cost of electricity in South Africa into account, we can evaluate the payback periods. Consider a 4.8 MW compressor with an installation cost of R11 million and an average electricity cost of R0.55/kWh. The situation will be evaluated for three scenarios:

- Control for 24 hours per day.
- Control for 18 hours per day.
- Control for 10 hours per day.

The 18-hour control period excludes the peak production times in a typical mine. The 10-hour control period is the period where control is usually permitted on CANs due to production time constraints.

When the control is only done during the 10 hours usually permitted on mining applications of compressed air control, the capital cost of VSDs can be a major drawback. With payback periods ranging from two to five years when savings of 1.1 MW to 2.7 MW should be achieved, this reduces the feasibility of this technology. By expanding the control to 18 or 24 hours per day as given in Table 10, the required savings are reduced considerably. Achieving savings for these extended periods of time are not generally achievable on CANs.

Table 10: VSD savings required to achieve payback period

Payback period	Savings required (kW)		
	Over 24 hours	Over 18 hours	Over 10 hours
1	2 283	3 044	Not feasible
2	1 142	1 522	2 740

<sup>10</sup> Statement based on actual findings in the South African mining sector.

<sup>11</sup> More than 100 DSM projects done in the mining sector.

3	761	1 015	1 826
4	571	761	1 370
5	457	609	1 096

Figure 18 gives a graphical representation of the payback periods when a power reduction of 10–50% is achievable, using the data in Table 11. Here payback periods range from one year to more than 11 years, depending on the control period and achievable savings. The mining industry in South Africa has experienced significant financial difficulties due to crippling strikes, increased operational costs and lower commodity prices over the past two years. With the financial difficulties experienced by the mining industry, projects with extended payback periods are not high on their priority lists. When the capital cost is considered with the increased difficulty of operating the compressor using variable speed technology [48], VSD technology is not a viable solution at this time. Reduction in installation costs of VSDs might see a change in the adoption of VSDs on large centrifugal compressors.

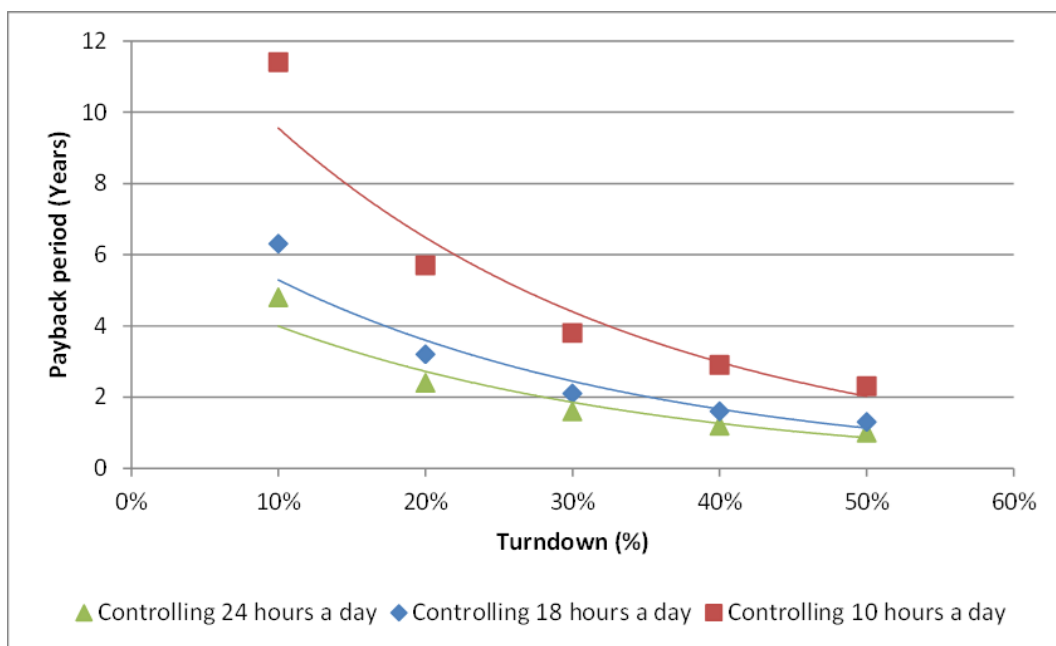


Figure 18: Graphical representation of VSD payback period versus required power reduction

Table 11: VSD payback period versus compressor power turndown

Power turndown	Payback period (years)		
	Controlling 24 hours a day	Controlling 18 hours a day	Controlling 10 hours a day
10%	4.8	6.3	11.4
20%	2.4	3.2	5.7

30%	1.6	2.1	3.8
40%	1.2	1.6	2.9
50%	1.0	1.3	2.3

### 2.3.2 Compressed air network controllers

#### *Supply optimisation*

Capacity control technology on individual compressors can now be used in a bigger CAN. In order to achieve the best results, control systems are usually implemented to control compressors automatically. Various technologies exist that perform different types of control in different parts of the CAN. Some of these systems also combine different control strategies to achieve improved results. Capacity control forms part of supply side control initiatives and various existing systems will now be discussed. Due to the long lifespan of centrifugal compressors, compressors undergo various upgrades on their control systems over the lifetime of a compressor [6].

Some of the older capacity control systems were commonly manufactured by Moore Industries International. These older capacity controllers regulated the delivery pressure of compressors by adjusting the inlet vanes or throttle valves on the suction side of the compressor, and by regulating the blow-off valve on the delivery side. The blow-off valve dumps the excess of generated compressed air to atmosphere, thereby limiting the supply volume of the compressor and maintaining positive airflow through the compressor to avoid surge [6].

The Moore controller, effective for pressure control, was an expensive way of capacity control. Although blow-off valves are still used today, dumping compressed air to the atmosphere should be avoided as far as possible. When compressors are run with their blow-off valves open and inlet guide vanes cut back to a minimum, the compressors are not contributing to the system anymore.

To reduce the energy wasted through blow-off valves, compressor manager systems have been implemented with great success in the mining industry [12], [13], [49]. These systems monitor system pressure, compressor set-point pressure, feedback from positioners installed on the guide vane/suction throttle valves, as well as the blow-off valve position. Timers are triggered when certain conditions are met, and once the timers run out a signal will be sent to the operators.

The signal indicates whether a compressor can be stopped or started to achieve energy savings while maintaining system requirements. Capacity control will still be done using Moore controllers, but the feedback from the Moore controller will be used as input together with pressure transmitters installed in the system. This provides significant savings, but further improvement is still achievable.

Compressor set-point control incorporated into a compressor manager system enables the system pressure to be reduced during non-production times. Lower system pressure results in significant energy efficiency savings [14], but requires PLCs to be installed to communicate with the Moore controllers.

With the installation of PLCs, improved functionality is obtained as compressor performance maps can be incorporated into the control system [6]. This enables improved intelligent surge protection, as the operating point of the system can be monitored. With the operating point of the compressor known, the compressor can be operated much closer to the surge point, thereby improving controllability [50], [51]. Compressors can also be operated at improved efficiency points on the compressor map, with increased capacity ranges through these control systems [6], [51].

By adding smart capacity control functionality to the compressor manager and control systems, systems using multiple compressors can be controlled more efficiently [51]. Whether operating in series, parallel or a combination of the two, load can be distributed to the different compressors using preprogrammed algorithms [50].

Smart systems have also been developed over time, adding dynamic simulation to the compressor control. Dynamic simulation technology usually entails the simulation of compressor operating points using various system characteristics as inputs, such as pressure, flow, temperature and pipe layouts. [50]. These inputs are then used together with historical data to predict system response for testing control philosophies before commissioning and for troubleshooting purposes [5].

Modern compressor control systems are used for capacity control, load distribution, pressure control and condition monitoring of compressors [52]. Intelligent controllers identified in the research have adequate features to control compressors effectively.

The controllers will now be explained shortly using their key features. Starting with basic controllers and moving to the more advanced controllers, a good understanding is obtained of

how controllers improved over time. Significant improvements have been made since the initial Moore controllers.

### **Initial REMS-CM controller [12], [13], [49]**

A controller that was initially implemented in the South African mining industry is the REMS-CM controller [13]. This controller made basic suggestions to operators to stop and start compressors as required in the early stages of DSM initiatives. The system was software-based and ran on a Windows® operating system. It retrieved the required information through an OPC that interfaced with SCADA systems. This was the first step in compressor management and it yielded substantial savings [49], [53]. Some of the key aspects of the systems were:

- ✓ combining Moore control between compressors (load sharing),
- ✓ PSP control,
- ✓ historical data server,
- ✓ start/stop of compressors through alarm indication to operator,
- ✓ alarm and condition monitoring, and
- ✓ software-based.

The system had some drawbacks that included:

- ✗ no prioritising of compressors,
- ✗ constant manual intervention required from operators, and
- ✗ only basic compressor control.

### **CAMS 320 [54]**

Compressed Air Management Systems (CAMS) 320 is a controller developed in Belgium and manufactured by Metys SA [54]. This system focused on supplying adequate amounts of compressed air and simultaneously achieving energy savings. The system was based on the following control strategies:

- ✓ capacity control,
- ✓ automatic stopping/starting of compressors,
- ✓ loading/offloading of compressors,
- ✓ prioritising compressors,
- ✓ load sharing,
- ✓ alarm and condition monitoring,
- ✓ hardware-based, and
- ✓ dynamic priorities.

Although the system had intelligent control, it did have some disadvantages:

- ✗ static demand scheduling – system demand was preprogrammed based on historical data,
- ✗ no demand control – compressor-focused controller, and
- ✗ no mention of surge control that requires additional components to achieve optimal efficiency of compressors.

### Ingersoll Rand controller ASC/ASM [55], [56]

Ingersoll Rand developed two controllers to manage the supply of compressed air. These controllers are the Air System Controller (ASC) and the Air System Manager (ASM). Figure 19 displays a typical set-up as configured in an ASM system.

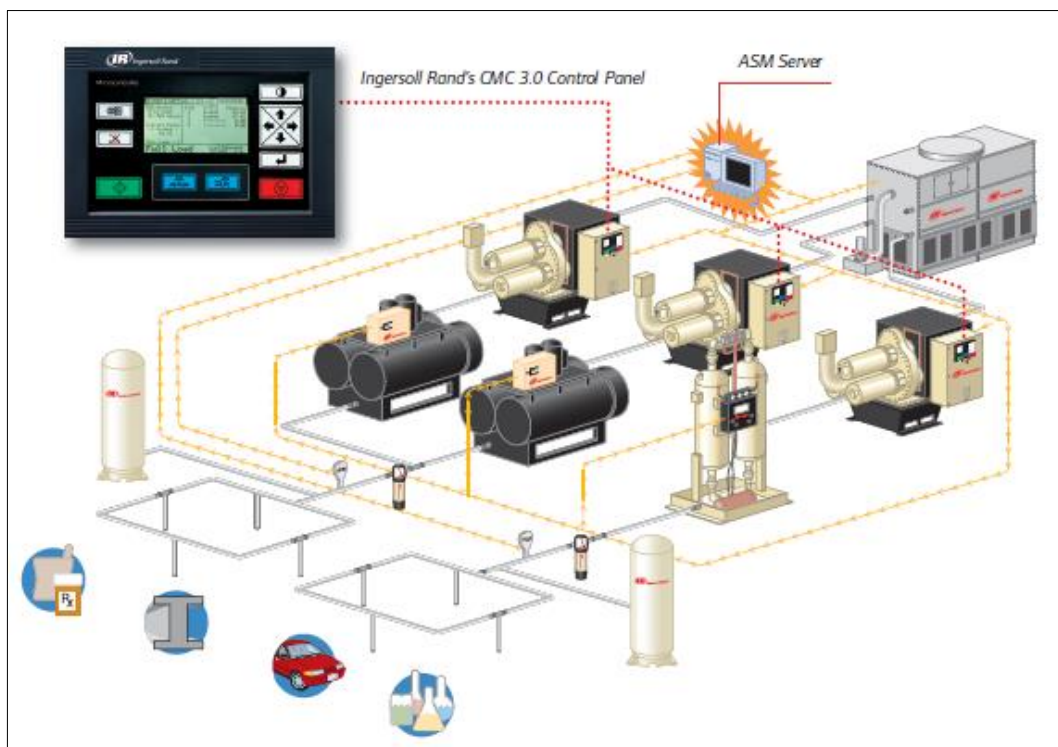


Figure 19: Ingersoll Rand ASM set-up (obtained from [56])

Focusing on optimising the supply of compressed air, the system interfaced with various system parameters that enabled the following control capabilities [55], [56]:

- ✓ automatic stop/start,
- ✓ capacity control,
- ✓ compressor prioritising – based on a predefined schedule,
- ✓ load sharing,

- ✓ PSP control,
- ✓ load/offload of compressors,
- ✓ auxiliaries control, and
- ✓ software-based.

With the system being software-based, it provided improved capability over hardware-based systems. Although the system provided improved functionality, it relied on other Ingersoll Rand components such as the CMC microcontroller (a type of PLC) for surge protection. The shortcomings identified included:

- ✗ no demand side control – compressor focused,
- ✗ static compressor priorities, and
- ✗ surge control handled by separate controller [57].

### **Techni-Systems LLC control system [58]**

Intelligent control on refrigeration compressors was developed by Techni-Systems, named the LLC control system. This system is software-based and functions similar to a SCADA system, with components designed for compressor control. The system monitors the whole refrigeration process in order to optimise the compressor supply to the demand of the cooling equipment. From the information available, the capabilities of the system can be summarised as follows:

- ✓ suction pressure control,
- ✓ capacity control,
- ✓ compressor prioritising,
- ✓ real-time demand/supply control,
- ✓ alarm and condition monitoring,
- ✓ rate of change functionality,
- ✓ historical data availability,
- ✓ VSD controllability, and
- ✓ software-based.

With the system focusing mainly on refrigeration systems, it limits the capability of the system to be used in other industrial applications. Limiting factors identified included:

- ✗ focus on screw compressors only,
- ✗ no demand control, compressor-focused controller,
- ✗ focused on refrigeration systems, and
- ✗ load/offload used as capacity control.

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**AIRtelligence Provis 2.0 [59]**

In Germany, Boge developed a range of compressor controls. These include the Basic, Focus, Prime, Trinity, Airtelligence and Airtelligence Provis 2.0 systems [59]. All of these systems are more focused towards screw compressors as capacity control is achieved through loading and offloading of compressors. The system is capable of calculating leaks, but this is subjected to labour-intensive inspections not feasible for the mining industry. Considering the Airtelligence Provis 2.0 controller specifically, the capabilities of the controller can be summarised as follows:

- ✓ automated stopping/starting of compressors,
- ✓ PSP control,
- ✓ compressor prioritising,
- ✓ demand control based on system pressure,
- ✓ calculate leakages,
- ✓ system alarm and condition monitoring, and
- ✓ hardware-based,

Some of the key factors that make this range of controller less suitable for controlling compressor systems in the mining industry are:

- ✗ controller is screw-compressor orientated (dynamic turbo-compressors are used mainly throughout the mining industry),
- ✗ no historical data server for troubleshooting,
- ✗ no surge control, and
- ✗ no demand control – compressor focused.

**Updated REMS-CM controller [13], [49], [60]**

The initial REMS-CM controller (as discussed earlier in this section) was a basic controller that was introduced the mining sector to do compressor scheduling and set-point control as part of the DSM program. This system had limitations regarding compressor controls as identified in the previous paragraphs. An updated controller was designed, building on the experience gained throughout the industry. Improvements that were made enabled the following functionalities:

- ✓ PSP control – configurable dead band,
- ✓ static compressor schedules based on 24-hour/weekday profiles,
- ✓ loading/offloading of compressors,
- ✓ historical data server,

- ✓ automatic stopping/starting of compressors,
- ✓ real-time demand/supply matching,
- ✓ software-based, and
- ✓ demand monitoring.

This was a significant improvement on the first system and system efficiency improved dramatically [13]. However, some limitations were identified when the system was implemented on numerous projects. These included:

- ✗ no intelligent load sharing, and
- ✗ no demand control – focused on compressors only.

### Other controllers used in industry

More advanced controllers have been developed that focus on the optimal control of compressor compressors. The controller systems include the integrated controller proposed by Mclin [61], the PL 4000 controller, and the control system developed by Compressor Controls Corporation (CCC), which a global corporation [50], [62]. The benefits of these intelligent controllers are summarised in Table 12 below.

Table 12: Intelligent controller capabilities

Capabilities	Integrated control system [50], [61]	PL4000 controller [63]	CCC control system [62]
Surge control	X	–	X
Capacity control	X	–	–
Auto stop/start	X	X	–
Compressor prioritising	X	X	–
Auxiliaries control	X	X	–
Historical data server	X	X	–
Real-time demand/supply matching	X	X	–
Alarm and condition monitoring	X	X	–
Set-point control	X	X	–
Manual customisable through SCADA interface	X	–	–
Load sharing between compressors	X	–	X
Everything combined in one PLC controller	X	–	–

Capabilities	Integrated control system [50], [61]	PL4000 controller [63]	CCC control system [62]
Hardware and software-based	X	X	–
Automatic priority handling	–	–	–
PSP control	–	–	–
Load sharing	–	–	–
VSD control interface	–	–	X
Rate of change	–	–	X
Compressor protection	–	–	X
Limiting compressor blow-off through load sharing	–	–	X

Intelligent controllers add significant controllability and improved energy efficiency to a compressor control system. One problem that these systems have in common is that they only focus on compressor safety and efficient operation of the compressors, as opposed to focusing on the system as a whole. The controller by CCC has advanced load sharing that enables the compressors to operate in their optimum efficiency range. This can be done through VSD or any form of capacity control. No application of the CCC controller has been found in South African mines.

Depending on the system integrator, these properties of compressor control and protection can be done through integrated control using PLCs, software, or ultimately a combination of the two. Compressor priorities can be determined using real-time flow data and compressors set points can be controlled using preprogrammed pressure profiles. All of the properties enable a system to run efficiently given the input data available.

Data is usually available in real time, but future predictions cannot be determined without the use of thermodynamic equations. Solving these complex equations [64] is a process-intensive task, which should preferably not be programmed into PLCs but should rather be executed through software-based control systems.

### *Demand optimisation*

By controlling or limiting where compressed air is used, wastages can be minimised. This is known as demand side control, and can be accomplished in various ways. As explained in

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Section 2.2 of this document, compressed air is applied extensively throughout the mining sector. Through extensive knowledge of the CAN, demand can be minimised without negatively affecting the processes dependent on compressed air.

Repairing infrastructure and minimising compressed air wastages have the highest impact that can be achieved on CANs [15], [65]. Studies conducted found that up to 40% of compressed air is lost through leakages in an unmanaged CAN [15]. This could be reduced to the industry norm of 10% [15], thus contributing up to a 30% improvement in system efficiency. Although leakages can contribute significantly to energy efficiency improvements, it is a continuous process.

Ownership of the problem and dedicated leak repair personnel are required to ensure continuous success [66]. When leak repair is executed correctly and maintenance is done regularly, the labour and equipment expenses of the repairs will be covered by the cost savings that are generated. Reporting on compressed air leak repairs could aid the success even further, expressing savings in monetary value. Systems exist that generate reports based on detected leaks [15], as well as technology that can aid the detection of leaks [67], [68]. Once the leaks are repaired, it is important that the control philosophy be adjusted to accommodate the reduction in demand by reducing the supply accordingly.

Creating awareness on managerial level through adequate reporting could further reduce compressed air consumption. Billing shafts according to their consumption and expressing their consumption versus production, are valuable tools implemented by mining houses to control consumption<sup>12</sup>. By billing shafts for the air volume that they consume, shafts can be encouraged to participate as they would benefit by reducing their consumption.

Reducing the operating pressure of a ring, a shaft, or per level is the next best improvement that can be made in a CAN as discussed in Section 1.2. Ring pressure, shaft pressure and level pressure could all be used in conjunction to reduce the supplied pressure as low as possible [69].

Pressure reduction is limited to the highest pressure requirement for the specific point in time. The equipment given in Section 2.2 of this document predominantly requires pressures in excess of 400 kPa to operate sufficiently. By knowing the operating times of the existing equipment at a given consumer, a pressure schedule can be drawn up for that specific end

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<sup>12</sup> Methodology as currently found in use at numerous mines in South Africa.

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user. This could then be used as the minimum requirement for the specific end user and the supply could be adjusted accordingly.

To further reduce the pressure to a specific end user, the demand should be reduced or removed from the system. This can be done by:

- removing the pneumatic demand altogether and replacing it with more efficient technologies such as electric, hydraulic [70] or hydromechanical [71], or
- improving the pneumatic equipment to operate at a reduced pressure [15].

Various technologies exist that enables the reduction of demand. These technologies will now be discussed in the following paragraphs.

Removing the demand and replacing it with more energy efficient technologies has been explored extensively over the last decade as energy efficiency became a higher priority. One of the technologies is transitioning from traditional pneumatic rock drills to electric drills. Electric drills have been implemented with mixed results and in some cases were proven to be more expensive to operate with slower penetration rates than their pneumatic counterparts [25], [72]. But, there might be benefits that could lead to the successful implementation of this technology.

Converting pneumatic rock loaders [26] to electrohydraulic loaders was investigated by Goldfields' Kloof operations in conjunction with Trident SA. Operational cost was reduced from R187 per eight-hour shift for the pneumatic loader to R21 per eight-hour shift using the electrohydraulic loader. Calculations were based on a pneumatic requirement of 939 cfm@480 kPa, an electric requirement of 15 kW operating at 525 V, and an electricity cost of 17c/kWh. This study was conducted in 2009 and electrical cost has increased significantly since then [73].

As is the case with rock loaders, loading boxes use pneumatic cylinders that require operating pressures of 400 kPa or higher. To reduce the operating pressure, two strategies can be implemented:

- increasing pneumatic cylinder diameter size, or
- replacing pneumatic cylinders with hydraulic cylinders.

By increasing the effective area on which the force is applied within the cylinder, the supply pressure (kPa) can be reduced to achieve the same pulling or pushing force. From fluid mechanics [74], the force exerted is calculated as:

$$F = pA \quad (2)$$

Where

Table 13: Definitions of symbols for force calculation

Symbol	Description	Unit
<b><i>F</i></b>	Force exerted	N
<b><i>p</i></b>	Gauge pressure supplied to the system	kPa or N/m <sup>2</sup>
<b><i>A</i></b>	Effective area of the cylinder	m <sup>2</sup>

When a 100 mm cylinder, is supplied with a pressure of 500 kPa, the force applied is 3 927 N. To achieve the same force at a reduced pressure of 300 kPa, the cylinder diameter will have to be increased to 130 mm. This is not a big increase in cylinder size and can be viable for mining operations. Some of the mines have legislature in place that requires cylinders to be inspected every two years, and to be replaced every four years<sup>13</sup>. With adequate planning, the changeover costs can be reduced significantly.

To control the air supplied to different end users, control valve stations have been implemented with great success as part of the Eskom Integrated Demand Management (IDM) program [14]. The control valve stations use actuated valves (both electrically and pneumatically actuated) to reduce the pressure supplied according to a predetermined set point. Control is done from a central control room using a series of intricate networks, PLCs and a dedicated control system [14].

Control valve set-ups are installed on the underground levels and on the surface network reticulation to reduce the compressed air supply pressure. Reducing the air pressure supplied to the various sections during non-production periods results in a lower airflow requirement. The pressure upstream of the control valves increases, resulting in system pressure build-up. Higher system pressure enables compressors to cut back on their delivery when equipped with the appropriate capacity controllers as discussed in the previous section.

Pressure control is done by investigating the pressure requirement of the end users based on a 24-hour profile. Profiles are created for each different type of production and non-production days, depending on the time of use of the equipment. Plants, shafts, workshops and different

<sup>13</sup> Information obtained from energy engineer at Lonmin PLC.

levels all have unique compressed air requirements. Once the information is available, the control can be set up, but has to be updated continuously as the demand varies.

When using pneumatically actuated control valves, the upstream pressure cannot be lowered below the minimum pressure requirements of the actuators as discussed in Section 2.2.1. When the pressure falls below this specified minimum, the actuator fails to the failed state (normally open or normally closed). When this happens, dams could empty, compressed air control could be lost, or critical water or compressed air supply could be shut off. The operating pressure can be lowered by using spring assist blocks on the actuators. Pressures can now be reduced to 300 kPa and still produce sufficient torque to actuate the valves successfully [75].

With hydraulic cylinders, the perception exists that the technology does not have a big impact on energy savings due to the low-flow requirement of the pneumatic cylinders that they replace. The savings, however, are not achieved by reducing flow, but rather by reducing operating pressure. By replacing high-pressure requirements with other alternatives, the system pressure can be reduced. As indicated by Marais, for every 10% reduction in supply pressure, energy savings of 16–18% can be achieved [14].

Agitation and aeration used in mining operations perform important roles in the gold-leaching process, as well as in avoiding dams from filling up with mud. These processes usually require high flow at reduced pressures (in the region of 380 kPa), but the flow could be higher when leaching tanks are higher than 20 m above the surface level or the slurry has a relative density higher than 1.56 [76]. To overcome higher pressure requirements, Pachuca valves, which require a differential pressure of >100 kPa, can be installed to establish sufficient aeration [77].

This means that if the pressure pressing down on the valve is  $200 \text{ kg/m}^2$ , the valve will open at pressures higher than 300 kPa. Optimum supply pressure is, however, 400 kPa according to the manufacturer<sup>14</sup>. Mechanical agitators can also be installed to reduce the compressed air requirement.

Compressed air usage in the stopes where the drilling takes place is often overlooked and excessive wastage occurs. Drill operators leave compressed air supply lines open after the drilling shift to help ventilate the stoping areas during drilling times [65]. Open-ended pipelines cause the working pressure in the system to reduce due to an increase in flow. According to simulations, a 25 mm open-ended pipe causes system pressure to reduce from 364 kPa to

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<sup>14</sup> <http://www.prepquip.com/multi-aerator.htm>.

314 kPa. This reduction in pressure can result in a one and a half hour increase in drilling time per single shift per rock-drill operator [78].

To combat these inappropriate uses of compressed air, a shut-off valve has been developed to automatically stop airflow when usage increases beyond specified levels. This valve closes when the backpressure drops due to an increase in flow rate [78]. The valve is still in the testing phase and actual results have not been verified. In addition to this valve, a different valve has also been developed that works on a timer function, thus allowing the operator adequate time to drill his allocated holes. When the timer runs out and an operator has not yet finished drilling, a temporary override will provide an additional 30 minutes of operation<sup>15</sup>.

Pressure requirement of CANs can also be reduced to low- and high-pressure requirement sections using control valves [16], [76]. Network reticulation improvements such as pipe diameter upgrades can also be used to reduce line pressure losses over long pipelines. Increasing the column diameter of high-flow pipelines, which stretch kilometres in length, can have significant improvements in delivery pressure. An average pressure increase of 100 kPa (from 350 kPa to 450 kPa) was obtained during high-flow demand periods by upgrading a 500 m stretch of pipeline from 450 mm to 600 mm<sup>16</sup>.

Compressor placement is also critical in the energy efficient transportation of compressed air in large networks. Compressed air should be supplied as close as possible to the point of demand. Due to practical limitations of the different sites such as electricity supply, compressor house location and network configurations, this is not as straightforward as it may seem. To determine the optimal location, detailed simulations as discussed in Section 2.2.3 are done using thermodynamic flow calculations.

Simulations can also be used to determine the optimal compressor combinations required over a 24-hour profile. These combinations can then be programmed into the dedicated control system as a control philosophy for the compressors. The only problems with simulations are, however, that control is based on historical data and that it is static in nature. As the system changes over time, demand varies resulting in an outdated control philosophy. Therefore, control simulations must be done regularly to ensure optimal control is implemented at all times.

Using simulation packages, optimal ring combinations can be determined improving system efficiency. Options include splitting larger CANs into different smaller networks, combining

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<sup>15</sup> Explanation given by mine personnel during an interview.

<sup>16</sup> Based on actual system data obtained from a platinum mine.

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smaller networks into bigger networks, or having different network combinations during different times in a 24-hour period depending on demand and supply restrictions. Optimal combinations of the above options are affected by compressors' installed capacities, compressor locations, demand pressure, flow requirements and various other factors changing continuously over a 24-hour period.

The correct specification of compressed air demand can also aid in system optimisation. High-pressure, low-flow users such as processing plants can be retrofitted with smaller stand-alone compressor systems, thus removing the processing plants from the network reticulation [76]. Correct sizing of compressors can also further contribute to energy savings initiatives by doing detailed compressed air audits on the networks.

Compressors with large installed capacity reduce controllability of a system if no intermediate sized compressors are available. By installing smaller intermediate compressors, the supply capacity can be closely matched to the demand of the system. The smaller steps between compressors also assist in compressors operating closer to their design specifications, thus further increasing system efficiency. Demand analysis can assist in determining the optimum compressor size for the given system.

### **2.3.3 Combination of demand and supply optimisation**

Control can be divided into supply side and demand side initiatives, which can be seen as a balancing scale. To achieve the most energy efficient control of the system, the compressed air 'scale' should be balanced, matching the demand with the appropriate supply. This is not being done as effectively as it should, with control systems discussed in the previous sections indicating that control is only being done on the supply or on the demand side.

Combining the supply and demand side initiatives mentioned in Section 2.3.1 and Section 2.3.2 was discussed by Marais in [14]. Although Marais did not go into the details of compressor control systems, he did recommend that they are the best value for money in terms of achievable savings. In his study, the assumption was made that compressors would do the capacity control efficiently.

Compressor settings were determined with a working knowledge of the system at hand. Compressor priorities, set points, location, pressure drop compensation and efficiency had to be calculated beforehand and then entered into the control system as static inputs. When the characteristics of the system changed, these steps had to be recalculated and reprogrammed.

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This is the same principle as followed by Booysen [12]. This provided adequate control with significant savings, subject to nothing changing in the system.

All of the information required for optimal control results was available in the system used, but simulations had to be done by skilled personnel. These personnel would typically be engineers or technical personnel familiar with the system operation. In order to have this system monitored by a control room operator and ultimately operating on its own, dynamic components were needed in the control system. Concluding from Marais [14] and Booysen [12], this capability was not yet available in the controllers at that time.

Apart from the controllers mentioned by Marais, Du Plessis and Booysen, no other control system were found in the South African deep-level mining industry that had similar capabilities. SCADA systems and PLC-based functional coding were being implemented, and these systems will be described in the following section. These systems had basic capacity control and set-point control of valves. This study found no evidence of thermodynamic simulations, calculations or dynamic network-solving algorithms that were implemented in the deep-level South African mining industry.

A theoretical control system was designed and developed by Venter [18] and Van Heerden [22] respectively. The accuracies of the systems had been tested using actual system data, but implementation had not been completed. This study follows the preceding studies by Venter and Van Heerden, combining their work with the actual system implementation. Practical challenges that have been encountered will also be addressed in Chapter 3 and Chapter 4 of this study.

Apart from the REMS control systems described in Section 2.3.2, no other compressor controller was found that combined demand side control with compressor control. Auxiliary controls were added to these compressor controllers, but focused more on start-up and shutdown procedures of compressors and their auxiliaries. PLC control could be used in conjunction with these controllers to achieve demand side control. The demand would then be matched with the supply by using the corresponding control technologies of the relevant controller.

Problems were encountered with static control systems when the systems operated outside normal operational requirements. Figure 20 shows a static control system subjected to out of the ordinary flow requirements of a mining shaft. Due to the system being preprogrammed to follow the average demand profile (red line), it was not optimal for the actual demand (blue line).

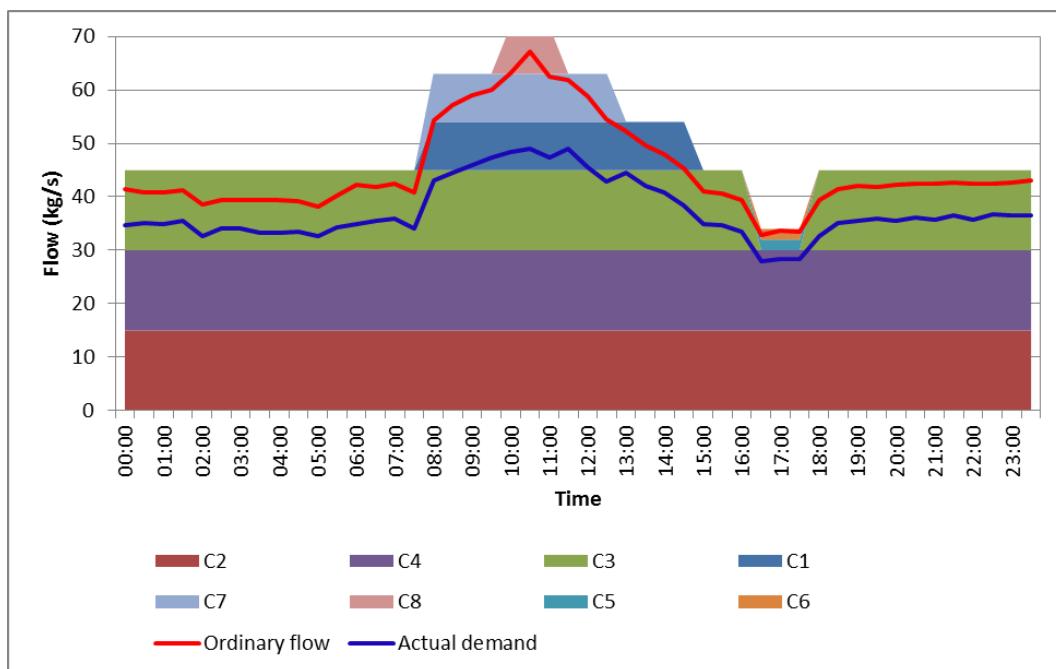


Figure 20: Static priorities subjected to ordinary flow requirements

The static priorities of the system as given in Figure 20 indicate the flow ranges of the corresponding compressors. When the demand was roughly 40 kg/s (from 18:00 to 07:30), the supply flow would have been sufficient. When the actual flow requirement for the system was roughly 36 kg/s, the scheduled compressor delivery flow would have been too high. This would have resulted in unnecessary energy wastage.

The opposite scenario may also be encountered with the actual flow being higher than the ordinary flow requirements. For example, if the flow was above 34 kg/s between 16:00 and 18:00 in Figure 20, an additional compressor would be started. With the remaining compressors usually prioritised according to their delivery capacity (small to large), C1 would typically be started up. Compressor C5 and Compressor C6 would still be running, although compressor C1 was capable of meeting the demand alone. Unnecessary energy would, therefore, be wasted.

If the system was capable of incorporating the demand with the supply by evaluating the system characteristics dynamically, an informed selection could have been made. This would ensure that the correct compressors were added according to the actual system demand, and unnecessary compressors would be stopped.

It may happen that from time-to-time a shaft may require higher pressures for development or maintenance deviating from the normal modus operandi. Normally, this will have to be prearranged with all of the relevant compressor personnel, and the system will be operated in

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manual control for the duration of the procedure. One mine is in the process of testing the effect of higher pressures (>700 kPa) on drilling times and energy efficiency<sup>17</sup>.

By having a dynamically adaptable control system, tests such as these can be performed by the control room operator increasing the shaft set point. The control system will then automatically adjust the control accordingly. Energy efficiency data can then be extracted from the system to evaluate the test results.

A study done in the European Union indicated that enhanced compressor controls could improve system efficiency roughly the same as demand side improvements [79]. A study done in Australia recommended that the best method to practically reduce compressed air energy usage is to match demand and supply [80]. This is done by identifying all of the end users by demand flow, pressure and operational times. By creating a master schedule, compressors can then be adjusted to meet the demand schedule. The only problem with this method is that once again it is a static control philosophy.

A best practice guide developed by Sustainability Victoria [80] recommends that compressor optimisation should be done after demand side initiatives have been concluded. Again, these recommendations have to be repeated when system changes are encountered.

According to Bhatia, centrifugal compressors should be run at 100% capacity. Therefore, these compressors should be used as baseload compressors, and VSD compressors should be used as trimming compressors to make up the variable load [35]. The primary goal for a plant should be to maintain the lowest pressure, with all running compressors operating at full load except for the trimming compressor. Capacity control can then be used to control the trim compressor [35].

Bhatia further discussed the possibility of using different techniques to ensure stable compressed air supply, all based on static schedules or human interference [35]. Bhatia also recommends the following [35]:

- using air receivers to absorb demand fluctuations,
- using efficient system auxiliary equipment (for example, intercooler, aftercooler and water cooling systems),
- using adequate pipe sizes to prevent pressure drops,
- using valves to control flow and pressure (ball valves preferred),

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<sup>17</sup> Platinum mine in the Rustenburg area.

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- using water traps to remove moisture from the system (automatic actuated systems preferred),
  - using air dryers,
  - maintaining or replacing filters regularly,
  - repairing leaks,
  - splitting systems into high- and low-pressure sections,
  - replacing compressed air driven equipment with more efficient alternatives,
  - doing heat recovery,
  - maintaining compressor systems,
  - using more efficient, correctly sized compressors, and
  - ensuring efficient compressor control.

Not all of the recommendations from Bhatia [35] are applicable to the mining industry due to the size of the systems encountered. The same principles are discussed in a reference guide compiled by CEATI in Canada [81]. These recommendations are, however, best practice suggestions and no systems are mentioned that can incorporate all of these control methods.

In a campaign to encourage industry to improve their compressed air energy efficiency, the German Energy Agency worked together with Atlas Copco, Kaeser Kompressoren, Schneider Druckluft, Ingersoll Rand, Boge Kompressoren and other compressor experts and manufacturers [82]. In their report, numerous system improvement techniques are discussed, most containing the best practice models as found in the previous paragraph's literature.

Compressor control systems are mentioned that can monitor system key performance indicators and do intelligent pressure-band control through compressor cascading and scheduling [82]. System characteristics (for example, losses, pipe layout and compressor position) and end-user control (through PSP regulation) are, however, not combined into the capabilities of the system. These have to be done as separate attempts to reduce compressed air wastage [82].

In most of the literature found, best practice models describe how to improve CANs, supply and demand [35], [60], [81]–[85]. No literature was found on a system that can combine all of these best practice models into a complete solution. It is, however, recommended to combine the demand and supply side interventions to obtain the best efficiency [82].

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## 2.4 Compressor control in South African mines

### 2.4.1 Non-automated manual control

Prior to the energy shortage in South Africa, compressed air seemed to be the logical choice to distribute energy to points of delivery. Electricity cost was negligible, compressed air distribution and installation required low-level artisans, and compressed air was used extensively in processes throughout the mining sector. The growing demand for compressors resulted in increased installed capacity as can be found in the South African mining industry today. Compressed air was always available and compressors were left to run 24 hours a day, seven days a week. Safety features were built in to avoid overpressurising the system. Typical systems included Moore controllers (as discussed in the previous section).

Although capacity control was done by Moore controllers, there was no drive for energy efficiency incentives. As a result, compressors were left to run with guide vanes on a minimum and blow-off fully open, until the demand increased again. It was argued that maintenance cost would escalate with the stopping and starting of compressors<sup>18</sup>. This, combined with the low cost of electricity, was the reason compressors were rarely stopped and started. In the event that compressors had to be stopped, a compressor operator would stop the compressor.

Electricity cost and DSM incentives resulted in energy savings intervention of CANs in industry. Studies proved that compressors were run unnecessarily. In cases where compressors could be shut down for extended periods, schedules were drawn up as to when compressors should run. The initial focus was to reduce electrical energy demand between 18:00 and 20:00 during weekdays. Compressors were shut down during these times, only to be started for the production shift again.

The production shifts would typically occur any time between 06:00 and 14:00 daily. Energy savings projects entailed operators being trained to stop and start compressors according to a schedule. In some instances, the compressors would be shut down when their blow-off valves have been open for a specified timeframe.

### 2.4.2 Semi-automated control

During implementation of DSM initiatives, control instrumentation was upgraded and opened doors to new opportunities. SCADA systems were installed which enabled the remote control of

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<sup>18</sup> General assumption made by shaft engineers during DSM project feedback meeting.

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compressors. Control room operators would monitor system pressure, and add or remove capacity when needed.

Compressors could be started in two ways:

- the control room operator would give the compressor operator a start command, or
- the control room operator would start the compressor.

This control would be executed through the SCADA system if the system enabled the operator to do so. Safety policies by some mining companies prevented the automatic start-up of compressors from remote locations. It was argued that an operator in the compressor house had to be able to see if something was out of place that could prevent the compressor from starting up<sup>19</sup>. To mitigate this risk, camera systems were installed at one of the mines to enable the control room to do a visual inspection from a remote location. The need for multiple operators at compressor houses was eliminated as a result.

A control room operator generally did not have extensive knowledge of the CAN. The control was simple and unreliable in the event that irregular situations were encountered. Operators had various operations to monitor and efficient compressor control was not their only priority. System efficiency improvements could be achieved with dedicated control systems.

The control done by operators improved over time as the operators gained a better understanding of the system responses under certain conditions. Although system efficiency was not always optimal under semi-automated control, an experienced operator could respond to abnormal conditions based on past experience.

System demands were matched by an operator through adding and removing compressor capacity of various sizes situated at different locations on the CAN. This was subject to the control room operators' experience and their knowledge of the system. Matching was, therefore, not an exact science, but it was based on a trial-and-error approach. This often led to mismatching of demand and supply under varying demand conditions.

Additional to the remote stopping and starting of compressors, the introduction of advanced SCADA systems enabled the remote control of compressor delivery set points. With the capability to control compressor set points remotely, a control room operator could vary the compressor set point during the varying demand times of the mining production.

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<sup>19</sup> As found at an Anglo American mine during DSM project investigation.

For instance, a set point of 600 kPa would be used during the morning drilling shift. The set point could be reduced to 500 kPa during the afternoon blasting shift to cater for a reduced pressure demand. During the evening peak, the pressure could be increased to 550 kPa for the evening cleaning shift. PSP control on compressors reduced the compressor power consumption due the work reduction of the compressor.

### 2.4.3 Fully automated control – static

A fully automatic compressor controller with static inputs was implemented on a platinum mine in South Africa. This controller was used by the control room and system operators to control the compressed air supply of the network. The controller was developed over time, and has been improved significantly since the initial concept was implemented.

The controller was developed by Hiprom Technologies in conjunction with the compressor department at the particular platinum mine. The control was set up as basic pressure monitoring control within predefined bands. The basic control philosophy of the system is given in the flow chart in Figure 21, which entails the adding and removing of capacity to and from the system. The adding and removing of capacity have been done using weighted guide vane averages.

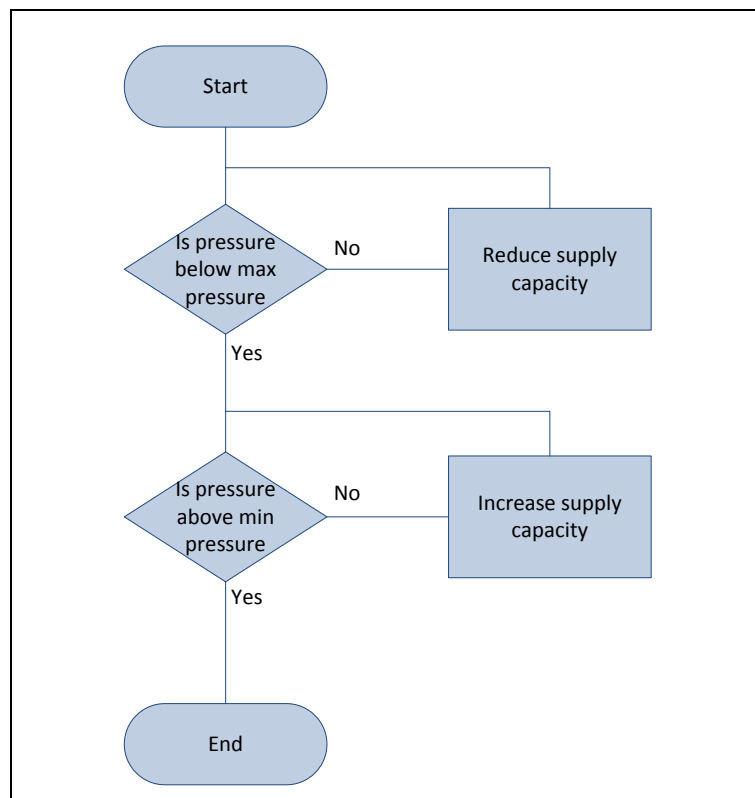


Figure 21: Pressure monitoring process

To reduce the effect of human error on the control of compressors, the control system has been implemented to automatically stop and start compressors. This was based on a previously determined set-point profile of the whole CAN. Control was done by monitoring system pressure, and when the pressure reduced by more than a predefined offset pressure, additional load would be added to the system. In return, when the system pressure rose by more than the predefined pressure band, the controller would remove some demand by switching a compressor off.

Compressors were fully automated to incorporate remote starting capability, as well as automated set-point control. Set points were defined for each of the different consumption periods of the mining schedule. To enable the controller to start the correct compressor, a technician with extensive knowledge of the compressors and CAN prioritised the compressors during each of the different consumption periods. Compressors would be stopped and started then according to this priority list.

Weighted guide vane averages enabled combined capacity control of all of the compressors through controlling the guide vanes. All of the compressors were set on the same master PSP, defined in 30-minute intervals over 24 hours. Smaller capacity compressors would cut back on the guide vanes first due to the smaller weight of their guide vanes. Larger capacity compressors would cut back last due to a heavier weight assigned to them.

When a significant reduction of supply was needed over a short period of time, the compressors with the bigger installed capacity would also cut back on their guide vanes. This ensured that surge was avoided, and no energy was lost by venting air through the blow-off valves. This proved ineffective for reducing power consumption since compressors were not easily switched off. All of the compressors would rather cut back on their output capacity than be switched off. When compressors were switched off, it was based on static input by the CAN technicians.

Due to the static nature of the control, the system could not adapt when system changes were experienced, and the system operator had to redefine the control philosophy. With changes happening throughout the mine under different responsibility areas, it was not always possible to adapt the system to changes in advance.

The changes were only implemented when problems were experienced on the supply side. This resulted in significant loss of energy efficiency due to mismatching of demand and supply sometimes going undetected for extensive periods of time. Problems encountered included, for

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example, excessive loading/offloading of compressors, incorrect priority lists and higher than required system pressures.

The added benefit of system monitoring and decision-making logging capabilities improved troubleshooting and maintenance task time. Compressor efficiencies could now be obtained from system data, as well as auxiliary system operating conditions. Dirty suction air filters, reduced compressor delivery capacity, condition monitoring of temperatures, vibrations and so forth could be used during compressor control decision making. Automatic control was a definite step in the efficiency direction, but the static nature of the control limited the full capability to improve energy efficiency.

#### **2.4.4 Capacity control found in mines**

Capacity control on compressors in the South African mining industry has not always been done optimally. To illustrate the impact of inefficient capacity controllers, data obtained from two neighbouring mining shafts from the same mining company will be compared. Both mines used PLC control on their compressor to avoid compressor surge.

Mine A avoided compressor blow-off as far as possible, using it only to avoid surge. Mine B used the blow-off valve in conjunction with the guide vane to control the capacity of the compressors. The maximum efficiencies of the compressors were compared with the average running efficiency to evaluate the control philosophies.

On average, the compressors at Mine A operated at 92% of the maximum efficiency point of the compressor [86]. On average, the compressors at Mine B operated at 85.8% of their maximum efficiency points. Therefore, inefficient capacity control resulted in a 6.2% reduction in efficiency. If 7% efficiency improvements could be made on three compressors operating in the region of 4 MW each, energy savings could amount to 840 kW on average. With the Eskom 2014/2015 tariff increases [87], this could result in annual cost savings of approximately R4 million.

By eliminating compressor blow-off, more energy savings could be realised. Once the PLC automation was in place, relative cheap programming changes could be made to achieve this. The key concept was to as far as possible safely avoid expensive blow-off of compressed air into the atmosphere.

#### **2.4.5 Evaluation of existing compressor system controllers**

Due to the nature of compressor systems found throughout the mining industry, a need was recognised to optimise compressor scheduling and prioritising. This, however, raised numerous challenges as the control systems found in literature did not cater for the systems encountered.

Large centrifugal compressors used in South African mines react differently than the smaller centrifugal and screw compressors found in various case studies on control systems [79], [81], [88]. From the research done in this study, various best practice methods were found to reduce compressed air consumption and improve system efficiency [35], [79],[85]. Although the best practice methods were separated into demand and supply side strategies, a holistic system approach was needed to achieve optimal results.

When demand is reduced by using one of the numerous methods investigated, the supply should adjust accordingly. This was a continuous process throughout the mining industry. For example, if demand was reduced due to shafts varying demand, labour unrest or shaft closure due to safety breaches, the supply should adjust accordingly. A system controller was needed that was capable of dynamically adjusting to the fluctuating demand.

Controllers found in research proved effective in controlling the demand as long as the system did not incur irregularities. This was unavoidable in the mining sector and the static controllers continuously needed inputs from trained technicians. Missed energy savings opportunities were a result of the systems not being able to match the demand and supply dynamically.

No link was created between demand and supply side control where continuous changing demand set points could be used as compressor set-point drivers. This added to the static nature of the investigated control solutions. A system capable of adapting to smaller changes – such as demand set point changes, varying demand patterns, systematic reduction of demand due to leak repairs, and other demand interventions – was required to enhance energy efficiency.

A need for simulation capability of a control system was also identified. Upgrades for failing infrastructure and network expansions/additions were required from time-to-time. In order to achieve the best placement of new infrastructure or to determine optimal pipe diameters, flow dynamic simulations were required [89]. Various simulation packages were available to industry to do this, but none of them was incorporated into the CAN control.

With the added simulation capability, optimal compressor locations could be used when adding and removing capacity to the system. When additional compressed air was required, the best compressor to be started up could be selected while considering the location of the compressor. Compressor delivery capacity, energy use, placement, pressure drop to the end user and other factors could be considered to obtain the maximum efficient compressor combination for the system at any given time.

Capacity control was done by different contractors on the mines that were investigated, predominantly using inlet guide vane control or suction throttling. The assumption was made that the control was done efficiently. Upon further investigation, it was found that significant energy savings could be achieved by upgrading the control philosophy. By avoiding compressor blow-off within safe operating conditions of these compressors, efficiency was greatly improved.

Compressor sizing was also important to consider, as it could have a negative impact on energy savings. Pipeline sizing, pressure drops encountered and various other system characteristics needed to be investigated as part of system implementation to obtain the best operational set-up. Information obtained from literature on VSD control proved that this technology was the best method to obtain capacity control. In the mining industry in South Africa, initial high capital cost prevented the adoption of VSD control.

The majority of sites that were investigated had some sort of capacity control and compressor automation. It was found that the control, scheduling and prioritising of these compressors were done either manually, or according to a static control priority list. Although sites were found to have automatic stopping/starting of compressors and PSP control, further improvements were possible with a dynamic control system. The system, however, had to be flexible to incorporate the different compressors and operational constraints encountered.

## 2.5 Summary

The need for dynamic adjustable control is evident from the literature and sites investigated. The control should be able to continuously update the supply to match the ever-changing demand. Control room operators do not have the necessary skill levels to update control philosophies on a daily basis. A control system that can incorporate all of the relevant information, network characteristics, simulation capabilities and system efficiency dynamically will improve system efficiency in these large compressor networks. Missed energy savings opportunities can be limited by matching supply and demand dynamically.

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## 3 Designing an advanced compressor control system

### 3.1 Introduction

From the literature study described in the previous two chapters, a definite need was identified in compressed air control requirements. A controller able to dynamically adapt to varying compressed air demand could realise missed opportunities created by outdated control philosophies. By combining various best practice models, fluid dynamic calculations and simulation capabilities, this is achievable. The following section will describe the design considerations, practical limitations and required capabilities of a dynamic compressor selector (DCS) controller.

### 3.2 Proposed controller

#### 3.2.1 Data interpretation

Modern day CANs are usually well instrumented and system information is readily available. In order to define and characterise the CAN accurately, input data, such as the following, is required from various areas of the system:

- compressor PSPs,
- compressor discharge flow rate,
- compressor delivery pressure,
- compressor guide vane position,
- compressor blow-off valve position,
- compressor running status,
- compressor air delivery temperatures,
- compressor power consumption,
- point of delivery PSP,
- point of delivery pressure,
- point of delivery flow rate,
- point of delivery upstream pressure (if available),
- point of delivery valve positions,
- pipe lengths, diameters and bends (network reticulation),
- average ambient temperatures, and
- atmospheric pressure at location/mine.

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All of these data requirements can be obtained with the installation of corresponding instrumentation. The most common data required can be measured using pressure transmitters, flow meters, power meters and temperature transmitters. With the exception of flow meters, this instrumentation is relatively inexpensive and can be installed at all supply and demand points in a CAN. Flow meters are an important part of the network characteristic requirements and are unfortunately required at all of these points.

The network reticulation data is usually fixed unless there are system upgrades. Therefore, the data required to characterise the network reticulation will not change dynamically. There is no need to have sensors installed to input the data into the system. Data can be entered manually when the system is set up, and again if system upgrades have been implemented.

PSPs at the end users are set up for each end user separately, and control is done locally at the end user using PLC controllers. Due to the varying nature of the pressure requirements, PSPs need to be updated in real time as well to ensure adequate pressure delivery at all times. The preferred method of control is the compressor controller assigning set-point profiles. This will ensure that all of the information is available to the controller at all times, and changes are coordinated from one dedicated controller.

### *Real-time data*

In order to control the CAN dynamically, the use of real-time data is critical. By connecting the controller to the SCADA system, the data from the sensor is available continuously. A typical communication network layout is given in Figure 22. Data is obtained from local PLCs from where it is relayed across an Ethernet or fibre network to the SCADA system. The server where the control system is installed connects to either the PLCs directly, or to the SCADA using OPC communication.

Data is logged on the controller in two-minute intervals and is synchronised to cloud storage once a day. Data from the cloud is used to report on key performance indicators which are an important aspect in sustainable maintenance. Real-time data in the cloud is, however, not required at this stage, and do not form part of this study. Data is solely used for reporting purposes, which is done in daily, weekly and monthly intervals.

Data that changes dynamically is usually monitored on the SCADA system through dedicated specialised instrumentation. This allows the monitoring of the system in real time, enabling dynamic response of a controller based on actual system data. System pressure and flow data accuracy is vital when calculating the flow direction and mass balance in the network. When

system input data is inaccurate, the supply and demand cannot be matched. Instrumentation is calibrated on a regular basis to ensure reading accuracy.

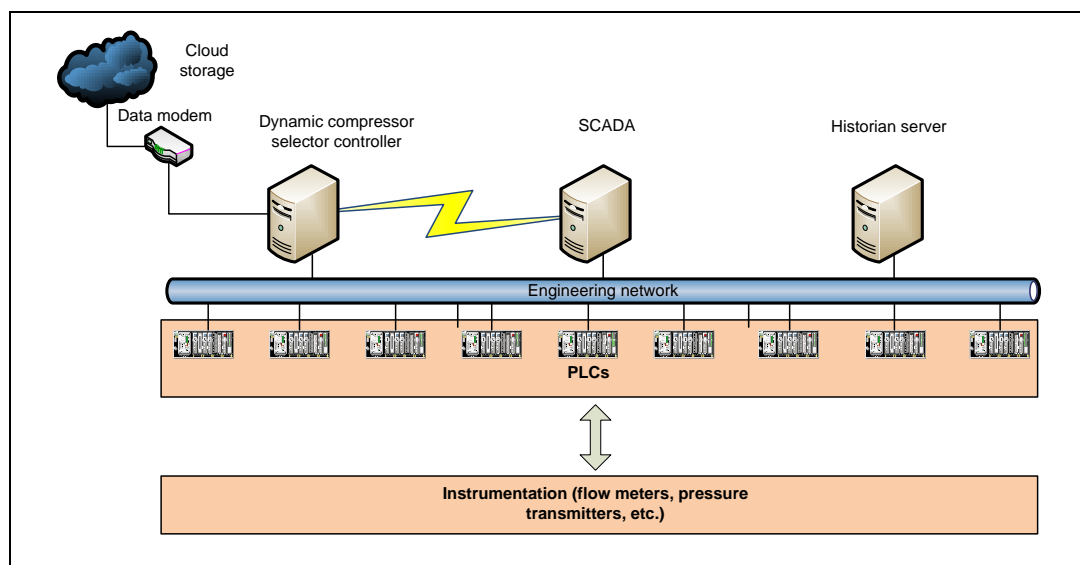


Figure 22: Network communication layout

With real-time data, instrumentation reading errors and spikes occur from time-to-time. To minimise the impact of these readings, filters need to be applied to ensure calculations are not done using erroneous data. Upper and lower boundaries are also defined for each sensor to avoid entering incorrect input data to calculations. Figure 23 gives a comparison between real-time data and smoothed filtered data of compressed airflow. Unfiltered data in this example will result in compressor cycling due to the magnitude of the fluctuations.

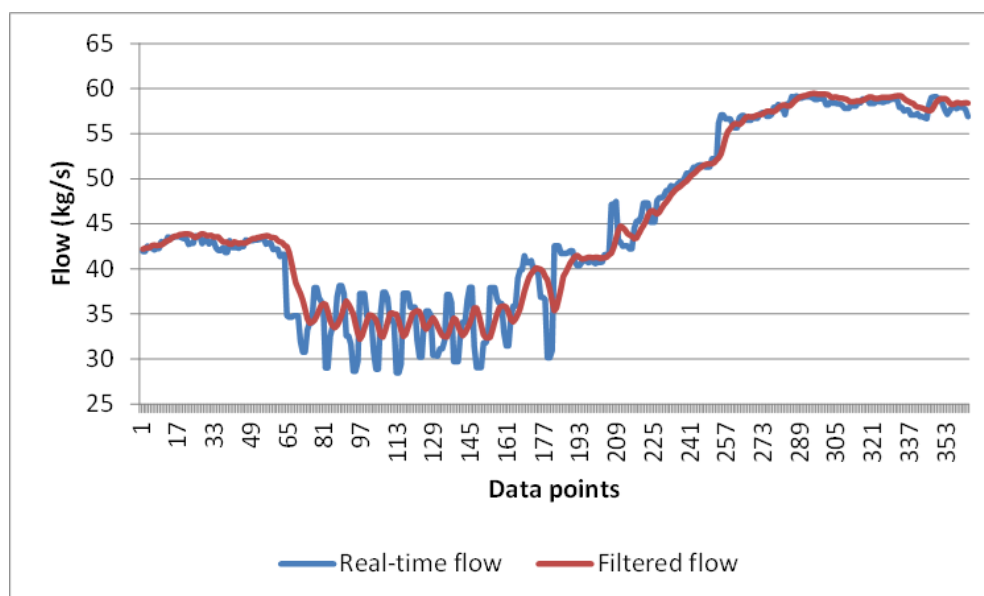


Figure 23: Real-time flow versus filtered flow

Real-time data for all of the CAN characteristics is available to the controller at all times. Not all decisions can be made on real-time data due to fluctuations. Real-time data is processed and stored in the controller to create a database for the required data. An example of this is compressor delivery capacity where minimum delivery, maximum delivery and power consumption should be available across a range of pressures. For this, historical data should also be available to the controller.

### *Historical data*

Not all decisions can be made using real-time data, as this may result in ineffective control philosophies. For some of the decisions to be less volatile to system changes, averaged data is used based on previous operational conditions. Averaged data can also be used to compare real-time data with simulated data of future calculated values to minimise erroneous calculation results. Typical information or decisions that would rely on averaged data points include:

- compressor efficiency and capacity characteristics (pressure versus power versus flow),
- future demand flow of end users,
- future supply flow needed from compressors,
- future set-point calculations,
- day-to-day comparison tools (flow, energy consumption), and
- estimated power consumption of compressors at demand.

Historical data is sometimes available on historian servers as indicated in Figure 22. Various communication protocols and database variations exist, each having specific set-up requirements. To minimise development time, the historical data required will be stored locally on the control system.

### *Data from third-party sources*

Not all data is always available from a mine's SCADA or Historian servers. One example is power data from meters being maintained by third-party companies such as IST Otokon and Energy Insight. These companies install and maintain power meters, and make data available to clients on dedicated servers. These services proved to be very effective in the mining environment, with minimal data loss. Data can be obtained from a web interface as comma-separated value (CSV) files, or directly from the companies' SQL-based servers.

The problem encountered with these SQL-based servers was that the servers were usually located on different networks (commercial or production networks) than the compressed air instrumentation data (engineering network). This prevented OPC connection to these servers

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due to IT policy restrictions. Therefore, real-time data could not be obtained. The CSV files created through the web interface could be mailed on a daily basis. The data was averaged half-hourly and could not be used to determine compressor power consumption at various pressure and flow specifications.

In cases where the power meter data server was on a separate network, energy efficient calculations could not be done until the data was made available on the engineering network. To mitigate this problem, the power meters and server had to either move to the engineering network, or a secondary connection (RS485) to the meter could be used to make data available on the engineering network as well. The type of power meter that was used most often usually had a spare port available for a secondary connection.

If a secondary connector was not available, or if the client was reluctant to move the power meters to the engineering network, separate power meters had to be installed. These meters were then connected to the engineering network via PLC and Ethernet communication.

### **3.2.2 Cost-benefit analysis of automatic compressor control**

Mine personnel at a gold mine in the North West Province of South Africa had a problem with compressor reliability. Due to compressor trips occurring in the early morning hours, mine personnel were reluctant to stop and start compressors. This resulted in reduced energy savings, as compressors were only allowed to cut back on capacity using guide vanes. Compressors could not be stopped and excess capacity was vented through blow-off valves.

Due to the size of the compressor at one of the platinum mines in South Africa (15 MW/125 000 cfm installed capacity), mine personnel prohibited the stopping and starting of the compressor. Extra mechanical stress was given as the main area of concern. This compressor was used as a baseload compressor, only controlling capacity by using guide vanes and a blow-off valve combination. The capacity controller was, however, configured in such a way to limit the blow-off valve operation only to prevent surge.

Numerous compressors with installed capacities above 10 MW and 100 000 cfm were encountered throughout the mining industry in South Africa. At all of the sites with such big compressors, stopping and starting was not preferred. To accommodate this, the controller was designed to allow baseload compressors to be selected, preventing the compressor from being rescheduled or stopped. Baseload compressors would always be the highest priority compressor, thus being the last compressor to stop.

Apart from mines with larger compressors, the perception was also encountered at several mines with smaller compressors. On one of the gold mines, the smallest compressor was a 4.8 MW 50 000 m<sup>3</sup>/h compressor. The client stopped and started this compressor as a trimming compressor several times during the day. At the gold mine mentioned at the beginning of this section, the biggest compressor was a 4.8 MW 50 000 m<sup>3</sup>/h compressor, and stopping and starting was prohibited. Both of these sites implemented the same soft starting technique to start the compressor.

Automatic control of these compressors was prohibited by mining personnel as it was believed to increase wear and tear, which in turn increased maintenance costs. Most of these decisions were made by personnel without adequate data to back it up. By preventing compressor control, energy savings opportunities were minimised. The effect of automatic stop/starts on maintenance schedules had to be evaluated and compared to missed energy savings opportunities.

Assessing the historical data of mines subjected to automatic control may clarify the financial viability of the stopping and starting compressors. The impact of maintenance cost must be evaluated against achievable savings. A break-even point can then be calculated to aid mine personnel in making informed decisions on compressor control strategies.

### **3.2.3 Combining various best practice models into a complete compressor control solution**

Projects that were done throughout the mining industry in South Africa proved the value of experienced and dedicated system operators. Best practice models and procedures encountered throughout projects that were completed gave valuable insight to further improve energy efficiency of projects. Due to the different types of industry where projects have been implemented before and during this study, experience has been gained on multiple scenarios. With the approval of the different parties involved, experience could be shared between industries.

Concepts proved through completed projects could be demonstrated to other parties to enable technology adoption at new clients. Due to a unique technology being developed for mining CANs, solutions were not widely known and adopted. By arranging meetings between mining personnel at different mining companies, knowledge could be shared between experienced system operators, improving system functionality, performance and sustainability. Feedback from these meetings was considered during the development of the dynamic control system.

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Best practice models found on the demand side could also be distributed between projects. These included hydraulic conversions, leak repair methodology, column upgrades, pressure control solutions and many other methodologies as mentioned in the Section 2.3 of this document. Best practice models have, however, not been limited to demand side initiatives, but included supply side technologies as well. Compressor automation methodology proved valuable in improving the energy efficiency of systems (as given in Section 2.4).

The controller had to be able to combine this energy saving solutions dynamically, adapting to continuously improving systems. Lower demand set points, demand flow reductions, system piping improvements and many other system improvements could now be automatically accounted for in the compressor scheduling and prioritising. Missed savings opportunities were, therefore, minimised. By having this capability, improvements were made in acceptance of this technology into industry.

Although best practice models were shared between clients, unique configurations were encountered. The controller was developed to be versatile, being able to connect to the different system types and configurations. For example, at one site the automatic system controller used static compressor priorities, schedules and compressor set points. In this situation, condition monitoring was done on the controller and the site was familiar with the system.

Familiarity with the system made the client reluctant to decommission the system, as compressed air was a critical part of their system operation. The controller was developed to automate the static inputs of the priorities, schedules and set points dynamically. The start-up and shutdown of compressors were still done by the existing controller. The option was also added to disable the dynamic input of the new controller as an added safety precaution.

On another site, no automated controller was implemented and operators were required to stop and start compressors. Due to missed energy savings opportunities, mine managers requested that the controller be able to replace system operators completely. Compressors were automated to the point that a simple start and stop command could be issued to control their compressors. The system was, therefore, created to be capable of adding and removing compressors through monitoring the pressure response of the system. Timeouts, allowable stop/starts, running times and other system characteristics were used to reduce compressor cycling done by the automated controller on the other site.

Fully automated control of the system was required, but versatility was the key to enable integration into existing systems. A communication interface between the controller, the local

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SCADA systems on site, and PLCs was needed to ensure all data was available for decision making. Communication was done using OPC, with additional software capable of bridging communication across different protocols encountered on site.

These are some of the system constraints to be considered in the development of a generic controller. The controller should be capable of controlling compressors dynamically across various system platforms and configurations. The system should also be able to adapt to future control upgrades. To understand the system and the implementation requirements fully, a systematic approach was followed for every project investigation. A typical system approach is described in the flow chart in Figure 24.

Each project is handled individually and the controller is adjusted to incorporate all of the components of each system should it be financially viable. System communication, controller interfaces, control parameters and so forth, are all system-specific and need to be evaluated accordingly. During the investigation and integration phases of individual projects, development is done when required to the dynamic controller and the compressor system in general. Adjustments made to these systems based on individual requirements have been rolled out to other sites, thus further improving control.

A system that integrates all of the best practice models into a dynamic controller will ultimately produce improved efficiencies. A summary of these models are as follows:

- capacity control of compressors,
- compressor set-point control,
- compensating for pressure drop to point of delivery,
- compressor location calculation,
- compressor delivery range database (updating dynamically),
- efficient compressor combinations,
- network loss compensation,
- demand control valves,
- adapting to varying demand,
- system usage monitoring and alarms,
- integrated reporting system,
- adapting to network infrastructure upgrades,
- high pressure/low-pressure ring split, and
- network simulations.

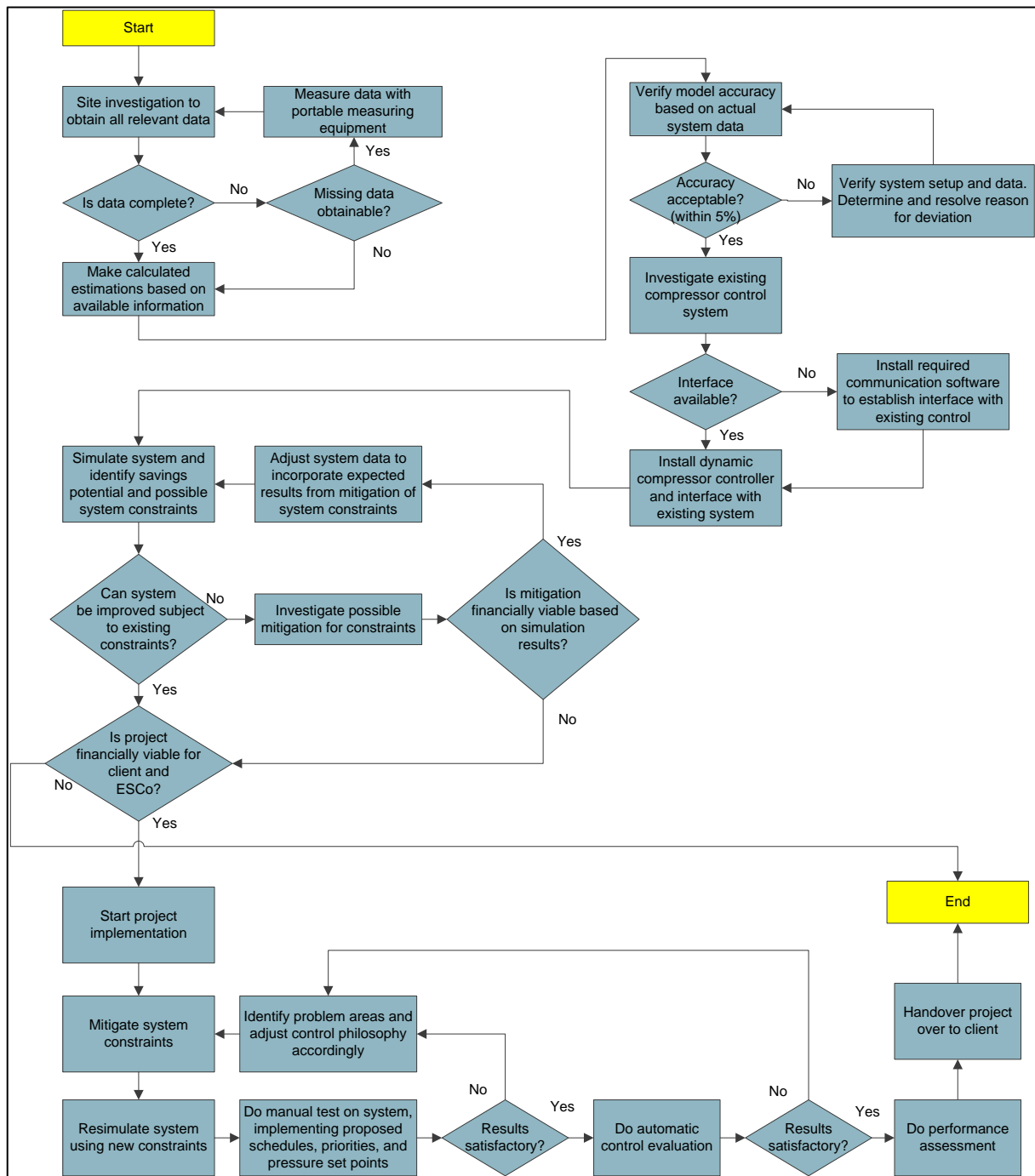


Figure 24: Systematic approach

### 3.2.4 Embedding dynamic selection criteria to determine most efficient compressor combinations into compressor controller

Control room operators are usually required to monitor and control compressed air supply in non-automated systems. These control room operators do not have detailed technical knowledge of the compressors, CANs or other equipment affecting compressed air consumption. Energy efficient combinations are, therefore, not regarded as top priority. The

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system is operated to supply adequate pressure to end users, but not necessarily in the most efficient manner.

Technically skilled personal usually determine the control philosophy of the CAN. This is based on past experience, best practice models and, in limited situations, on proper engineering flow calculations and equipment-specific operation parameters. Due to the workload of these personnel, control philosophies are not updated daily or even weekly. Missed opportunities are, therefore, also created irrespective of skill level.

Past experience and technical knowledge of system operators are not always as thorough as required to operate these complicated systems. Gut feelings, resistance to change, lack of knowledge and many other aspects may limit energy savings to the skill level of the system operator. If the system operation is linked to a specific person, operational efficiency may be lost if the person decides to leave the site, mine, company or position. A dedicated dynamic controller, using engineering calculations and system parameters combined with best practice design considerations obtained throughout industry, ensures efficient and sustainable system operation.

Actual system data used as inputs into decision making, combined with flow dynamic calculations result in optimal control philosophies. Practical limitations, physical limitations and challenges can all be considered to provide the best-fit control philosophy for a specific system. By using real-time system data as inputs, actual compressor delivery and system pressure enable the controller to combine theoretical and practical approaches.

The system characteristics monitored in order to add and remove compressed air supply are the following (present requirements):

- demand flow,
- supply flow,
- demand pressure,
- supply pressure (compressor PSPs calculated according to demand), and
- actual system pressure.

In order to know what the magnitude of the compressor is that can be started or stopped, the following additional information is required (future requirements):

- demand flow,
- supply flow,

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- demand pressure,
  - supply pressure, and
  - system pressure.

To enable the future prediction of flow and pressure requirements both on the demand and supply side, flow dynamic equations are used to simulate the system. A detailed model of the CAN is programmed into the controller. Piping configurations, piping diameters, compressor locations in the network, compressor characteristics (power versus flow versus pressure for all guide vane positions), end-user profiles and system constraints (such as baseload compressors and stop/start limitations) are required by the controller.

By having the capability to calculate future requirements of the system, compressor cycling is limited. Compressors are now started given they will run for the minimum allowed time as specified by the client. In other words, compressors will not be started only to be stopped 30 minutes later. This reduces the number of stop/starts, and in turn reduces the heat and mechanical stresses on the compressors.

The energy efficiencies of the compressors are continuously available to the controller at different pressure and flow requirements. Therefore, the most efficient combinations of compressors are selected subject to the system-specific constraints. System constraints include baseload compressors, location of compressor in the network, pressure losses due to network piping and distances to end users, and other system-specific operational requirements.

Future calculations are done based on set points of end users over a 24-hour profile. Present demand flow is also compared to the future flow to increase the accuracy of the calculations. Calculated future values are compared with predicted values based on historical data, scaled to the present operational conditions of the system.

To illustrate the predicted values based on historical data, consider the profile given in Figure 25. At a given day, for this example a Monday, the flow at any point in time can be compared with the average flow for a weekday. For example, at 05:00 the demand starts to increase, thus requiring a compressor to be started. When the scaled profile of Monday is compared with the average profile for weekdays, it can be seen that the same demand pattern is followed. An increase of almost 80 000 Nm<sup>3</sup>/h is expected over the next three hours. After the increase, the flow needs to be sustained for another three hours. If a compressor is added, it will run for at least six hours.

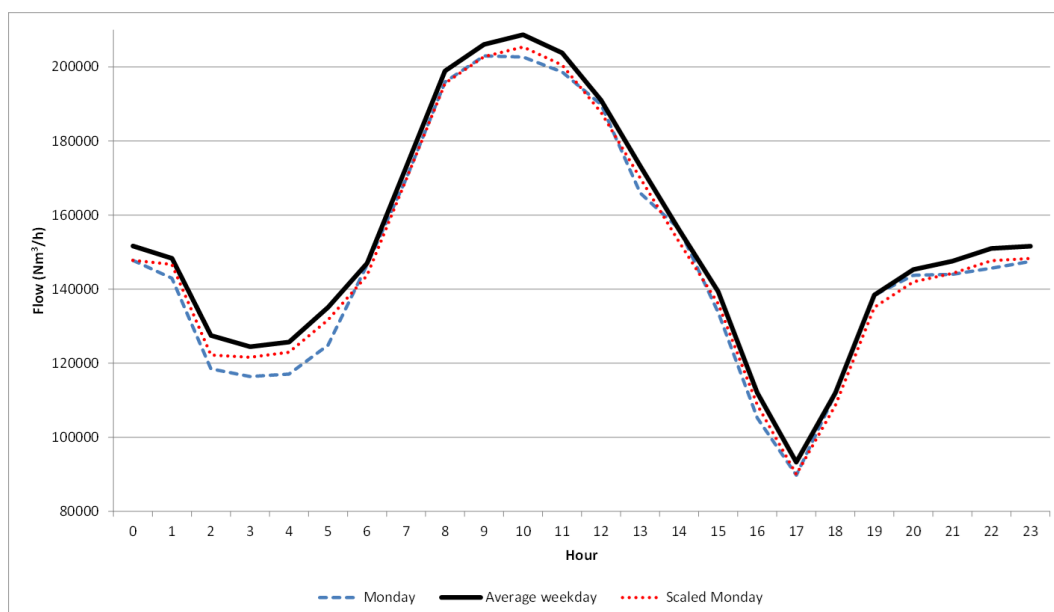


Figure 25: Actual, average and scaled data for future predictions

Compressors in the system are characterised according to actual pressure, power and flow of the compressor obtained from operational data, entered into a matrix. OEM compressor data is not used due to the difference between actual and rated capacities of the compressors. Power consumption is recorded against flow for an average delivery pressure.

Compressors are capacity controlled in a network, resulting in flow delivery variations. By monitoring the compressor delivery, minimum and maximum flow is recorded per compressor as the compressor is controlled using guide vanes. All the values between the minimum and maximum delivery flow are used to determine the compressor range. Power consumption at the different delivery flow ranges is also captured in the system. From here, the efficiency of the compressor is calculated at the different system flow requirements. A typical example of a characterised compressor is given in Table 14 and Table 15 for flow and efficiency, respectively.

Table 14: Compressor flow characterised

Pressure range (kPa)	Flow	
Pressure	Minimum flow (kg/s)	Maximum flow (kg/s)
440	13.01	14.39
460	13.01	11.16
480	13.01	10.92

Pressure range (kPa)	Flow	
500	13.40	14.39
520	13.01	14.77
540	13.01	14.66
560	13.01	14.62
580	13.01	14.46
600	13.01	13.78
620	13.01	13.39
640	11.16	14.39
660	13.01	14.11
680	8.90	13.75

Table 15: Compressor efficiency characterised

Flow (kg/s)	Power (kW)
8	5 340
9	3 640
10	3 780
11	4 420
12	4 540
13	4 952

Compressor characteristics data is updated continuously to ensure the latest relevant data is used when a compressor is selected. Outdated information could result in compressor sizing being inadequate for a specific point in time, resulting in compressor cycling. Filter differential pressure (dirty versus clean), ambient temperature and other factors affect compressor delivery and, therefore, data is updated continuously to ensure dynamic operation of the controller.

Flow calculations are then used to determine the compressors' contributions to a specified demand. Compressors are selected based on flow requirements at the relevant pressure. Different compressor combinations are compared to determine the most efficient compressor

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combination for the system demand. All system-specific constraints are considered when calculating compressor combinations.

Abnormal system pressure losses in the system can also be detected using flow dynamic calculations. System pressure losses are sometimes attributed to isolation valves being partially closed, piping restrictions due to accumulated moisture in the pipeline, incorrect pipeline sizing for flow requirements, compressor sizing, compressor placement and other physical restrictions. Mitigation for identified problem areas can be evaluated and implemented should they be financially viable.

### **3.2.5 Developing a dynamic selection model to optimise compressor system efficiency through effective scheduling of priorities and PSPs**

During the research done in this study, various mine compressor systems were investigated. The most advanced controller found operated automatically using static inputs from skilled technical personnel. Upon further investigation, missed opportunities were found that could be addressed with dynamic prioritising of compressors. Many systems were found to have very little or no automatic compressor controllers.

All of the control philosophies and compressor controllers were reliant on skilled operator input and constant maintenance. Although energy efficiency of these systems was the top priority of operators, missed opportunities existed due to the system operators lacking experience. Some systems were even found to be operated without a drive for energy efficiency.

Advanced SCADA systems are already implemented on most mines and adequate instrumentation is available to measure key performance indicators. However, this data is rarely used by system operators when developing a compressor control philosophy. Control philosophies are based on hearsay, experience and assumption, which limit the effectiveness thereof. By integrating available system data, more informed decisions are made based on actual system requirements.

Due to the constant fluctuations in demand, static controllers are not usually the best fit for energy efficient control solutions. Existing controllers found in industry could not automatically adapt to variation in demand or supply of compressed air without some form of operator interference. Missed opportunities detected were small per event, but still enough to justify the development of a dynamic control system. Missed opportunities included:

- compressor started unnecessarily,

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- compressor left to run after demand had decreased enough for the compressor to be shut down,
  - incorrect compressor sizing due to efficient control of end-user demand,
  - compressor cycling due to incorrect priorities, and
  - unnecessary high compressor PSPs.

Missed opportunities were mainly due to compressed air demand fluctuations from day-to-day. For example, two subsequent Mondays do not necessarily follow the exact same demand, neither do two other successive weekdays. System operators adjusting the compressor control philosophy in real time is impractical. A controller capable of evaluating all key performance indicators and production schedules in developing a continuous, dynamically optimised control philosophy could realise a fair amount of currently missed savings opportunities.

The first common mistake made in energy efficient strategies was found to be on the capacity control of the compressors. Although it was known that the savings opportunities to be achieved were on the compressor side, assumptions were made. Literature available on compressed air projects indicated that it was assumed that once demand was lowered, compressors would automatically reduce their capacity when automated, resulting in energy reduction.

Compressor automation was done by third-party contractors taken to be experienced in the field of compressor automation. This is not always true, and situations were found where compressor control could be vastly improved. As part of the implementation of the controller investigated in this study, proper compressor automation was required to realise the energy saving potential. Typically, this would only include the reprogramming of the capacity control configuration as the majority of the compressors found have already been automated to some extent.

With the compressors automated and properly instrumented to include power meters, flow transmitters and pressure transmitters, the compressors were characterised according to efficiencies. This was then used to determine compressor priorities based on true compressed air delivery into the system, as well as the corresponding power requirements. This enabled the minimum amount of compressors to be operated supplying the needed flow at the required pressure using the least amount of energy.

Demand at the end users was controlled using control valves to reduce the supplied pressure. This was done on surface, on the underground levels, or on a combination of the two. PSP profiles were determined according to operational requirements for each individual end user and/or levels. The set points (current and future values) were relayed back to the controller and

were used in calculating the required system pressure. As the set points were able to change daily, set points were updated continuously in the controller to ensure that the relevant pressure was available at all times to prevent production losses.

In order to do this, all of the system characteristics had to be evaluated and considered in the decision making of compressor selection. Individual point of delivery pressure and flow requirements, compressor delivery flow and pressure statistics, system losses and so forth, give a better understanding of the system. With all of the correct instrumentation in place, it is possible to adjust dynamically to varying supply.

PSPs of all of the shafts can be mapped together to calculate the required PSP of the network at any given stage. With the pressure requirement known, the requirements could be adjusted to account for pressure drops over longer distances to calculate the required set point of the compressors. Flow meters at the various points of delivery gave a clear indication of the system flow requirements, which determined compressor priorities.

With the demand and supply characterised, the system could almost be implemented. The only requirement was the characterisation of the system mechanics. These included the following:

- all compressed air piping diameters, configurations and dimensions (network configuration),
- compressor placement,
- demand locations relevant to compressor locations, and
- ambient temperature and ambient pressure of the relevant site.

These requirements were required to calculate system pressure drops across the network to ensure adequate pressure was supplied to all end users. Due to the complete characterisation of the system, future flow requirements could be calculated using future PSP requirements. With future requirements known, compressor stop/starts could be limited and controlled within acceptable limits. Complete system requirements were evaluated and the supply was prioritised to meet the demand in an energy efficient approach. This was done dynamically using real-time system data and physical system constraints.

### **3.2.6 Simulation component model to simulate the effect of dynamic compressor prioritising and PSP on actual system characteristics**

Various simulation packages exist that can be used to simulate CAN response. The two packages regularly encountered in the South African consulting environment are Flownex and KYPipe. These packages require processed system data entered manually into the software

package from where the required simulation can be done. No interface is available to access real-time system data to simulate system response. This requires that data be entered for each scenario to be evaluated, which can be a time-consuming process.

A working knowledge of these simulation packages is required to obtain accurate results. Considering the skill required and the time-consuming data entry process, these packages are unappealing solutions for the mining environment. By combining the functionality into the controller, various control philosophies can be tested and simulated using real-time data. With all of the data required available to the controller, minimal input is required from the user.

Pressure drops, flow requirements and compressor combinations can be determined beforehand and all risks can be identified. Before any changes are made to the CAN control philosophy, simulations can be done to evaluate the effect on the system. Piping upgrades, compressor moves, PSP changes and so forth, can be tested and evaluated to determine financial viability, and their impact on energy efficiency. Each system change can then be simulated with minimum input required, considering all system constraints based on actual system performance.

### 3.3 Addressing limitations

#### 3.3.1 Minimum requirements of a DCS system

Various different compressor control combinations and systems are encountered throughout industry today. To ensure the controller developed in this study will be capable of interfacing with existing controllers, minimum system requirements have been set. The system should:

- efficiently control compressor capacity,
- automatically accept PSPs from a control system,
- automatically stop/start compressors (using a start/stop command),
- control end-user demand using pressure control valves, and
- have adequate instrumentation on supply and demand points (flow, power, pressure and temperature).

All compressors encountered in the mining industry have some form of capacity control installed. This could range from the older to the newer Moore-type controllers, to PLC-based controllers. The efficiency of these controllers has to be evaluated to ensure capacity control is done with energy savings in mind. Older capacity controllers are not always set up to control capacity efficiently (as described in Section 2.4) but to rather focus on avoiding surge.

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A fine balance should be obtained between upgrading the surge controllers to operate the compressor closer to the surge line, and operating the compressor safely. With the technology available today, this can be achieved easily. The focus of this study is, however, on developing a DCS and not on automating compressor capacity control. Various contractors have been identified in the South African automation industry that are capable of performing the required automation. As part of the implementation of this controller on client sites, automation will be subcontracted to third-party contractors.

During the investigation of mine compressor systems, it was found that not all capacity controllers were capable of receiving set points from control systems. In instances where this was the case, compressor control had to be upgraded. Set-point control is crucial in energy savings projects as it allows the compressors to operate at lower PSPs during low-demand periods. When the set point is reduced by 10%, compressor power reduction in the region of 16–18% is achievable [14].

Capacity control and set-point control are responsible for one part of the energy savings achievable in efficient compressor control strategies. The second part of energy savings is the stopping of unnecessary compressors during low-demand periods, and the starting of compressors when air is required. In order to ensure that compressor control can be done automatically, the start and stop sequence of compressors should also be done automatically.

The DCS control system will only issue a single stop or start demand to a compressor depending on the requirement, and a compressor will be removed or added accordingly. The compressor to be started or stopped will be calculated by the DCS developed as part of this study.

To ensure that the demand at the end users is controlled according to the absolute minimum demand, control valves are installed on the compressed air supply. This can be done on surface, per level, or on a combination of the two. A minimum PSP is then constructed by evaluating all of the compressed air requirements of the various users. Requirements include pressure, flow and time the compressed air is required.

The requirements are then superimposed to construct the end-user demand profiles. Figure 26 is used to explain the concept of superimposing. The pressure requirement of the particular point of delivery (dashed black line) is obtained by calculating the overall maximum pressure requirement of all the pneumatic equipment. All the compressed air users should be taken into account to ensure normal operation is not affected due to insufficient pressure.

In order to characterise the system as described in the previous section, measurement data from the system is required. All supply and demand points should be equipped with pressure transmitters, temperature transmitters and flow meters. The compressors should also be equipped with power meters to ensure an efficiency matrix can be constructed for every compressor. This information should then be made available to the DCS controller.

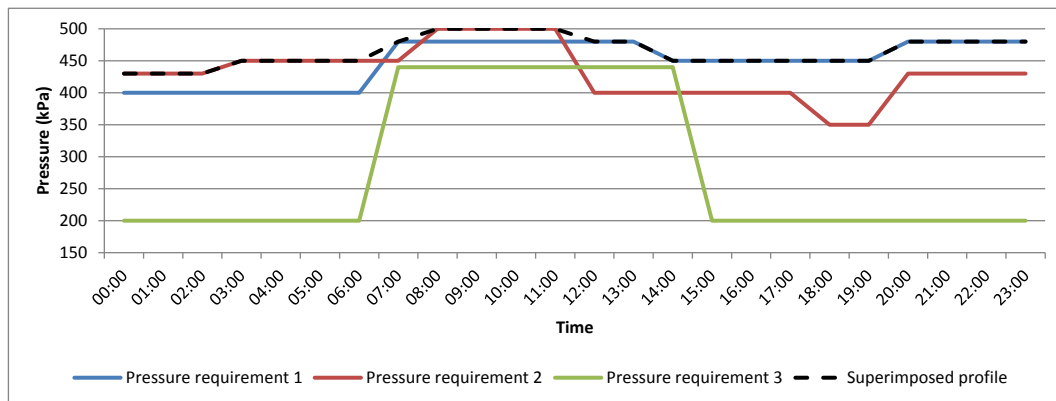


Figure 26: Superimposed profile

### 3.3.2 Improving existing compressor control systems

The DCS is a stand-alone control system that interfaces with an existing SCADA. On some of the sites, compressor controllers with automatic stopping and starting capability were already implemented. Compressors are stopped and started according to a specific priority list predefined by a compressor system operator. These systems have their own constraints programmed into the controller. The constraints were defined through trial and error during the implementation of various control strategies.

To ensure the best control philosophy is implemented, each system has to be evaluated specifically per site. System constraints, configuration settings and baseload compressors have to be scrutinised and system efficiency evaluated. Suggested improvements have to be tested manually before implementation to evaluate the feasibility of the solution. In some instances, the compressor scheduling can be completely transferred to the DCS to ensure efficient control.

Some of the systems encountered do more than compressor scheduling, where compressor auxiliaries, cooling towers, pumps and other subsystems are all encountered in one SCADA system. Where it is difficult to separate the compressor control from the existing SCADA, compressor PSPs, end-user demand set points, compressor prioritising and stop/starts are controlled by the DCS using control tags.

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Individual tags are created that act as handles to the stop, start, set point or priority commands on the SCADA machine. Each tag can be manipulated, using an OPC interface on the DCS system to change the corresponding parameter on the compressor, valve or other item to be controlled. By having this capability, the existing compressor control on the SCADA can be enhanced without drastic changes required on the client SCADA system.

### 3.3.3 Factors influencing control

#### *Limitations due to compressor capacities*

The literature that was reviewed indicates that compressors can be added and removed according to the demand of a system with existing system controllers. Systems on which this are based, however, consist predominantly of screw compressors. Installed capacities of these compressors are seldom above 500 kW, and the start-up procedures of these compressors are fairly simple.

The starting procedures of electric motors, which have installed capacities of 4–5 MW, are influenced by various factors. Voltage dips, maximum demand, state of switchgear installed and the impact on compressors due to mechanical and thermal stresses are just some of the effects that need to be considered when compressors are stopped and started on demand. Time limitations may even apply between starts and stops to allow proper cool-down of motor windings.

Compressor control systems should, therefore, aim to limit stopping and starting of compressors to an absolute minimum. Disregarding these factors could result in financial losses that nullify the energy savings achieved by the control system. It was found that the alleged disadvantages of stopping and starting compressors with outdated control resulted in some clients forbidding this control philosophy. To address this issue, the controller was adapted to allow for manual configurations of:

- the baseload compressors to be selected,
- the maximum allowed stop/starts per day (per compressor or per system), and
- the minimum allowed time between stop/starts.

These system parameters were obtained by discussing the limitations, possible solutions and required hardware upgrades with relevant client personnel.

A baseload compressor will not be stopped by the control system. Baseload conditions can be defined per compressor for each day of the week. Clients usually do not allow large

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compressors with installed capacities of more than 8 MW to be stopped during the week. This is mainly due to safety reasons in case the compressor cannot be started back up again before the production period, which may result in compressed air shortages. However, these compressors can be shut down over weekends when the demand is significantly lower.

Upgrades such as switchgear upgrades, soft-start technology upgrades, control upgrades and instrumentation upgrades were all investigated. If it was found that if these upgrades were financially viable with an acceptable return on investment of less than 12 months, they would be done as part of the project. Longer return on investment upgrades should be discussed with the client for future implementation.

### *Condition of infrastructure*

#### **Compressors**

As can be seen from Figure 27, the peak in the South African gold mining industry happened from 1960 to 1970 [90] during which the mining industry in South Africa expanded. During this time, the majority of mining infrastructure was built, imported and commissioned. Compressors are some of the biggest, most expensive compressors in the mining industry. As a result, the majority of the compressors, which date back to the 1960s, are still in operation today.

Due to the age of these compressors, spare parts are hard to come by. With the mining production reliant on compressed air, it is understandable that mine personnel are reluctant to do anything that might affect the operation of these compressors. Although this is not the case at all of the client sites, this has to be considered when developing a universal controller. Therefore, the controller should be able to control the compressors in such a way as to not switch off the compressors when they are required by mine personnel.

Mine personnel may require that compressors are not stopped or started automatically, or even at all. This can be addressed in one of two ways. The controller can issue a command to stop or start a compressor. An alarm can be triggered, whereafter the operator should respond. This may affect performance as the operator will not always respond immediately or effectively. However, improved performance may still be achieved this way.

Another option is to disable stop/start altogether by controlling using only set-point pressure. Compressor control can then be set up in such a way as to offload unnecessary compressors during low-demand periods. This will typically occur when compressor capacity is reduced to the minimum using an appropriate capacity control technique as described in the previous

chapter. Once the compressor has been operating in this minimum delivery region for a predetermined time (typically 10–20 minutes), the compressor is offloaded, but not switched off.

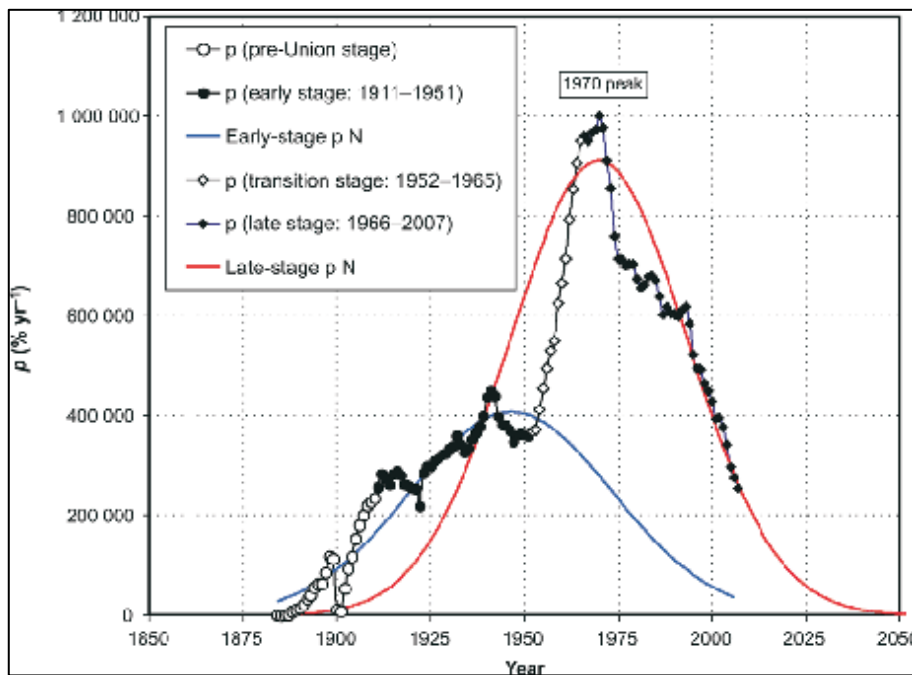


Figure 27: South African gold production history (obtained from [90])

This can be repeated for all compressors in the system. Once a compressor is offloaded, it can be seen as switched off, as it delivers no compressed air to the system. One benefit of controlling compressors this way is that the compressor can be added to, and removed from, the system more often. A narrower pressure control band can then be implemented to make up for lost savings. The down side of this control method is that the compressor still consumes power when offloaded, albeit at a reduced rate of 29% as seen in Section 2.3.1.

The optimal solution would be to have the ability to switch a compressor off, and to automatically start it back up again. Various improvements in compressor start-up techniques have been developed since the manufacturing of these compressors. Soft starters, liquid starters, autotransformers and even VSDs can be applied to ease compressor start-ups to reduce stresses on equipment. The financial viability and client approval of these improvements have to be evaluated against achievable savings to allow the upgrades.

### Control valves

Controlling the demand side is essential to the success of controlling the CAN as a whole. Controllability of the demand is directly related to the effective operation of demand control valves. Although this is not a new technology to be implemented at the mines, improvements

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are required from time-to-time. Incorrect sizing of valves, failure of actuators or control, and worn out valves result in missed energy saving opportunities.

Valve sizing is critically important to ensure adequate control is obtained from the equipment installed. A valve that is too big for the application will result in loss of controllability at low-flow scenarios. On the other hand, a valve that is not big enough for the air requirement may result in choking of air delivery, causing an excessive pressure loss across the valve. Both of these scenarios may pose a problem for the mine and may result in control being discontinued.

Electric actuators have a design specification of a finite number of modulations per time period. As the flow requirement of the end user varies continuously, the actuator has to adjust the valve position on a continuous basis to maintain the set-point pressure of the end user. Each of these adjustments causes the actuator to react through the electric motor driving a gearbox that turns the valve. These stop/starts may ultimately lead to the failure of the actuator.

With pneumatic actuators, water in the compressed air line may pose a problem to the correct functioning of the device. Moisture is usually removed through the use of water traps, but some water may still pass to the actuator and over prolonged use the water will damage the actuator's mechanical internal components. Actuators may become stuck, unresponsive or slow to react. Under any of these circumstances, controllability and the associated energy savings are lost.

Valves are operated on a continuous basis, and failure may be encountered from time-to-time due to normal wear and tear. To ensure effective control, valves should be able to fully close when required. This is usually done using seals (called seats). The seats are fitted inside the valve and can be made from various highly durable materials such as polytetrafluoroethylene (PTFE) or stainless steel. Although these materials are highly durable, it does wear down when used extensively.

When the material wears out, the valve does not close as tight as it should and some air passes through. Large quantities of air can be lost through defective valves, resulting in unnecessary energy loss. These seals can often be replaced on site by trained artisans. Another approach is to have spare valves available, one for each size of valve. The defective valve can be replaced with a spare valve, and the defective valve can be refurbished.

In order to address these issues, all control valve configurations need to be evaluated when a control system is implemented. Control valve sizing, actuator functionality and valve condition need to be inspected and faulty equipment repaired or replaced where necessary.

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## Network infrastructure

Network infrastructure degrades over time due to rust and corrosion, resulting in compressed air leakages occurring. Due to compressed air being invisible, leaks in the system often go unnoticed thus increasing compressed air demand systematically over time. The system will not notice the systematic increase in compressed air usage and will respond to the rising demand with increased supply. If leaks are not properly managed, supply cost will rise continuously.

A compressed air leakage documentation system is implemented as part of a comprehensive compressed air optimisation drive. This system has been developed in-house, with a detailed description in [15]. Audible leaks are documented during routine inspection using a robust handheld computer. Data is then synchronised with a desktop computer from where it is processed into reports. Reports, which express the effects of the detected leaks in monetary terms, are distributed to relevant client personnel.

When documented leaks are repaired as part of a continuous energy strategy, the system will automatically respond to the reduction in demand. Leak repair causes system pressure build-up, which in turn lets compressors reduce capacity through capacity controllers. When the demand is reduced sufficiently, the DCS will enable the shutdown of a compressor. By reducing the demand, the matching reduction in supply will lead to improved energy efficiency of the CAN.

The effectiveness of an advanced compressor scheduler can be nullified without regular maintenance on the CAN and all of its subcomponents. Compressed air leakages can account for the majority of compressed air usage in an unmanaged system as seen in a previous study done [15]. Dedicated personnel are recommended to actively manage compressed air leakages. The electricity cost saving achievable will be sufficient for paying the salaries of these personnel [15].

### *Personnel perception*

One area that directly affects project achievement is personnel perception regarding compressor control. Decisions are based on assumptions without having the data or evidence to back them up. Decisions are made regarding compressor control, preventing automated control and stopping and starting of compressors. The reasons given are risk of production losses, possible increases in compressor maintenance, compressor failures, compressor cycling, and many more. These decisions, however, are not supported by data.

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The effect is, however, not limited to compressor control, but in some instances also affect demand side control. Some of these believes include minimum pressure allowed during the various production shifts, and that control valves will take away needed air at end users. The adoption of hydraulic cylinders on one project was discarded due to an engineer believing that the small reduction in flow was not worth the effort.

The actual reduction could, however, be achieved by lowering the required pressure during non-production times. The minimum supply pressure of 450 kPa required by the cylinders could be reduced to 200 kPa should the hydraulic conversion be installed. A reduction of 250 kPa in supply pressure could result in significant energy and electricity cost reduction.

To address this problem during implementation, manual testing is done in conjunction with the relevant client personnel. On the compressor control side, the system is commissioned in parallel with the existing system. Control parameters are calculated by the DCS controller and manually entered into the existing system. The system response is then evaluated for an extended time period using manual intervention.

Once the results are found to be adequate, they are discussed with management personnel. When all parties are comfortable with the results, the system undergoes an automated evaluation phase where it is closely monitored. The financial impact of the system is then used to prove the system functionality to all relevant parties. Data from previous implementations can also be used to convince client personnel of the system functionality.

On the demand side, investigations are done to determine the minimum set points of the system during each of the different operation shifts. Client personnel are engaged, from where a list is compiled of equipment requiring specific pressures during specific shifts. Once again a manual test is done, from where the set points are tested with client personnel present. These tests are evaluated over an extended period of time.

Control room operators keep a log of all complaints regarding air pressure from the various points of operation. If complaints of inadequate air pressure are received, PSPs are gradually increased until air requirements are met. Abnormal air requirements are investigated to prevent misuse of expensive compressed air, and the set points are adjusted accordingly. Once manual tests prove satisfactory, set points are signed off by client personnel and entered into the controller for automated control.

Data is required in all instances to prove the functionality of the system during manual test procedures. The DCS system is developed in such a way that it will log all of the test data. The

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data is then available for calculation and illustrative purposes. With adequate data, personnel perceptions can be changed to adopt energy saving strategies.

### 3.3.4 Dynamic control requirements

To accurately control a system dynamically, detailed system information is needed. Information can be broken down into the following segments:

- system measurements,
- operational constraints,
- physical limitations,
- static system information, and
- dynamic system information.

System measurements are system input data obtainable from installed instrumentation. Measurements include, for example, pressure, flow, power, temperature, valve positions and equipment status. These data points are retrieved in real time. 'Real time' is a relative term, and for the purpose of this study two-minute interval data will suffice. These data points should be accurate and filtered to remove any spikes in measured values before they are used in calculations. To ensure accuracy, instrumentation is calibrated on a regular basis as part of the normal client maintenance procedures.

Operational constraints need to be updated on the system to ensure that accurate profiles for the different time periods are followed. Constraints will be, for example, a public holiday that does not follow normal operational procedure. For this day, the PSPs at the shafts need to be changed to follow a non-production work schedule. The system will have default values for weekdays, production and non-production Saturdays, and Sundays. Any settings that may change due to operational changes need to be updated in the control system. This will ensure that control inputs stay relevant, and energy savings are optimal.

Due to the fact that these systems are not ideal, physical limitations still exist to which the system must adhere to. To match theory with practical application, these limitations need to be preprogrammed into the system specifically for the respective sites. Limitations include, for example, upper pressure bands (to prevent column from bursting) and compressor delivery limitations in terms of pressure/flow delivery. The limitations are usually static, but can be altered if system changes are implemented. All of these constraints are defined specifically for the equipment to enable system flexibility. Changes to these system values are made by system implementation specialists or the DCS system developers.

Apart from the physical limitations of the system, other static system inputs are also required. CAN configuration (for example, bends, column diameter, length of pipelines and compressor placement), baseload compressor selection, compressor lockouts due to maintenance/repairs, and other low-frequency varying system information are also entered into the system. System operators are trained to change these settings in the system as it may be required on a more frequent basis than the physical system limitation changes.

To ensure that the DCS system performs as expected, regular system monitoring should be done:

- the operator monitors the system from time-to-time,
- daily reports to relevant client personnel on system performance are created, and
- alarms are activated for unusual events.

These measures will aid in the sustainability of the DCS system.

The system operator can monitor the system as part of a routine maintenance check. Reports are generated on a daily basis by a centralised reporting system and sent to relevant client personnel. Key performance indicators such as pressure, flow and power are used to verify operation against a predetermined baseline profile. Over- and underperformances are highlighted to assist when fault finding. Alarms, by means of email and text messages, are set up to alert personnel who are out of the office. Different personnel can be allocated to different types of alarms if required.

## 3.4 Integration and execution of control parameters

### 3.4.1 System terminology

The following section will describe the DCS interface for setting up the controller. Although the system is set up by in-house project engineers, training is given to client system operators. Training will allow these operators to do troubleshooting and small customisations of the system platform. Major network changes and control philosophy changes are still recommended to be implemented by the project engineers of the developing company.

The DCS system consists of various components working together. The components can be grouped into four groups:

- Network reticulation
  - Pressure Node component
  - Air Pipe component

- 
- Node Feedback component
  - Air Solver component
  - Supply side
    - Compressor component
    - Compressor Controller component
    - Compressor Prioritiser component
  - Demand side
  - Tools component

Network reticulation and supply side components have an icon that is displayed in the software, as well as its own Edit form. Specific component icons provide system operators with sufficient detail on system operational feedback (such as pressures, flow meter readings and set points). The Edit form is used to set up the controller through the various components used.

Components are used to make the system adaptable to the varying demand from clients. Some of these components are interdependent and cannot function on their own. The following paragraphs will briefly explain the set-up and functionality of each of these components. For ease of reference, these components have been grouped according to the groups mentioned above.

The demand side components are built into the network reticulation components, and do not have specific Edit forms. Tool components are also available to personalise the user interface and to display key performance indicators on screen. These tools are, however, for illustrative purposes only, and will not be discussed in detail as part of this study.

### **3.4.2 Network reticulation and point of delivery**

The network reticulation set of components is used to do the dynamic flow calculations of the network. Pressure drops, flow balance calculations, future and present flow in the different parts of the network are all obtained from these components. Instrumentation readings and calculations are used in combination to obtain the necessary feedback. Although the majority of the calculations are done in the background, these components provide the necessary system input. Only the components required to set up the DCS system will be covered in the following section.

#### *Pressure Node component*

A node can be defined as (Merriam-Webster online dictionary):

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“A place where lines in a network cross or meet.”

In the DCS control system, this definition defines what the Pressure Node component is for. At each section in the CAN where piping ties off or junctions occur, a node is used. Due to the system working on mass-balancing of flow in the network, the node aids by defining which pipes are connected to which specific nodes. On the system, a node will be displayed as depicted in Figure 28.

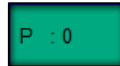


Figure 28: Pressure Node icon

A node can be defined as a normal, supply or demand node. A normal node will be used where it depicts a piping network configuration. A supply node will be selected for a compressor or compressor house, and a demand node for a point of delivery. When a supply node is selected, the corresponding compressor controller should also be selected. System data is added into the node using the following fields on the Pressure Node Edit form (Figure 29) as summarised below:

- *Pressure tag* – Either the compressor delivery pressure tag (supply node), or the shaft pressure tag (demand node). For a normal node, this pressure can be left blank as it will be calculated. Pressures can be in bar, pascal or kilopascal depending on client specifications.
- *Flow tag* – Either the sum of the compressor delivery flow tag (supply node), or the sum of the shaft consumption flow tag (demand node). For a normal node, this flow can be left blank as it will be calculated. Flow can be given as volumetric ( $\text{m}^3/\text{h}$ ,  $\text{m}^3/\text{min}$  or  $\text{m}^3/\text{s}$ ) or mass flow ( $\text{kg}/\text{s}$  or  $\text{kg}/\text{h}$ ) depending on client specifications.
- *Set-point pressure tag* – Only defined for demand and supply nodes through the corresponding tag values. For the supply node, this will be used as a starting pressure when the system has been reset. On demand nodes, the value will be read from the tag value as input into system set-point calculations.
- *Node variance* – Fixed pressure variances can be specified here. The value will be added to the set point returned from the field instruments to obtain a new demand set point. Values should be stated in pascal.
- *Future flow tag to write out* – Used if future calculated flow needs to be displayed on the DCS platform for the relevant node.

- *Upstream pressure to write out* – Upstream pressure as calculated from valve position and downstream pressure (when no upstream pressure transmitter is available). This feature is used at a demand node only for display purposes.
- *Compressor controller linked to* – If supply node is selected, the corresponding compressor controller should be selected.
- *Valve position tag* – Applicable to demand node only; used to calculate supply pressure before a control valve.

By selecting the *Show values in kPa* option, the values displayed on the icon will be scaled to kilopascal. The number of decimals to be displayed can also be selected. If the valve position is defined as percentage closed, the checkbox for *Switch to 0 full open* should be selected.

Figure 29: Pressure Node Edit form

### *Air Pipe component*

The Air Pipe component is used to define the corresponding column characteristics. The Air Pipe icon will display the calculated flow in the pipeline defined by the Air Pipe component as displayed in Figure 30.

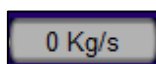


Figure 30: Air Pipe icon

Airflow is calculated through mass balance flow dynamic calculations. If flow direction is reversed (from right to left) the value will be preceded by a negative sign. By accessing the Air Pipe Edit form (Figure 31), the pipeline can be defined using diameter, length, K-loss factor and roughness. The default value for roughness is taken as 45  $\mu\text{m}$ . This is an average value as calculated empirically from historical data on mines in South Africa. The K-loss factor is obtained through simulation software using site-specific data. This value can be reverse-engineered to obtain more accurate values once the system has been installed. The two nodes interconnected by the air pipe should be specified and displayed under nodes in the Air Pipe Edit form.

 A screenshot of a software dialog box titled "EditForm". The dialog has a purple title bar and a white background. It contains several sections:
 

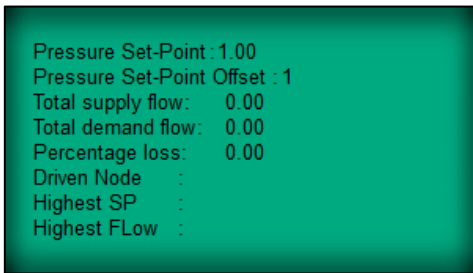
- Description:** A text field containing "AirPipe 1".
- Flow out tag:** A yellow text field.
- Set-point out tag:** A yellow text field.
- Characteristics:** A section with four input fields:
  - Diameter(m): 0.5
  - Length(m): 2000
  - K Loss: 1
  - Roughness: 45
- Nodes:** A section with two input fields:
  - In: AirNode 1
  - Out: AirNode 2
- Flow unit:** A dropdown menu currently set to "Kg/s".
- Decimals:** A spin box set to "0".
- Absolute value:** An unchecked checkbox.
- Buttons:** "OK" and "Cancel" buttons at the bottom right.

Figure 31: Air Pipe Edit form

### *Node Feedback component*

The Node Feedback component is used to display system information as calculated from the nodes in the system. Figure 32 displays the icon used in the DCS platform environment. From here, the information given can be seen. System PSP, supply and demand flow, as well as the nodes with the highest demand, highest set point and highest flow requirements are displayed.

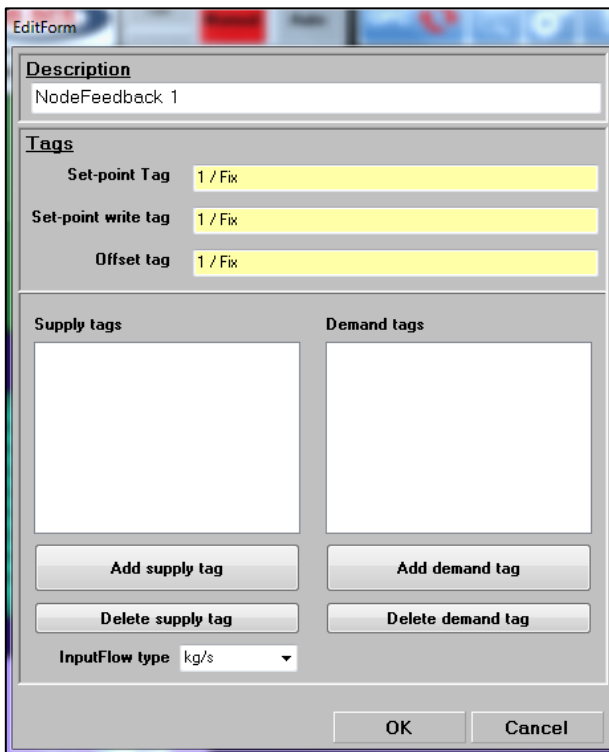
The driven node gives the node that drives the compressor set point. This is not necessarily the demand node with the highest set-point requirement, therefore, the highest set-point and flow requirement node are also displayed. This information can be used as an energy management tool to determine whether compressed air use is justified at the driving node. Compressed air usage can then be altered to reduce wastages.



```
Pressure Set-Point : 1.00
Pressure Set-Point Offset : 1
Total supply flow : 0.00
Total demand flow : 0.00
Percentage loss : 0.00
Driven Node :
Highest SP :
Highest FLOW :
```

Figure 32: Node Feedback icon

To set the Node Feedback component up to function correctly, the Node Feedback Edit form (Figure 33) is used. Supply and demand flow tags are added, as well as the set point calculated by the DCS controller. If a constant pressure offset is required, this can be specified as well. The value will then be added to the set point. Flow differences between demand and supply will be corrected in further calculations.



The Node Feedback Edit form is a graphical user interface window titled "EditForm". It contains the following fields and controls:

- Description:** A text field containing "NodeFeedback 1".
- Tags:** Three text fields for "Set-point Tag", "Set-point write tag", and "Offset tag", each containing "1 / Fix".
- Supply tags:** An empty list box with an "Add supply tag" button below it.
- Demand tags:** An empty list box with an "Add demand tag" button below it.
- Control buttons:** "Delete supply tag" and "Delete demand tag" buttons.
- InputFlow type:** A dropdown menu currently set to "kg/s".
- Navigation:** "OK" and "Cancel" buttons at the bottom right.

Figure 33: Node Feedback Edit form

### *Air Solver component*

The Air Solver component is the most important component of the DCS system. No icon is used as this component does all of the background calculations and no feedback is given for display purposes. The Air Solver Edit form shown in Figure 34 is used to double-check that all nodes

are used. Nodes and pipes are automatically added to the Air Solver component and are displayed under the *All nodes* column in the Air Solver Edit form.

Once a node is selected, the interconnected pipes will be displayed in the *Pipes* column. If the pipe is selected, the node connected to the pipe will be displayed in the last *Nodes* column on the right.

Compressor control safety margins can be specified using the *Pressure* and *Flow* boundary fields. Minimum and maximum boundaries can be entered wherein the controller will always operate. Once the controller calculates values outside the boundaries, the system calculations will reset and will be recalculated. If the problem persists, an alarm will be activated and values clamped to the minimum or maximum values specified.

The screenshot shows the 'Air Solver Edit form' with the following details:

- Description:** AirSolver 1
- All Nodes:** AirNode 1, AirNode 2, AirNode 3, AirNode 4, AirNode 5, AirNode 6, AirNode 7, AirNode 8
- Pipes:** (Empty)
- Nodes:** (Empty)
- Pressure Boundaries:** Max: 800000, Min: 100000
- Flow Boundaries:** Max: 50, Min: 1
- Control Properties:** Calc rest time: 60, Max Thread count: 20
- Time last calculation took:** 0
- Buttons:** OK, Cancel

Figure 34: Air Solver Edit form

The controller will keep on calculating system requirements in the background. Once calculated values are within the boundary conditions, the newly calculated values will be used for system scheduling. Minimum and maximum boundaries will ensure that the output of the controller is always operating within acceptable limits as specified by the client.

The control properties are also set up using the Air Solver component. Time between system calculations (*Calc rest time*) is specified in seconds, with the default being 120 seconds. The *Max thread count* field is used to enter the maximum number of possible different solutions for

the system. Higher values increase system accuracy, but significantly increase calculation time. The default value is set to 20, but it can be adjusted to the system's requirements. The *Time last calculation took* field displays the time that elapsed while calculating the last solution in order to adjust the value in the *Max thread count* field for optimum system performance.

### 3.4.3 Supply side

#### Compressor component

One of the more important components in the DCS system is the Compressor component. Figure 35 shows the icon of the Compressor component as used in the DCS platform environment. A compressor can be in one of three states:

- on,
- off, or
- offloaded.

As can be seen from Figure 35, the status of the compressor is indicated at the bottom of the icon. Colours are used for easy reference of the three compressor states: red (off), green (on) and yellow (offloaded) respectively.



Figure 35: Compressor icon

In order to set up the relevant control information for the compressor, the Compressor Edit form (Figure 36) is used. By using the relevant OPC tags, information is automatically processed for calculation purposes. On the left-hand side of the Compressor Edit form, *Control*, *Permission*, *Status* and *Measurement* tags are added in yellow blocks. The tables on the right-hand side of the Compressor Edit form are used for the characteristic data of the corresponding compressor.

Compressors are characterised according to flow ranges at different delivery pressures, as well as power efficiency at these pressure and flow ranges. These characteristic data is used by the compressor controller for selecting the next compressor to be added or removed from the system. Manual data entries can also be added when the system is installed using historical

data. This will enable improved accuracy at start-up. This data will automatically be updated given that the *Auto-update* functions are selected under the *Control Parameters* section.

The screenshot shows the 'Compressor - Compressor 1' edit form. It features several sections for configuration:

- Control tags:** Start, Stop, Load, Unload (each with a 'High Active' checkbox).
- Flow ranges:** A table with columns for Pressure (Pa) and Flow Range (kg/s).
- Power efficiency:** A table with columns for Flow (kg/s), Pressure (Pa), and Power.
- Permission tags:** Start, Stop, Load, Unload, Set-point control (each with a 'Def True' checkbox).
- Status tags:** Running (InternalTag run), Loaded, Availability, Priority.
- Measurement tags:** Power usage, Delivery volume (m³/h), Delivery pressure (Pa), Guide vane position (invert), Running hours, Efficiency, BlowOff Position (invert), Efficiency out.
- Control Parameters:**
  - Auto update Flow:
  - Auto update Efficiency:
  - Enable table logging:
  - Min Vane Position: 0.00 %
  - Max Vane Position: 100.00 %
  - Max BlowOff Pos: 0 %
- Power rating:** 15000.00 kW, Type: --, Make: --
- BaseLoad:** 0 / Fix
- Reserve:** 0 / Fix
- Max Stops per day:** 100

Figure 36: Compressor Edit form

The *Min vane position* and *Max vane position* fields are required to characterise the compressor. The vane positions enable the DCS system to register when a compressor is at the minimum and maximum flow delivery. The *Power rating* and *Type* fields are purely used for recording and reporting purposes. *Maximum stops per day* are specified to limit compressor cycling according to a client-approved limit. Compressor baseload (*Baseload* field) and reserve classification (*Reserve* field) can be set up using OPC tags, fixed values or according to a schedule (*Max stops per day* field).

*Delivery volume* and *Delivery pressure* measurements and units need to be specified. Volume (flow) and pressure are converted to kg/s and pascal units, respectively, to be used by the controller. *Guide vane position* and *Blow-off valve position* are indicated in percentage open, but can be inverted to accommodate percentage closed. Control tags (*Start/Stop/Load/Unload* fields) are usually in binary, with a '1' indicating a true state. By deselecting the *High Active* options next to the respective fields, the values will be inverted.

### Compressor Controller component

The Compressor Controller component, as displayed by the Compressor Controller icon in Figure 37, was initially developed as part of a simplistic controller for stopping and starting compressors. The original controller used static control inputs and schedules. The controller was retained in the DCS system but was only used to allocate compressors to specific compressor houses.

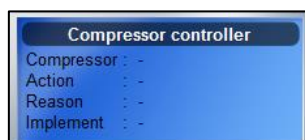


Figure 37: Compressor Controller icon

The static control functionality is still available, but it falls outside the scope of this study. In the DCS system, the Compressor Controller Edit form (Figure 38) is used only to specify which compressors belong to which specific compressor houses. A Compressor Controller component will, therefore, be required per compressor house. The compressor-specific details will be obtained from the Compressor component described in the preceding section regarding compressor selection.

 A screenshot of a software interface titled "DCS Compressor Controller - CompressorController 1". The interface is divided into several sections:
 

- Description:** "CompressorController 1"
- Publish:** "Control enabled : 1 / Fix"
- Control parameters:** "Control enabled : 1 / Fix", "Number of compressors" (Min: 0 / Fix, Max: 20 / Fix), and three delay sections: "Controller delays" (Warm-up: 1, Suspend: 10), "Implementation delays" (Buffer: 1, Implementation: 5, Retry: 1), and "Post-implementation delays" (Start: 30 min, Stop: 30 min, Load: 30 min, Unload: 30 min).
- Compressors:** A table with columns for "Description (Tick for Baseload)" and checkboxes. "Compressor 1" is unchecked, "Compressor 2" is checked, and "Compressor 3" is unchecked. Buttons for "Add", "Delete", and "Edit" are at the bottom.
- Control according to pressure (Adjust compressor set-points):** Includes "Set-point tag : 500.00 / Fix", "Pressure monitor tag : 150.00 / Fix", and "Backup Set-point tag : 150.00 / Fix".
- Control according to combined vane positions (Detect low vane position):** Includes "Decrement" and "Increment" buttons and a table with columns "Running" and "Min vane position".
- Control according to pressure (Keep pressure within limits):** Includes "Upper set-point offset : 100" and "Lower set-point offset : 100".
- Control according to flow (Select compressor according to flow):** Includes "Flow monitor tag : 1 / Fix", "Set-point tag : 1 / Fix", "Future set-point tag : 0.00 / Fix", and "Override : 0.00 / Fix".
- Stop unloaded compressors:** A checkbox.
- Maximum allowable starts:** "Maximum 1000" with a note "(This is the maximum amount a compressor is allowed to start)".

 At the bottom right, there are buttons for "Reset Ideal", "Run Prio", "OK", and "Cancel".

Figure 38: Compressor Controller Edit form

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### Compressor Prioritiser component

The Compressor Prioritiser component is used to prioritise compressor load according to a pressure offset. If the pressure offset is defined by the client, the *Manual set-point stagger control* checkbox should be selected. This will enable the controller to assign offset pressures to the different compressor as specified (in pascal). If one value is entered, this value would be added to the compressor set point as the priority of the compressor reduces. For example, if the set point is 500 kPa, and the pressure offset is 5 000, the priorities will be as follows:

- Priority 1: SP = 500 kPa,
- Priority 2: SP = 505 kPa,
- Priority 3: SP = 510 kPa,  
to
- Priority x: SP = 500 + [(x-1) × offset in kPa].

Offset pressures can also be specified in more detail, where the controller will assign the offsets according to the priority entered. The compressor with Priority 1 will get the first offset, Compressor 2 the second offset and so forth. The last specified offset will be repeated for the remainder of the compressors if left unspecified. The icon used for the Compressor Prioritiser is given in Figure 39.



Figure 39: Compressor Prioritiser icon

The *Description* field (as seen in Figure 40 in the Compressor Prioritiser Edit form) will give a summary of the compressor control set-up as specified under the Compressor Prioritiser.

The screenshot shows a software interface for editing compressor prioritiser settings. It features a 'Description' field at the top, followed by an 'Inputs' section. This section includes a checkbox for 'Manual set-point stagger control' and a table for 'Pressure Offset' with values 0 and 5. Navigation buttons (Add, Remove) and a 'Last write out' timestamp (2014/08/08) are also present. The form concludes with another 'Description' field and 'OK'/'Cancel' buttons.

Figure 40: Compressor Prioritiser Edit form

### 3.5 Summary

By addressing the need identified in Chapter 2, a system was developed. The mathematical model has been tested by the software developers as discussed in the literature study. Demand side initiatives have been implemented with DSM projects on most of the CANs on deep-level mines in South Africa. By implementing the comprehensive system as discussed in this chapter, energy savings may be achieved. Chapter 4 will evaluate the functionality described in Chapter 3 by implementing the DCS system on a gold and a platinum mine. The results will then be extrapolated to the precious metal mines in South Africa.

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## 4 Implementation of a dynamic control system

### 4.1 Introduction

The system developed in the previous chapter will now be tested in a practical environment. This will be done by:

- physical installation and evaluation (Section 4.3.1), and
- simulation and manual implementation of the control philosophy (Section 4.3.2).

Gold and platinum mines make up the majority of sites where compressed air is used at this magnitude (above 10 MW installed capacity). The results of this thesis will, therefore, consist of a study on a gold mine and on a platinum mine.

Before this, we will first take a look at system set-up and integration methods for the different site requirements. Due to confidentiality agreements, mine names will be excluded from this study. The naming convention used only refers to Mine A and Mine B.

### 4.2 Control system set-up

#### 4.2.1 Integration of control into existing systems

##### *Mine A*

At Mine A, the compressors are located at two compressor houses situated roughly 2 km apart. The mine uses fibre communication between sites and Wonderware™ ArcestrA SCADA systems. The compressor data is located on one SCADA computer, the surface instrumentation on a second computer, and each shaft is fitted with its own SCADA system. All of the historical data from the PLCs is available from the different SQL servers. However, an OPC connection, the preferred method of communication, is not available to obtain data in real time from these SQL servers.

The multiple data sources at Mine A should be consolidated into one OPC data server to allow the integration of control parameters. To achieve this, it was decided by the client that the data should be collected from the PLCs directly. The mine uses the Allen-Bradley ControlLogix® series of PLCs. A software package was required which could interface with these PLCs directly over the existing network infrastructure. Software Toolbox™ TOP Server software package was installed which was capable of receiving data from a PLC using TCP/IP protocol.

This software package would act as a data server for the DCS system. Each PLC needed to be addressed individually, and an address had to be specified for feedback from each required

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sensor. The OPC server was installed on the server where the DCS system was located. This would minimise communication delays and ease the set-up of any additional information from instrumentation should it become available or be required.

The client also requested that the valve control be done on the local PLC. This would require the 24-hour PSP profile to be added to the PLC as well. Due to this feature not being available on the PLC as a standard option, the client developed a functional block which would enable profile scheduling. With the valve profile captured on the PLC and not on the DCS system, it had to be possible to retrieve the set points via the OPC. The problem with the OPC server is that it only relays real-time data from the PLC. Historical data was, therefore, not available.

Development was required again to enable the PSP profiles to be available from the OPC interface. The PSPs of the valves were used to calculate future flow requirements. The profile had to be available in real-time to enable the DCS system to adjust to a change in set points. Development time of the additional functionality negatively affected project implementation time and energy savings. It was, therefore, suggested that all valve control be incorporated in the DCS system.

#### *Mine B*

At Mine B, the client also used Wonderware™ ArchestrA SCADA systems. Mine B, however, did not allow the DCS system to connect to the PLCs directly due to network policies. Here, the OPC server had to obtain data from the SCADA system and relay it back to the DCS system. An OPC server was required that could interface with the Wonderware™ ArchestrA software package. Wonderware™ created FactorySuite Gateway for this purpose as OPC, which is an industry accepted standard.

Due to both software packages being created by the same company, compatibility eased the set-up. Tags were automatically created from the SCADA database for all instrument data required. Tags were, however, only available for real-time data, and profiles were not accessible over the OPC protocol used by the DCS system. All PSP control functionality had to, therefore, reside in the DCS system. If this was not permitted future network state calculations could not be done.

#### **4.2.2 DCS system control philosophy**

The compressor control philosophy followed by the DCS system varies between networks, as the control is network-specific. The basic operation of the system can, however, be summarised as follows:

- 
- superimpose system demand pressures to obtain minimum pressure requirements continuously,
  - characterise compressor actual delivery at range of system pressures, constantly updating with real-time data,
  - calculate present and future total flow requirement of the system,
  - calculate driving node of pressure requirement to determine lowest possible PSPs to meet actual demand,
  - adjust compressor set points according to system losses dynamically,
  - determine compressor supply allocation based on compressor characteristics, efficiency and location using mass balance calculations,
  - monitor actual system performance to compensate for deviations from calculation values, and
  - make adjustment as required to meet network demands.

The system will aim to meet the system flow and pressure demand by minimising the power required to supply the compressed air. Shaft air requirements will take precedence in the control, as energy savings do not outweigh production losses. The shafts should, therefore, be optimised to the absolute minimum lower compressed air set points. PSPs can be optimised over time and the DCS system will adjust the supply accordingly, thus increasing energy savings. It is crucial to the successful implementation of the DCS system that DSM capabilities be available in the network. DSM capabilities include, but are not limited to:

- pressure control valve to all points of delivery with realistic PSP profiles,
- leak detection and reporting structures,
- compressor automation and intelligent capacity controls, and
- adequate instrumentation at all delivery and demand points (such as pressure and flow).

The DCS system can be implemented without these DSM capabilities, but this will require high infrastructure cost and extended implementation periods. It is advised to do the implementation systematically and in the following order:

1. automate compressor and intelligent capacity control,
2. add pressure control valves on demand points, with leak repairs and other demand reduction initiatives, and
3. implement DCS system to dynamically match supply to demand.

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### 4.2.3 Operator training

To ensure that the DCS system is fully adopted by the client, the DCS system should be integrated into the daily operation of the CAN. This approach was formulated from experience gained from implementing over a 100 similar DSM projects. The relevant people responsible for the different aspects of the CAN are given adequate training on the corresponding functionality in the DCS system. This promotes the use of the system across the different responsibility levels.

Operator priorities are specified for each of the responsibility levels of the operators. Control room operators are given basic permissions such as changing point of delivery PSPs, opening and closing valves, selecting weekdays and stopping/starting compressors manually. Supervisors have permission to change compressor baseload configurations, add or remove tags in system set-up and reconfigure control philosophies.

Administrators and owners have permission to change network layout and configurations, as well as add and remove system components. Each operator level is given training on his/her responsibilities. User accounts are also set up for each operator level to ensure unauthorised changes are not permitted. Training certificates are issued to the operators upon completion of training. During the performance assessment period, further assistance is given to the operators to ensure proficiency in system operation.

### 4.2.4 Maintaining/expanding the system

By training the operators and ensuring proficiency in the system, proper system operation is ensured. Small changes and additions can be made at the different levels of responsibility by appropriate operators. This will be sufficient for the average operational performance of the system. But, even with all of the precautions to ensure performance sustainability, projects' savings may deteriorate over time. To mitigate this problem, maintenance contracting is proposed to clients.

For a monthly subscription, prompt response is given in the event of missed savings opportunities. Daily performance tracking is done and reports issued to the relevant personnel. Weekly or monthly reports are also distributed to senior management giving a summary of the reporting period performance. By continuously monitoring the performance, missed opportunities are quickly identified and addressed.

Support such as expanding of the system, adding or moving compressors/valves and changing of control philosophies are all included in the maintenance fee. By having this additional

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support, energy savings strategies can be continuously improved to ensure optimal savings. Project engineers are assigned to projects with maintenance agreements to ensure short response times in the event that troubleshooting is required.

Maintenance has proved to be financially viable when considering the effect of minimising missed savings opportunities. The cost analysis of the maintenance fee versus the missed savings opportunities is a separate study, and does not form part of this thesis.

## **4.3 Case studies**

### **4.3.1 Physical installation and evaluation**

For the physical installation and evaluation, a DSM project completed on a platinum mine (Mine A) will be used. This project entailed a 3.3 MW peak clip between 18:00 and 20:00 during weekdays. This project is the pilot study for the DCS system as discussed in this thesis.

Mine A comprises three compressed air rings. This study focuses on two of these rings. Adequate instrumentation was not installed on the third ring by the completion of this study and is, therefore, excluded. All of the compressors were fitted with automatic control capabilities and intelligent capacity controllers. There were no operators, and stop/start of compressors was done from a centralised point. An automatic controller was installed, using static inputs set up by the compressor instrumentation technicians. Static inputs resulted in inefficient combinations, as well as unnecessarily high PSPs at the compressors.

The user interface of the initial control system is given in Appendix A of this document. Small programming changes were required on the existing compressor control system to accommodate external inputs. The contractors responsible for the existing system were used to implement these changes.

Control valve stations were fitted to the columns that supplied compressed air at all of the shafts. These stations comprised a main line isolations valve and a bypass valve to control flow in low-demand periods. Pressure tests were performed at each shaft to determine the pressure profile requirements by lowering the pressure systematically until a process was affected by the reduced supply.

The pressure was then set at a safe threshold above the minimum requirement. This process was repeated for all of the different shift periods at the shafts, for example, drilling, blasting and cleaning. Each demand profile was then signed off by the relevant shaft engineer. When a

change in the production cycle was made at a shaft, the pressure profile was adjusted. If required, the test could be performed again to obtain a new profile.

Instrumentation required for the monitoring, characterisation and control of the compressed air demand and supply nodes were also fitted. These included instruments such as pressure transmitters, flow meters and temperature probes needed for the controller to function adequately. Power meters were installed on the mine but were installed on a separate network that could not be bridged due to IT policies. This prohibited the functionality of the efficiency index in the DCS system at the time of this study.

The compressed air ring being considered is referred to as a simple network. This is due to the set-up of the network. Shafts were situated relatively close to each other, typically less than 3 km apart. Small, medium and large compressors were available for scheduling thus enabling close demand- and supply-flow matching. No stop/start restrictions were specified by the client. Nine Demag centrifugal compressors were installed. The installed capacities of these compressors are summarised in Table 16.

Table 16: Mine A compressor location and capacities

Location	Compressor reference	Installed capacity (MW)	Delivery capacity (m <sup>3</sup> /hr)
Shaft 1-A	Compressor 1	4.8	40 000
Shaft 1-A	Compressor 2	5.1	50 000
Shaft 1-A	Compressor 3	5.1	50 000
Shaft 1-A	Compressor 4	5.1	50 000
Shaft 1-A	Compressor 5	1.0	10 000
Shaft 1-A	Compressor 6	1.0	10 000
Shaft 1-B	Compressor 7	4.8	40 000
Shaft 1-B	Compressor 8	4.8	40 000
Shaft 1-B	Compressor 9	5.1	50 000

The network consisted of five shafts connected to the CAN. Of these five shafts, only two shafts were high-flow consumers requiring in excess of 40 000 m<sup>3</sup>/hr compressed air during peak production periods. Shaft 1-A was the main consumer of compressed air, using more than 70% of the compressed air generated in the network. With Shaft 1-A being the highest flow

consumer, focus was shifted to this shaft for energy efficiency. Pressure control valves were also installed underground to enable an enhanced control philosophy.

Each level was given a 24-hour set point profile, enabling a higher level of control. As the initial cost of level control valves was high, only the main consumer shaft was retrofitted. Production losses could also be avoided with level control valves in the event of compressor trips or failure. All levels could be closed to enable ring pressure build-up, and opened level-by-level for main production levels. Some of the operations could then still continue on the main production levels. Figure 41 shows the underground layout of Shaft 1-A. A minimum pressure of 200 kPa always had to be available at the refuge bays as indicated in Figure 41.

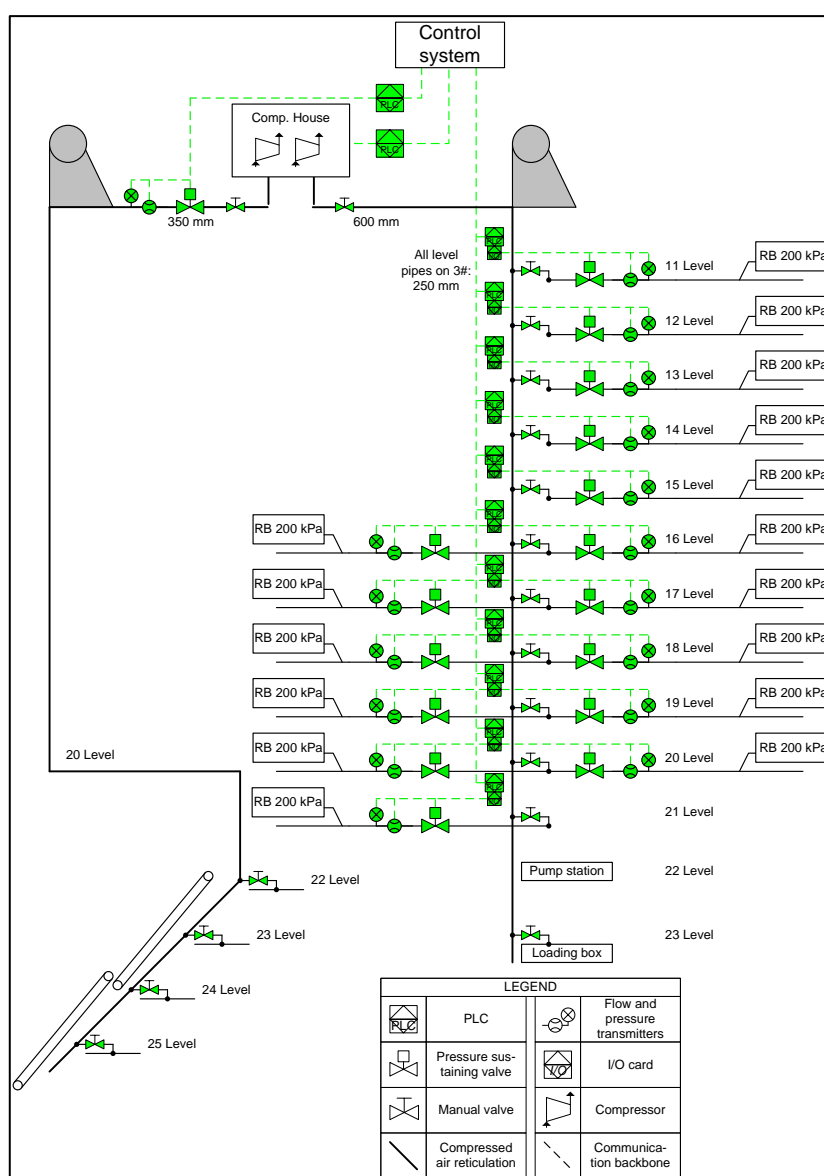


Figure 41: Shaft 1-A underground layout

Set-point profiles of the levels were superimposed on each other to determine the overall highest pressure requirement of the shaft. This would be used as the set-point profile of the shaft. At that time, it was not possible to update the shaft set points automatically with the underground control valve information. The client requested that valve set-point control be done locally using a PLC situated at the shaft. Further SCADA development was necessary to incorporate the underground valves with the shaft set-point profile. This functionality was available in the DCS system, but was not allowed by the client.

The network was characterised and compiled in the DCS system platform, as displayed in Figure 42. Orange blocks represent the shafts, green blocks the nodes and light-blue blocks the compressor houses. Pipe lengths were determined using the measuring functionality in Google Earth™. Pipe diameters were obtained from the compressor maintenance department at Mine A.

Graphic representation of key performance indicators has been added to the home page. Shaft pressures, shaft flow, as well as the demand versus supply flow are illustrated. This serves as a quick reference on key performance indicators of the system performance on both the supply and the demand side.

Figure 43 shows the set-up page for the compressors in the DCS system. Display functions were used for compressor power, guide vane angles, blow-off valve position, delivery flow and delivery pressure. These values were displayed in real time and were only used for illustrative purposes. Graphic illustrations were also used to display compressor running statuses, delivery flows, guide vane angles and blow-off operation. Each page is a custom view and was set up according to client requirements. Each individual component was set up; the configuration tables can be seen in Appendix B.

After all of the prerequisites have been installed at Mine A, the DCS system was implemented and commissioned. Due to the mine having automated control, resistance to change to the new system was encountered. A manual evaluation phase was proposed where after the results could be discussed. Upon successfully completing this testing phase, a decision would be made to adopt the control or not.

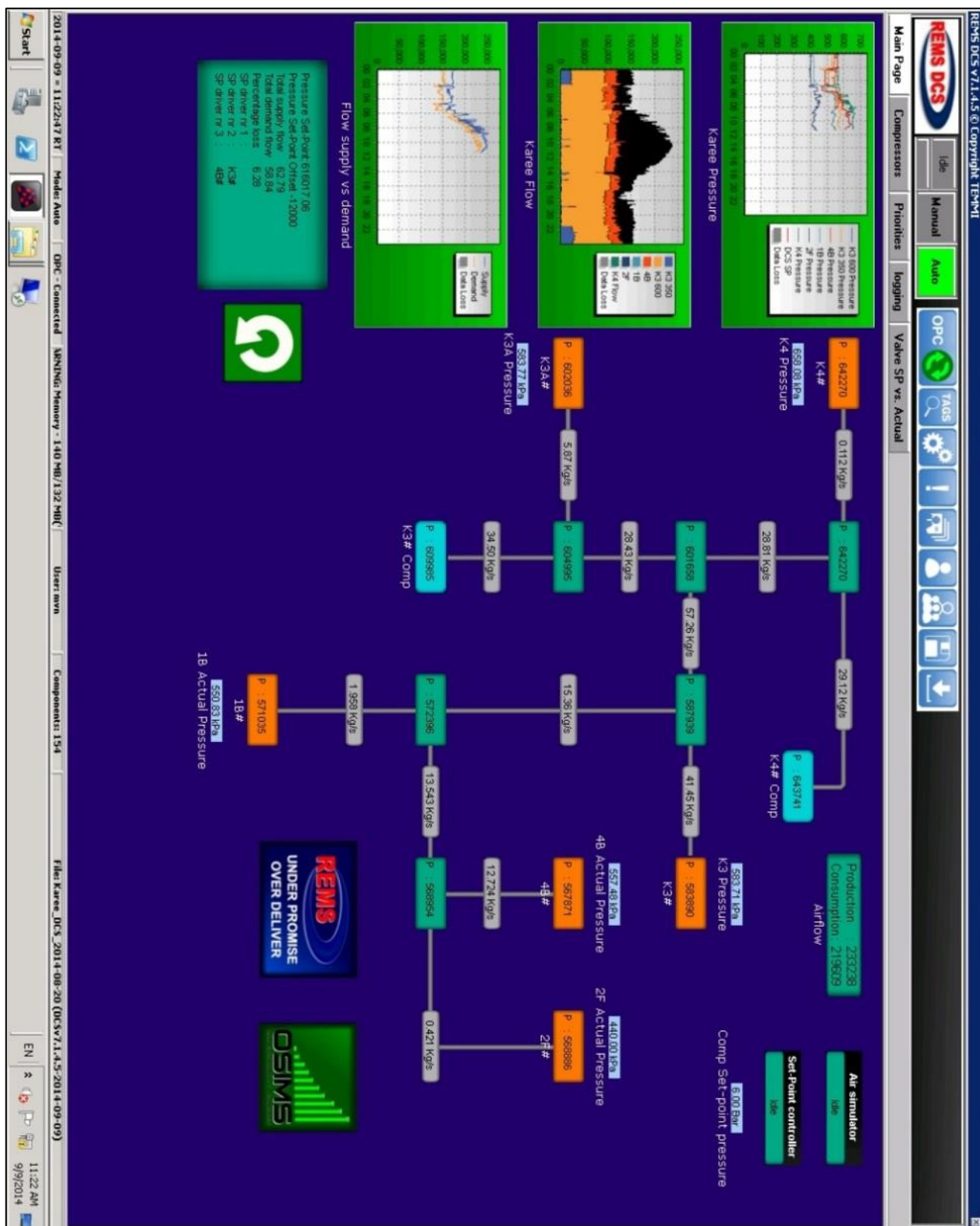


Figure 42: Mine A layout in DCS system

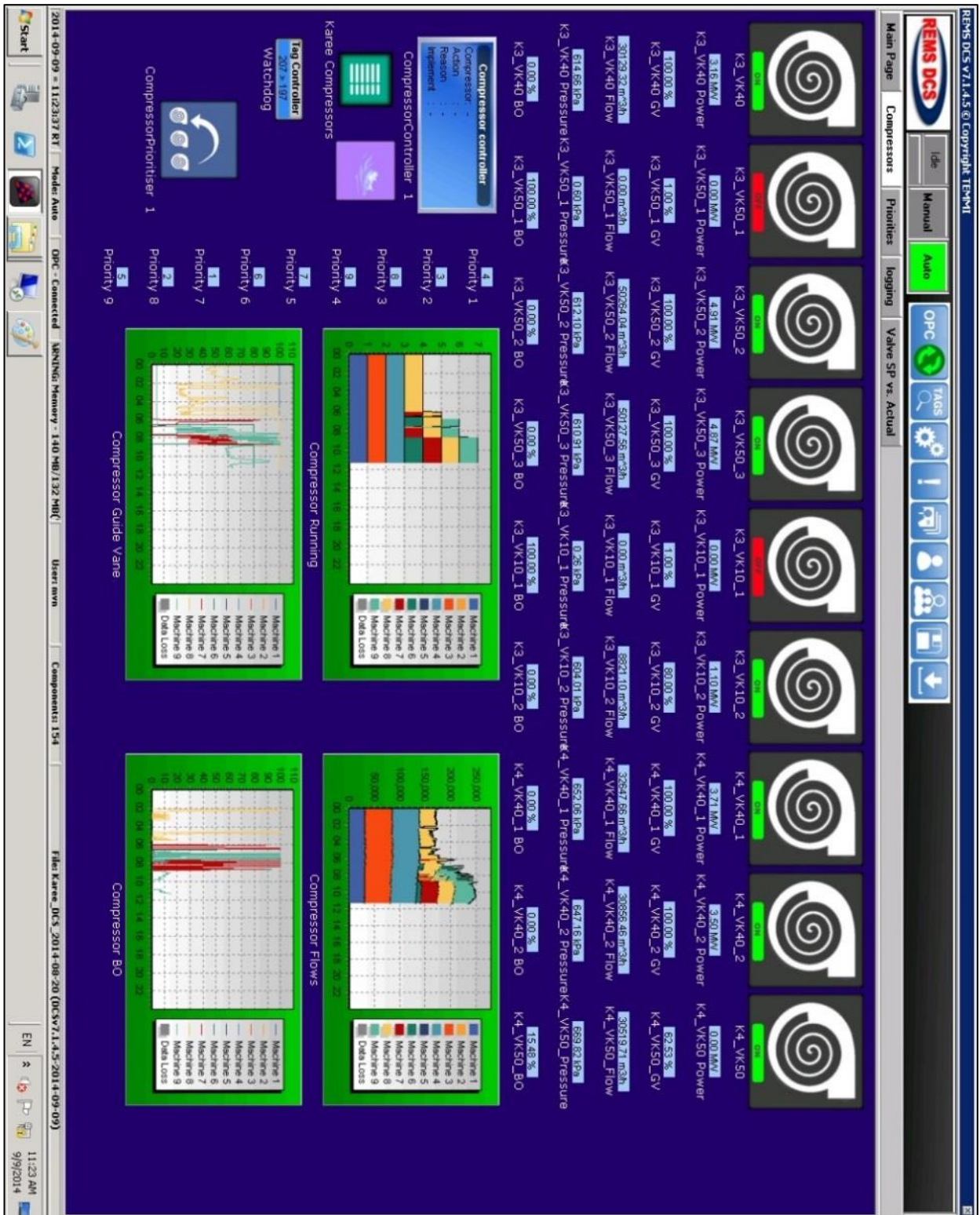


Figure 43: Compressor set-up page of Mine A

The first stage of the test entailed the testing of the master set point to the compressors. Results obtained from this test over a period of a week are given in Figure 44. The blue line gives the set point as calculated by the DCS system; the red line the set point of the existing compressor controller. Based on these results, permission was given to test the prioritising functionality of the DCS system.

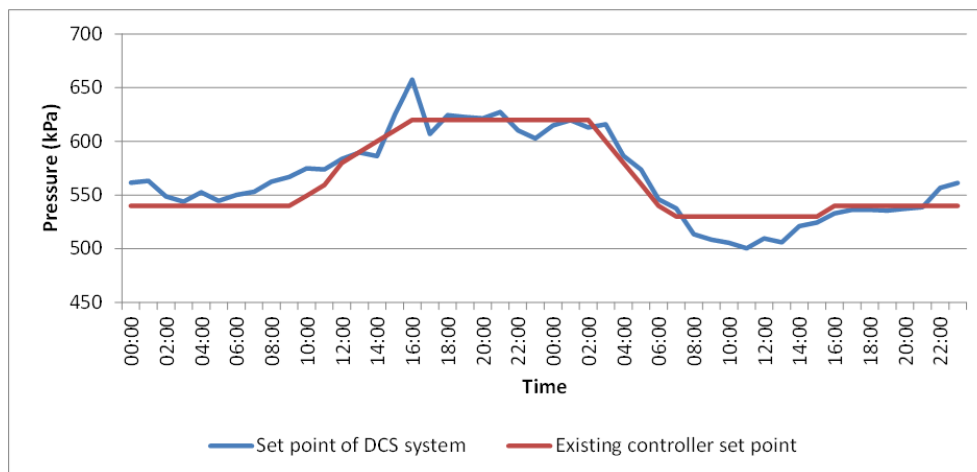


Figure 44: DCS set point versus existing controller set point

Outdated priorities in the system resulted in erratic capacity control of compressors. Compressor delivery flow is given in Figure 45 – from 01:30 to 05:30 erratic flow is present in the system. This was experienced again in the afternoon from 16:30 to 18:30. This coincided with the low-demand flow times at the consumers, when control valves reduced the PSPs to the shafts. When flow demand varies too much, guide vanes cannot reduce capacity in time, thus resulting in compressor trips.

This presented the ideal motivation for dynamic priorities as the flow variation was inconsistent. Priorities could vary from day-to-day and, therefore, had to be adjusted accordingly. Testing was again performed over the course of a week to obtain a good average. The tests were conducted when there were only eight compressors installed in the ring. The ninth compressor was added at a later stage in the project.

The test results were affected by the actual system response due to the dynamic nature of the controller. The actual flow in the system at a specific point in time, as well as the priorities of the compressors at that moment, determined the compressor priorities calculated by the system. If there was erratic flow, calculations would be affected. The system would also try to change priorities as little as possible to avoid compressor cycling.

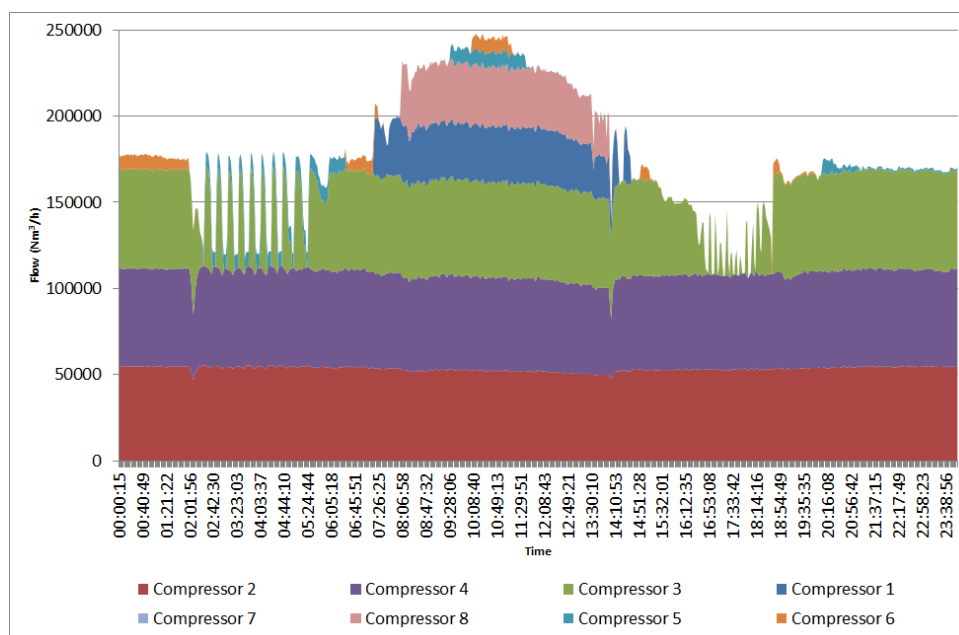


Figure 45: Compressor delivery flow before DCS intervention

To obtain the outputs of the system, internal functions were created to present the ideal situation where priorities were calculated by excluding system fluctuations. These values were then compared with the existing priorities, and the priorities calculated by the DCS system at that specific point in time. Figure 46 indicates the existing compressor controller priorities on a single day during the week the tests were conducted, as well as the system demand flow. Scaling factors were used to differentiate between compressor capacities based on compressor delivery capacity.

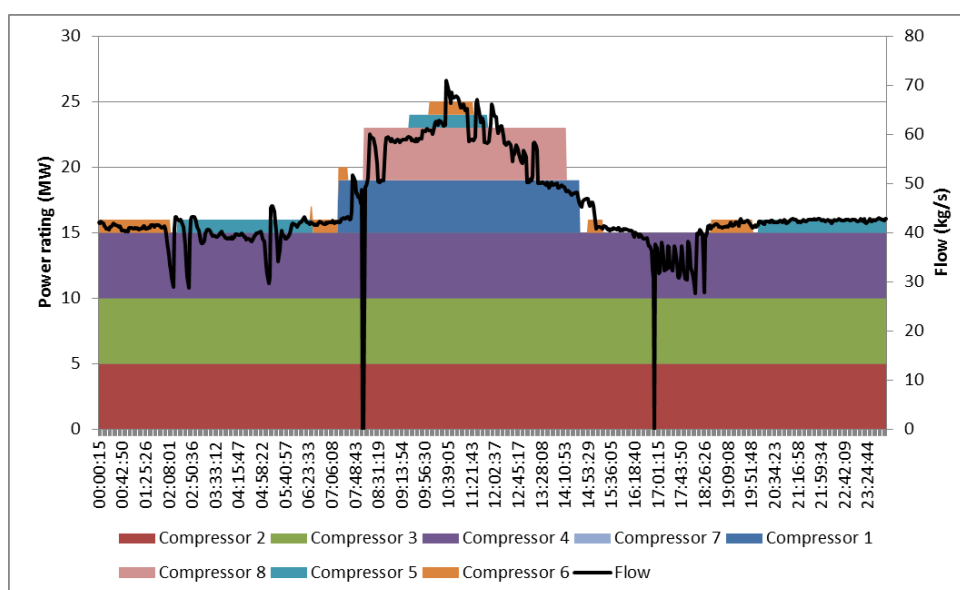


Figure 46: Existing compressor controller priorities

Figure 47 indicates the corresponding priorities of the network as calculated by the DCS system. These priorities were affected by real-time fluctuations and existing system operations. When demand flow was considered and smoothed using the techniques built into the DCS system, ideal priorities were calculated disregarding the existing mode of operation.

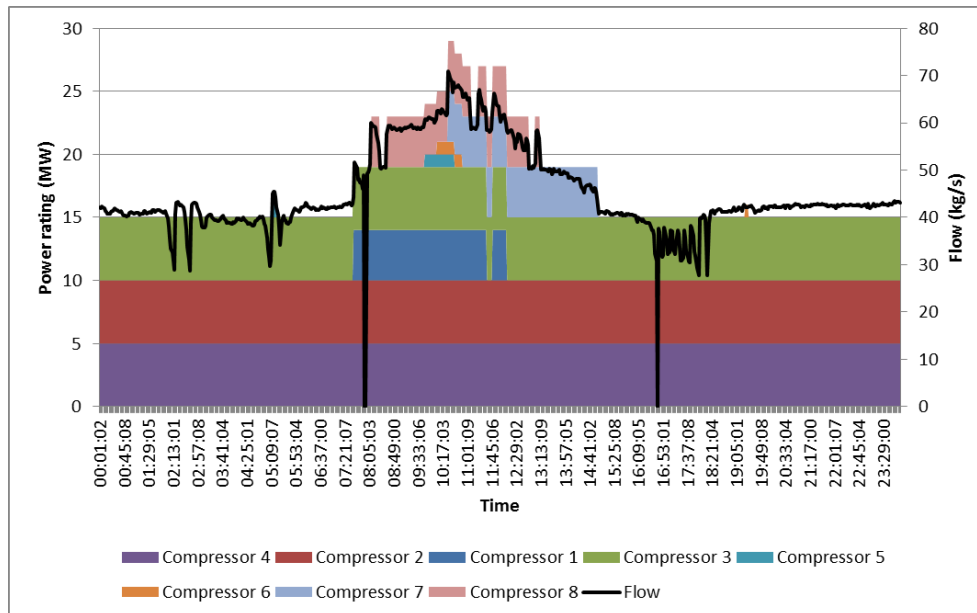


Figure 47: Priorities calculated by DCS system

Priorities calculated using this method depicted the ideal priorities of the DCS system. Reduced stops and starts were evident in the ideal priorities calculated (Figure 48). The results were presented to the client who approved automatic testing of the system. Testing was done over a three-month period. Results, expressed in energy savings achieved, were measured and verified by a third party as required by IDM programme specifications.

Final commissioning of the system resulted in an average evening peak period power reduction of 3.6 MW between 18:00 and 20:00. The project scope was to reduce the power usage only during this time. For testing purposes, DCS was only implemented on one of three rings at Mine A. The system was, however, optimised as a whole, which resulted in an energy efficiency component of 55.8 MWh per day.

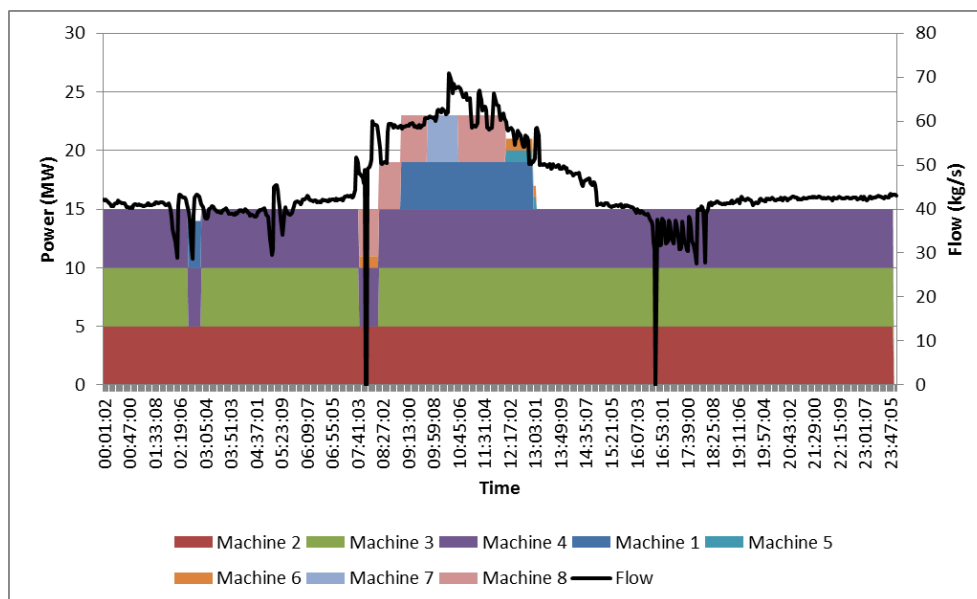


Figure 48: Ideal priorities calculated by the DCS system

A power profile of the performance assessment periods can be seen in Figure 49, measured against the verified baseline. Baseline energy consumption was 1 026 MWh, therefore, the total energy efficiency achieved was 5.4%. Total electricity cost saving of this project amounted to R11.8 million per annum. Savings achieved were obtained on the whole of Mine A comprising three compressed air rings.

Optimal results were achieved during the third month of the performance assessment phase. This was largely due to fine-tuning the control philosophies and ironing out small system issues that were encountered. Energy savings achieved could be attributed to optimal valve control set points, improved priorities and intelligent compressor capacity control all integrated in a comprehensive energy management solution.

Although the DCS system was only commissioned on one ring at Mine A, other interventions were also installed on the other two rings. Compressor priorities on the other two rings were adjusted manually to match demand and supply as best possible using DCS methodology.

Control valves with PSP control and compressor automations upgrades formed part of the project scope. PSPs were defined for all end users, limiting wastages during non-production periods. Lower flow demand by end users during these periods resulted in pressure build-up in the network. This pressure build-up led to capacity control being done on the compressors, ultimately limiting the delivery flow into the system. Once capacity was reduced enough, unnecessary compressors were switched off, resulting in energy efficiency in the network.

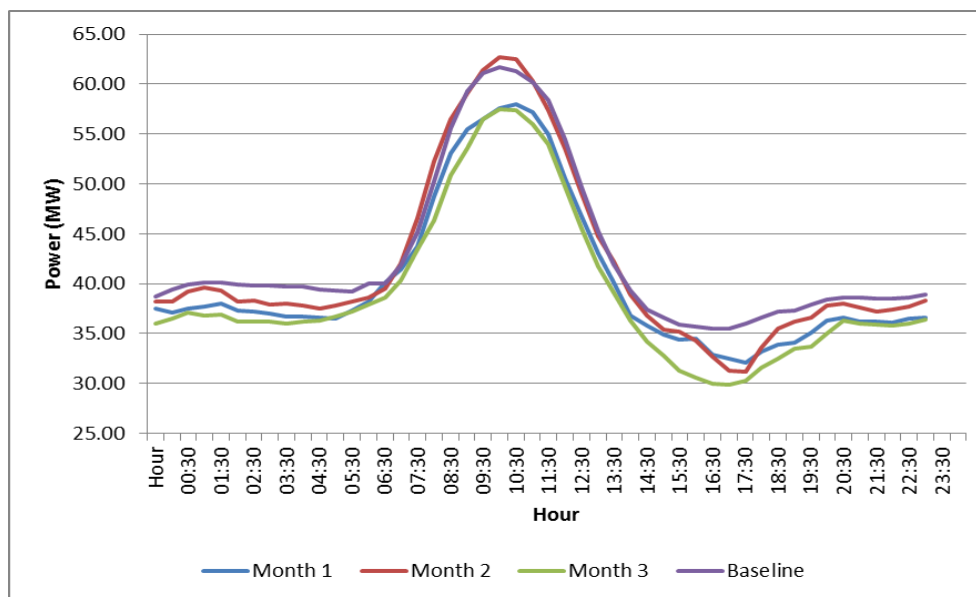


Figure 49: Performance assessment savings at Mine A

Because of the complex integration between the various components, it was difficult to assign energy efficiency contributions to a specific intervention. To obtain a better feel for the savings achievable in a system subjected to DCS control, results achieved during tests were evaluated. Each day of the test was measured against the preceding corresponding day, for example, a Monday in one week was compared with the Monday during the previous week. Although this did not give an exact reflection of the savings achieved due to varying demand, it was adequate for the purpose of this study.

To negate the effect weekends might have had on the production intensity, a Wednesday was used to illustrate the impact of the DCS system at the network where DCS was implemented. Figure 50 displays the network power profiles of the corresponding test days compiled from data logged before and during the test. Blue indicates the Wednesday without DCS implemented; red the Wednesday used for testing purposes. The energy efficiency obtained between the two modes of operation was 1.8 MW, or 5.1%.

In Figure 50, the red line spikes at 02:30 and again at 06:30. When priorities of compressors change drastically, the existing controller does not allow the DCS system to shut a compressor down. Compressors should be allowed to run completely for ten minutes while cutting back the guide vanes with blow-off valve open, before they can be shut down (idling). The DCS system was customised to start an additional compressor to force the unnecessary compressor to be switched off. Compressor characterisation and flow prediction capability embedded in the controller allowed the correct compressors to be added to prevent compressor cycling.

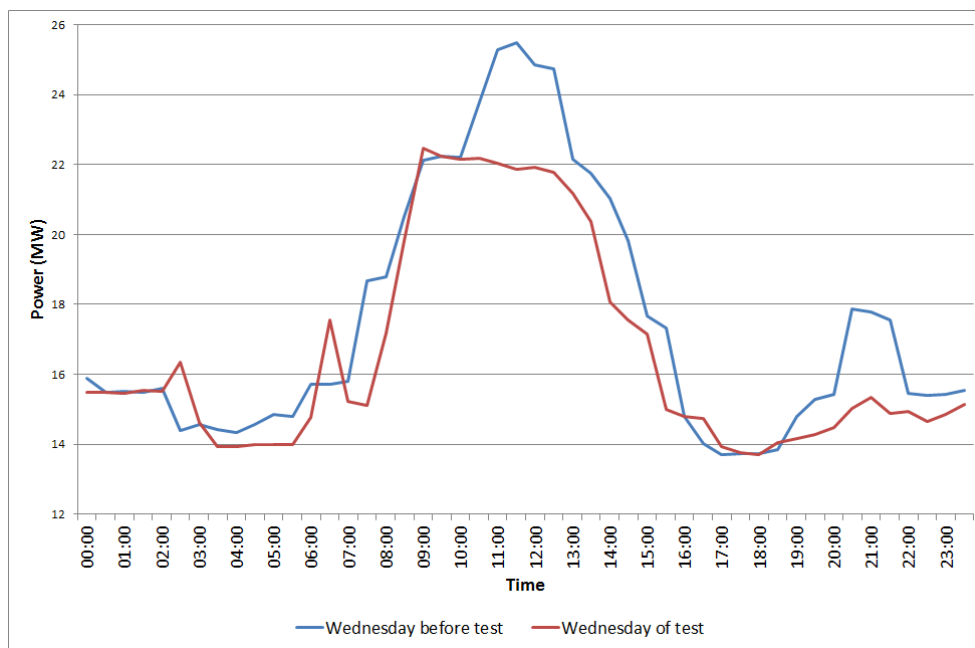


Figure 50: Power profile before and after test

#### 4.3.2 Simulation and manual implementation of the control philosophy

Mine B is a gold mine situated in the North West Province. Compressed air is supplied by various compressors into a common compressed air ring. All of the end users are supplied from the compressed air ring. A total of three shafts and four processing plants are connected to the CAN. Seven compressors with installed capacities of 4.8 MW to 15 MW supply the network with compressed air. The different compressor capacities are given in Table 17.

Table 17: Compressor capacities at Mine B

Location of compressor	Electrical installed capacity (MW)	Delivery capacity (m <sup>3</sup> /h)
Shaft A	5.9	68 000
	5.9	68 000
	5.9	68 000
Shaft B	8.6	100 000
	4.8	50 000
Shaft C	15	170 000
	15	170 000

One compressor at Shaft C was continuously operated as a baseload compressor, and the 8.6 MW compressor at Shaft B was operated as a baseload compressor only during high demand-demand periods. The other compressors were used to supplement the compressed air

supply as the demand varied. With the smallest compressor being 4.8 MW and 50 000 m<sup>3</sup>/h, the steps between compressors were relatively big. The average compressors used between January and February 2014 is given in Figure 51. This was before the investigation was conducted at Mine B.

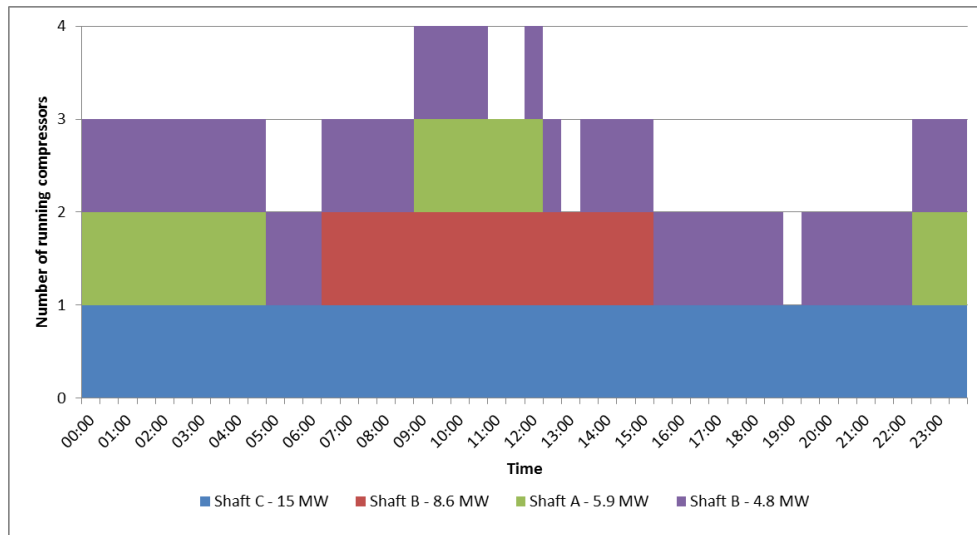


Figure 51: Average compressor usage at Mine B before investigation

During that time, the demand of the end users and the supply of the compressors were not adequately matched. Figure 52 indicates the difference between the demand and supply flow at Mine B. During some of these instances, the difference was 5 kg/s that could result in significant energy wastage. The big differences occurred during the low-demand periods when the shafts' consumption was reduced with pressure control valves.

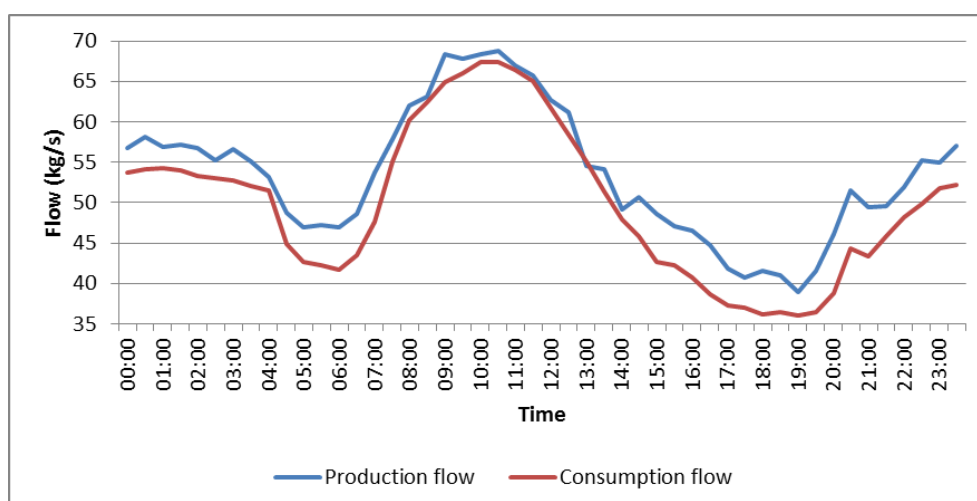


Figure 52: Mine B supply versus demand flow

The shafts were retrofitted with pressure control valves on the surface columns feeding the shafts. Each shaft had its own 24-hour pressure profile, programmed into the local PLC controller. The plants were also equipped with pressure control valves, but the pressure profiles were outdated and control was decommissioned. Due to the plants having low-flow requirements, these valves were not recommissioned as part of the initial feasibility study. The PSPs of the shafts are given in Figure 53 together with the average ring pressure.

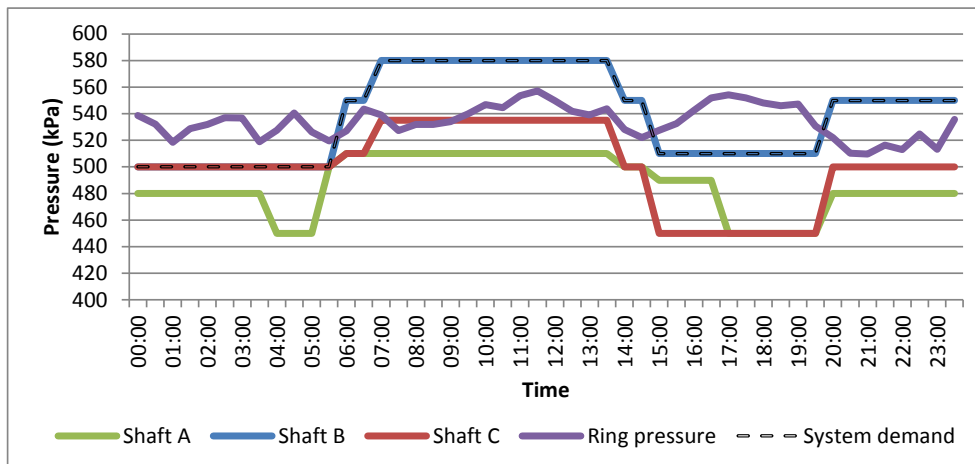


Figure 53: Mine B pressure requirements

When the demand set points of the three shafts are superimposed on each other, the system demand is obtained. Figure 53 shows the system demand (indicated by the dashed line), as well as the actual supplied ring pressure before any changes were made to the system (purple line). The plants had to be supplied with a minimum of 400 kPa. The system demand for this investigation would, therefore, always be higher than the plant requirement and the plant set points could thus be excluded.

During the low-demand periods, the system pressure was higher than the maximum pressure requirements of the end users. By improving the flow and pressure control on the system, additional savings could be realised. To achieve an improvement in the control, the system needed to be evaluated as a whole. Points of delivery and consumption needed to be defined in the system in order to ensure they would be accounted for in the system calculations.

The systematic approach as given in Section 3.2.3 was followed to evaluate available system data. Not all of the data was available for the investigation and some assumptions were made:

- Individual flow meters were not available for the compressors at Shaft A. Calculations were made to determine compressor delivery flow based on running statuses. These calculated capacities of the compressors would suffice for investigation purposes.

- 
- No power data was available for the 15 MW compressor at Shaft C. This prevented the kW/m<sup>3</sup> efficiency index to be used by the simulation. Compressors were selected only on best-fit demand and supply flow matching.

Apart from the lack of system data, some operational constraints were also defined as part of the control philosophy. Operational constraints were defined by the client and entailed compressor permissions that had to be adhered to when developing the control philosophy. Constraints for the system at Mine B were the following:

- The 15 MW compressor at Shaft C was a baseload compressor and could not be switched off. This compressor was not retrofitted with energy efficient capacity control, and, therefore, could not reduce its energy consumption during low-demand periods.
- The 8.6 MW compressor at Shaft B failed during normal operation and was not available during the test period.
- The 4.8 MW compressor at Shaft B had to be operated as a baseload compressor as well. This compressor was used by the change houses to generate hot water as part of a heat-exchange system. The compressor could be offloaded, but not stopped. When offloaded, the compressor still operated at a 1 MW load.
- The compressors at Shaft A were not allowed to be stopped between 13:00 and 18:00. These compressors were required to ensure capacity was available should an increase in demand be encountered.

A simulation was done using the DCS system to obtain both the supply flow and PSPs required to sustain the network demand. The values obtained were based on a theoretical approach using historical system data. The assumptions, as described above, were made in order to have adequate data available for the simulations. The PSP calculated by the DCS system is given in Figure 54.

The values were calculated using actual system pressure data compared to the required set points over an extensive period of time (two months). Where lower than required pressure was received by the end user, the lower value was used as the set-point requirement. This was done to maximise energy savings while still meeting operational requirements. The set point was at times higher than the system demand. Pressure drops were encountered in the CAN when the demand was further away from the point of supply, and had to be compensated for.

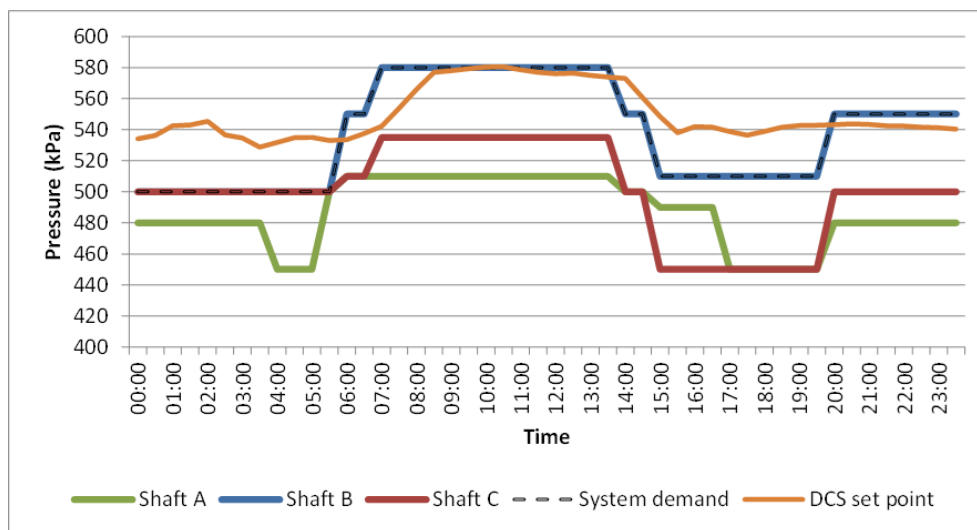


Figure 54: Simulation set-point calculation

Together with the pressure requirements of the shafts, the flow requirements also had to be accounted for. All of the compressors were characterised as described in Section 3.2.4, and the minimum and maximum flow ranges of the compressors were matched with the flow requirements. Figure 55 indicates the recommended flow ranges of the system over a 24-hour cycle against the flow required at the point of supply. Between 16:00 and 18:30, the minimum and maximum flow were the same due to the compressor at Shaft C not being capable of controlling its capacity. Although compressed air could be dumped to atmosphere, blow-off air was excluded during compressor characterisation.

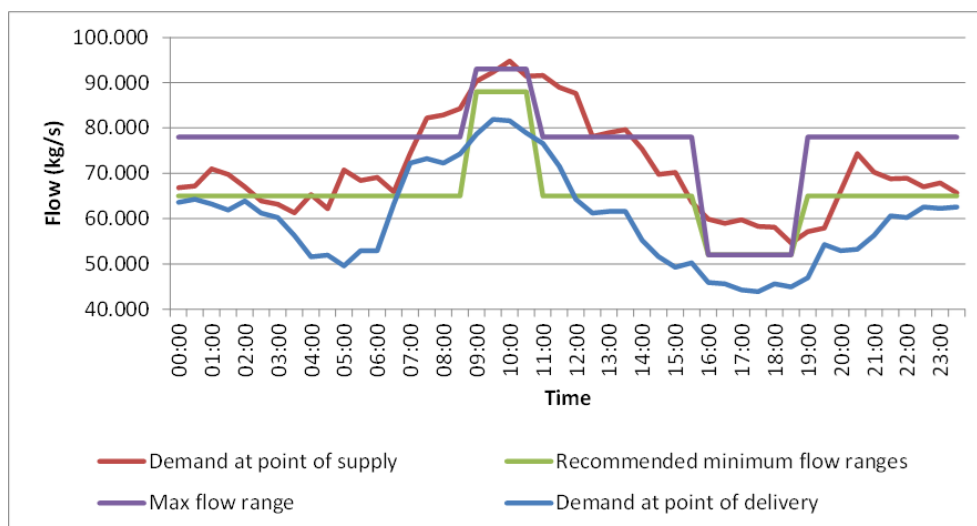


Figure 55: DCS calculated flow ranges from simulation

The simulation was done using historical data, where both the demand and supply flows were considered. Where the difference between demand and supply was high, it was typically due to

incorrect combinations of compressors being used. With the long list of operational constraints at Mine B, optimal energy efficient control could not be achieved. With the installed capacities of the compressors being so large, steps between adding and removing compressors were also big. This meant that energy was wasted to ensure production was not negatively impacted. From Figure 55 it can be seen that the flow requirements at the point of supply was sometimes far outside the ranges of the compressors. This could not be overcome with the compressors available at the mine and with the operational constraints that were specified.

The simulations were presented to the client and permission was obtained to do a manual test on the system. The test entailed manually executing the recommended control philosophy calculated by the DCS system. Calculations were based on real-time data, obtained by interfacing the DCS system with the client's SCADA system. This was achieved using an OPC interface as previously discussed. The test was done over the course of two days.

Given the constraints of the system, compressor priorities could not vary too much. The test was nevertheless conducted and the priorities of the two test days are given in Figure 56 and Figure 57, respectively. The system demand on these two days varied a bit, which resulted in two completely different sets of results. Although the opportunities were limited, energy savings were still realised.

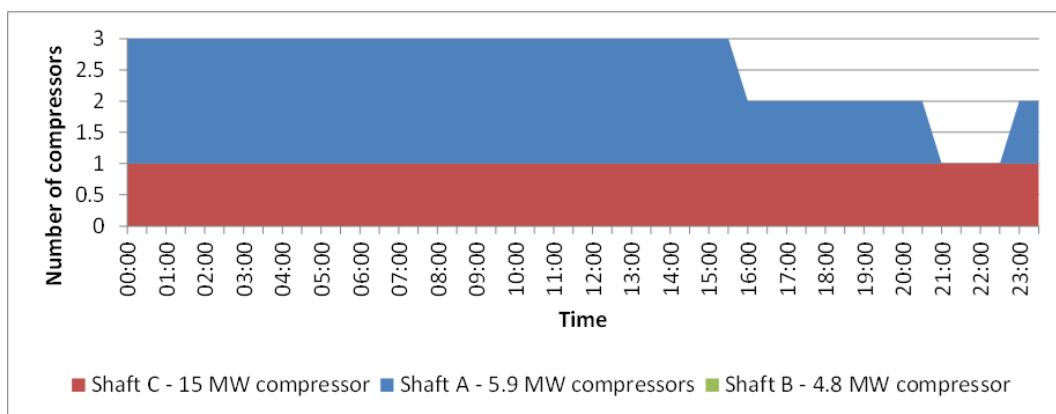


Figure 56: Compressor running status during day 1 of the test

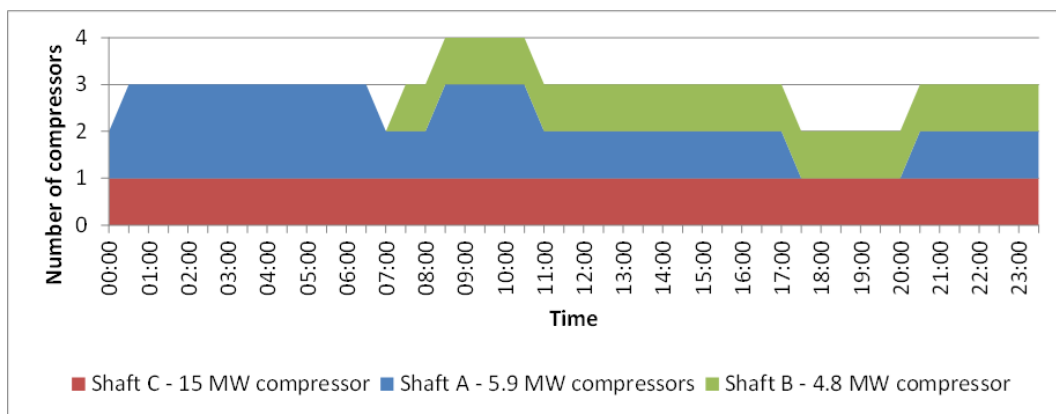


Figure 57: Compressor running status during day 2 of the test

Compared with the power consumption of the corresponding days a week prior to the tests, energy efficiencies of 0.6 MW (2.5%) and 1.2 MW (5%) were achieved. These correlated closely with the savings achieved at Mine A. These savings were calculated using only the time periods during which the tests were conducted. Tests done on day 1 were only done during the drilling shift, thus resulting in limited savings opportunities.

Tests were conducted from 08:00 to 13:00 on Day 1, and from 10:00 to 18:00 on day 2. The power profiles of the tests compared with the baseline are given in Figure 58 for day 1 and Figure 59 for day 2. The periods when the tests were conducted are highlighted in blue. If the 5% energy saving was extrapolated over a 24-hour period, electricity cost savings of R5.3 million could be realised per annum.

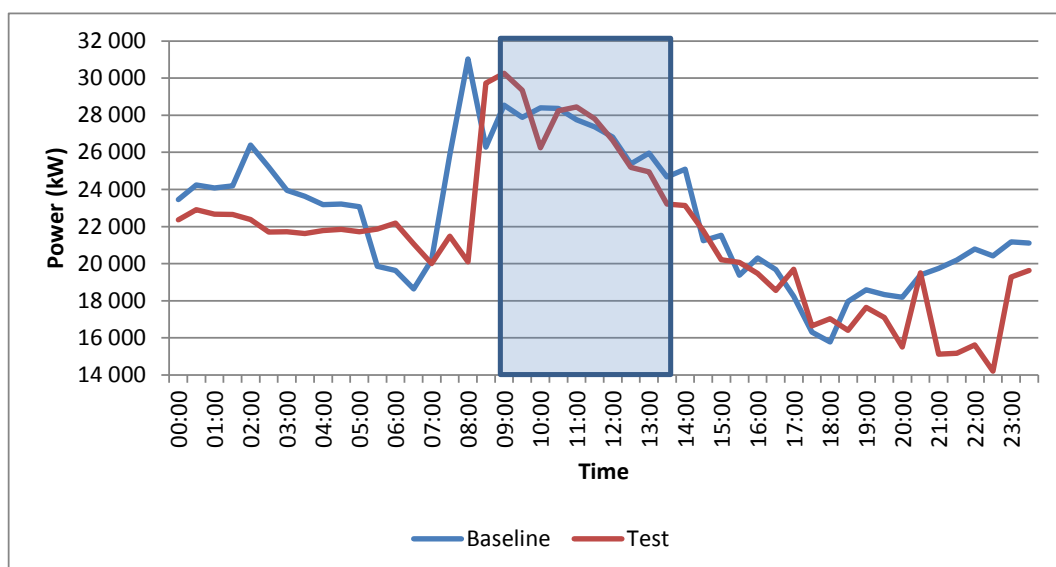


Figure 58: Power profile comparison for day 1 tests

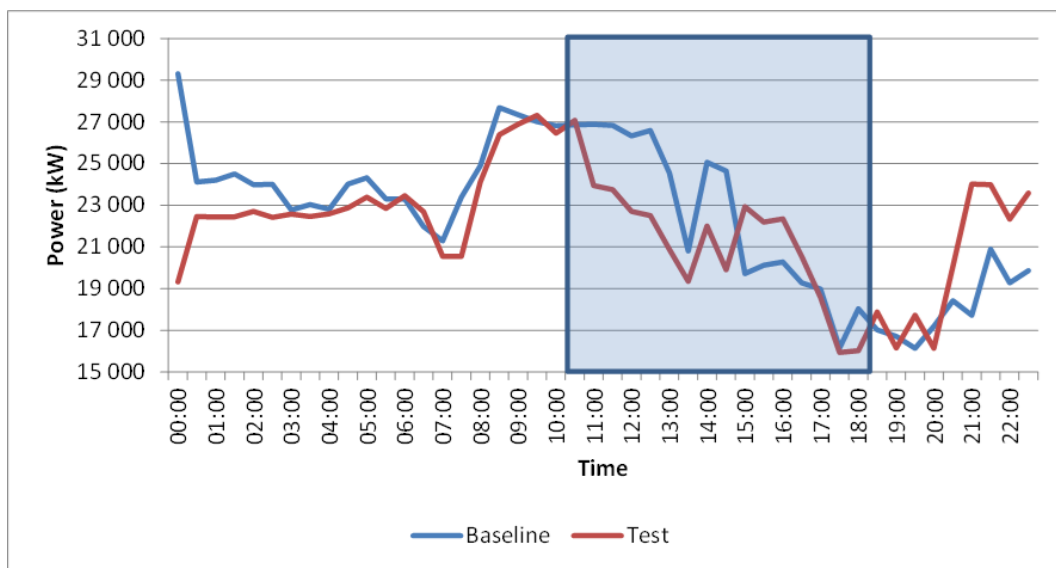


Figure 59: Power profile comparison for day 2 tests

To further enhance energy efficiency in the system, it was proposed that the mine installs two compressors with reduced delivery capacity. Compressors installed at Mine B were large, offering no intermediate sized compressors. Manual testing of DCS indicated that compressors with smaller installed capacities could result in significant energy efficiency improvement. With the damage incurred on the 8.6 MW compressor at Shaft B, it would have been the appropriate time to replace the damaged compressor with two smaller alternatives. These compressors would provide the intermediate steps that were not available at that time, and because they were centrifugal compressors they could be stopped and started on demand.

Various combinations of two smaller compressors were investigated using the DCS methodology and simulation capability to obtain the best fit for the compressed air requirements at Mine B. Historical data was used to determine the required demand. Theoretical power consumption was also compared with the existing system operation to determine added energy saving opportunities. The combinations investigated included:

- 2 × 1.5 MW compressors (3.3–4.8 kg/s at 500 kPa),
- 1 × 1.5 MW compressor (3.3–4.8 kg/s at 500 kPa) and 1 × 2.6 MW compressor (5–9 kg/s at 500 kPa), and
- 2 × 2.6 MW compressors (5–9 kg/s at 500 kPa).

Figure 60 compares the delivery flow capacities of the different combinations. The average flow requirements of the shafts at Mine B for January and February 2014 were used as the baseline requirement. When a 1.5 MW compressor and a 2.6 MW compressor were combined, the flow

profile could be closely matched. This would result in minimal energy wastage, as well as an increased capacity range for the system.

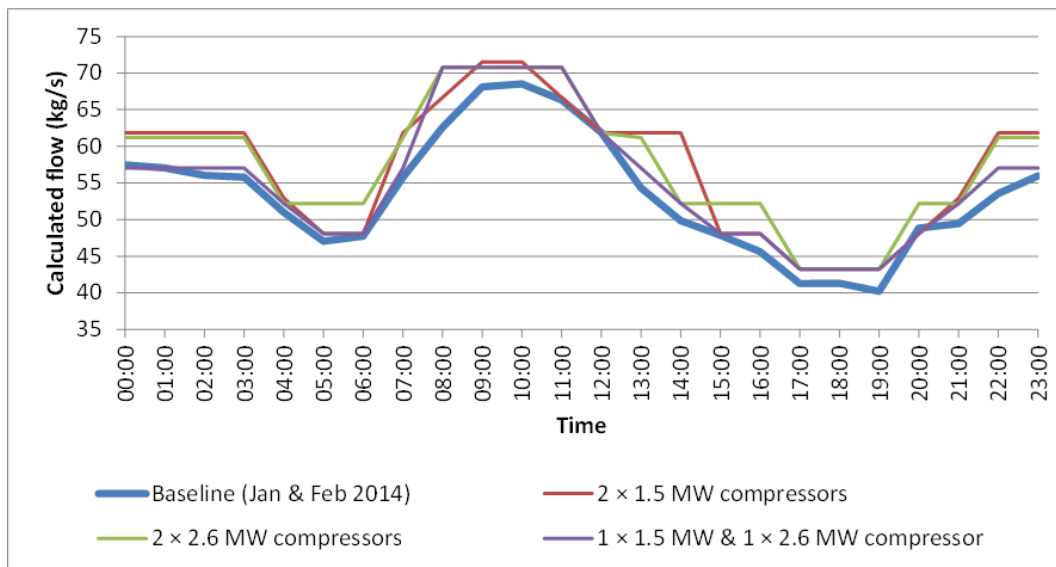


Figure 60: Calculated delivery flow using smaller compressors

By using the power consumption curves of the compressors, as supplied by the OEM in DCS, the theoretical power usage of the three combinations were evaluated. All three combinations resulted in decreased energy usage. The implementation of a 1.5 MW and a 2.6 MW compressor combination would result in an estimated 4.5 MW energy efficiency over a 24-hour period. Energy efficiency of the network could, therefore, be improved by as much as 20%. The theoretical power profiles of the combinations can be seen in Figure 61.

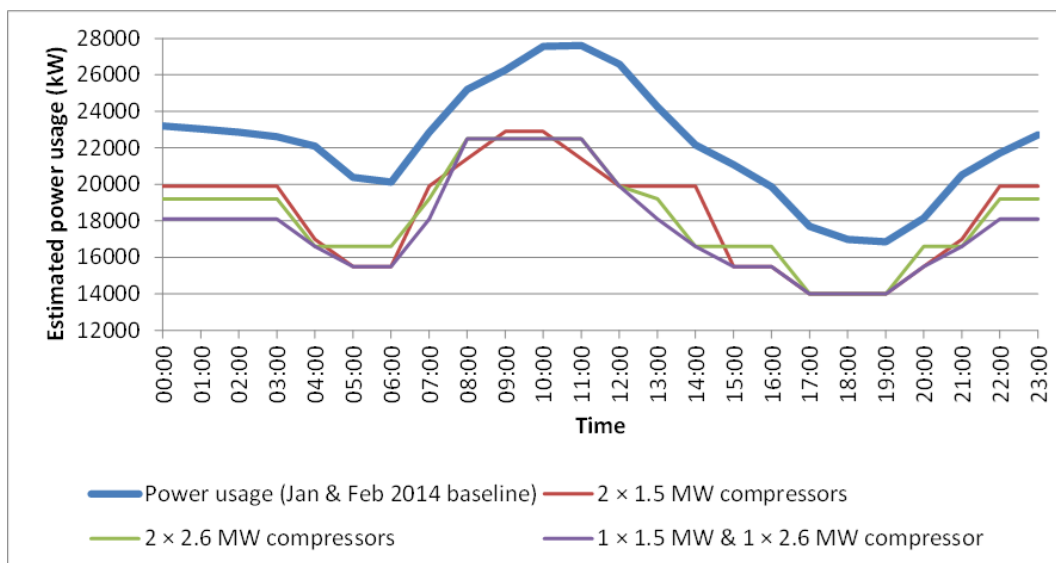


Figure 61: Estimated power usage of smaller compressor combinations

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After the investigation, the following compressors were suggested:

- a 1.5 MW compressor capable of delivering 3.3 to 4.8 kg/s at 500 kPa, and
- a 2.6 MW compressor capable of delivering 5 to 9 kg/s at 500 kPa.

A 4.5 MW energy efficiency would result in R21.6 million electricity cost reduction per annum. With the total installation cost of the proposed compressors estimated at R10 million each, the payback could be realised in less than a year. A report was compiled and delivered to the client. The client did not make a final decision during the course of this study, and actual implementation results could not be obtained.

Savings achievable were largely attributed to the inability of the larger compressors at Mine B to lower their capacity to the required level of the network demand. Compressor stop/start restrictions also impacted the energy usage of Mine B at that time. Compressor blow-off wastage and compressor inefficiencies were high at Mine B due to the incorrect sizing of compressors to the system demand. The compressors suggested were capable of efficient capacity control and would improve system controllability by improving demand and supply matching.

#### **4.4 Opportunities for the South African mining industry**

Two case studies were done on different mines to evaluate the impact the DCS system might have on a compressor network. From the results, average savings in the region of 5% could be realised. Due to the installed capacity of these compressors, a 5% reduction resulted in a significant cost savings component. This study builds on previous work done by Marais [14]. Marais reported on the savings achieved at 22 mines throughout South Africa where demand side initiatives had been implemented. DCS was the next step to be implemented on these sites, since the majority of the infrastructure had already been installed.

By realising a conservative 5% reduction in energy usage, an additional 12.67 MW load reduction, or 304.2 MWh of energy per day could be saved. Cost savings achievable from this incentive was R61 million per annum based on the 2014/2015 Eskom Megaflex tariff structure. Further improvements in CAN infrastructure, such as those implemented at Mine B, could see this figure rising to as much as 20%. Figure 62 indicates the original baseline before DSM interventions. The red line indicates the reduction in power usage achieved through previous DSM initiatives, the green line gives the projected power reduction should DCS be implemented on the 22 projects.

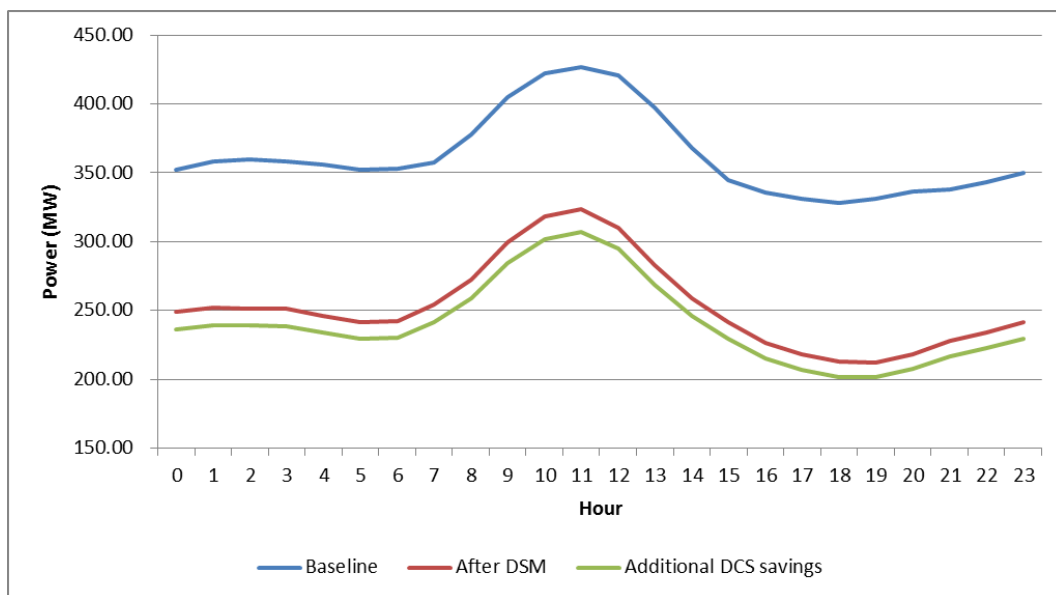


Figure 62: Reduction in power usage achievable on 22 projects

This saving may not seem that high, but it should be noted that the saving is only based on 22 projects done in the South African gold and platinum mining sector. At the conclusion of this study, investigations have already begun in other previously unexplored mining sectors. Investigations have also started in other industrial sectors such as the metal production sector and the cement industry. The controller is furthermore not limited to the mining sector specifically, or restricted to the South African industry.

When the 5% reduction in energy usage is applied to the global compressed air energy consumption, considerable savings can be achieved. Total compressed air electrical energy consumption is estimated at 4.2% of global electrical energy consumption [91]. This equates to 764 TWh of electricity consumed by compressors globally [91]. A 5% reduction in global consumption could realise a potential saving of 38.2 TWh – equating to 17% of the total energy produced by Eskom for use in South Africa in 2013 [92].

#### 4.5 Maintenance versus energy cost savings

To assess the impact of automated control on compressors, interviews were held with the compressor department managers at two platinum mines. These mines adopted automatic stop/starts on their compressors, based on static priorities and set points. Although the results were obtained from two different mine groups, the impact was found to be the same. Both mines changed from time-based service intervals to condition-monitoring based intervals. Compressors would, therefore, only be serviced or repaired if monitored values were outside predefined safe values.

At Mine C, the mechanical and electrical maintenance budget was 5% of their annual electricity cost for operating their compressors. With an annual electricity bill in the region of R500 million, the budgets for their 2013/2014 financial year were as indicated in Table 18.

Table 18: Maintenance cost of a mine subjected to automatic control

Maintenance type	Amount
Mechanical	R17 060 000
Electrical	R4 748 000
Instrumentation	R7 246 000

Mechanical maintenance included oil and aftercoolers, bearings, gears, chemicals for water treatment and network piping repairs. Electrical maintenance included motor repairs, brushes, cabling and other electrical faults. Instrumentation maintenance included, for example, the PLCs, guide vane and blow-off positioners and actuators, valves repairs and instrumentation cabling. The total maintenance budget of this particular mine amounted to R29 054 000. An additional working cost of R40 000 for electrical maintenance and R60 000 for mechanical maintenance were also available for day-to-day work done by mine personnel.

Motor repairs done at this particular mine usually cost between R400 000 and R500 000 per event. Included in the electrical maintenance budget were the brushes for the electric motor. According to the manager of the compressor department, maintenance on brushes did rise since the inception of the stopping and starting of compressors. The existing budget for the brushes was R281 212 per annum. Since the adoption of liquid-resistive starters, the mine noticed a decrease in motor failures. However, no data was available as to when the liquid starters were installed.

Of all the motors installed at his particular mine, the induction motors had the least failures. Synchronous motors tended to fail more regularly, and the mine was opting to replace the remaining motors with induction motors. The same problem had been encountered at the second mine where maintenance data had been received.

All of the synchronous motors at Mine A had already been replaced with induction motors at the time of the study. Motors at one of the compressor houses had been fitted with liquid-resistive starters, and at the other compressor house with resistive starters. A discussion regarding which technology is better falls outside the scope of this study. Compressor and motor failure

rate were analysed to assess the impact that stopping and starting compressors has on maintenance cost.

At Mine A, the running maintenance cost of the compressors compared well to Mine C. At Mine A the budget was approximately R92 000 a month, compared to R100 000 at Mine C. Full budget figures were not made available due to confidentiality requirements. Labour cost was given at roughly R700 000 a month, but this cost would apply even if the compressors were not automatically controlled. Maintenance occurrence data had been made available and is summarised in Table 19.

Table 19: Maintenance occurrences at a mine with automatic compressor control

Event	Occurrences
Motor failures	7
Compressor overhauls	4
Service of coolers	20
Inspections	9
Filters	7
Oil-related events	8
Gears	5
Other	7
<b>Total number of events</b>	<b>67</b>

Data is available from 2002 onwards, and over the course of 12 years, 67 maintenance occurrences had been recorded. In 2007, the mine started controlling their compressors automatically. Figure 63 shows the number of maintenance occurrences over time. The red line indicates the average of occurrences before and after automatic control was adopted. Since adopting automatic control, the average number of occurrences decreased. Full details on the occurrences can be found in Appendix C.

Both of the mines experienced increases in brush and contactor wear, but not to a level that they ceased automatic control. On Mine C, the budgeted 33 compressor motor brushes were only R281 212. With electricity cost of R500 million per annum, a 5% reduction could realise R25 million savings. This is equal to the existing budget for all compressor maintenance. An annual saving of R11.8 million was realised through implementation of DCS and its control methodology.

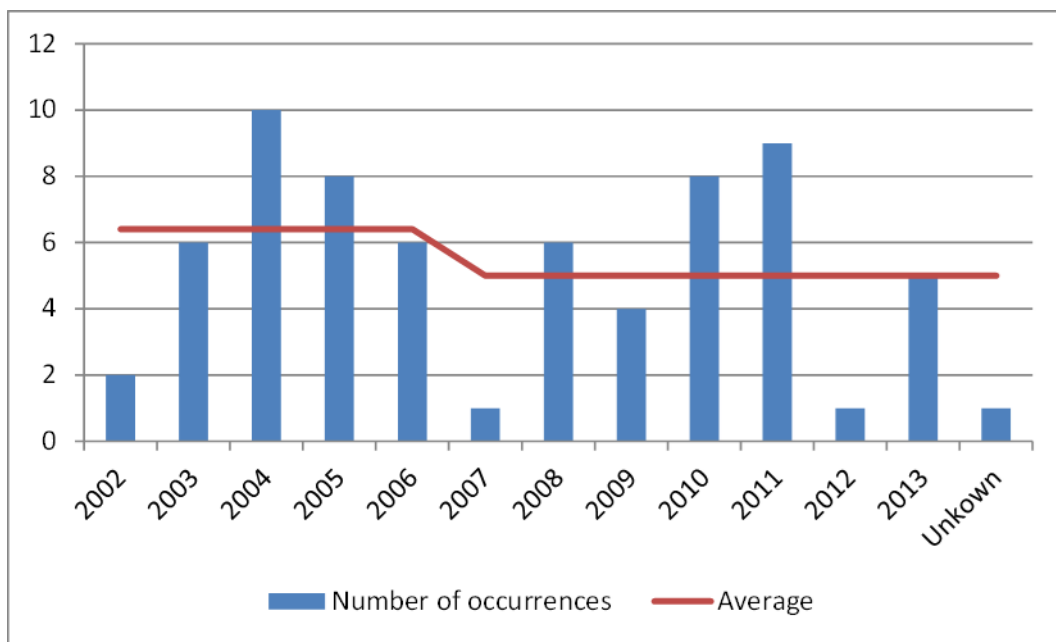


Figure 63: Number of maintenance occurrences

Therefore, the implementation of the DCS system could cover the existing maintenance cost of compressor networks subjected to automatic control. Some of these maintenance costs would, however, still be required without the automatic control. Implementation of the DCS system could cover all of the required maintenance of mine compressor departments on their compressor systems from the savings alone. Unless the existing maintenance cost would double due to the automatic control of compressors, the mine would still benefit from implementing the DCS system.

Regarding the stopping and starting of compressors, the following knowledge has been gained from this study:

- liquid-resistive starters tend to reduce motor maintenance,
- service intervals should be based on condition-monitoring intervals instead of time-based intervals to reduce maintenance cost,
- induction motors tend to reduce problems with stop/starts, and
- maintenance of brushes and contactors may increase.

## 4.6 Summary

The practical application of the DCS system realised a 5% on average reduction in compressed air power. By optimally and dynamically combining demand side initiatives with supply side control, additional savings could be realised. Savings of R11.3 million was achieved with the

successful implementation of the DCS system. A potential annual saving of R5.3 million was identified through manual testing of the DCS system on a gold mine. This could be increased to R21.6 million if DCS-proposed hardware changes were implemented. A total saving of 12.67 MW in energy efficiency has been identified in addition to savings achieved on 22 compressed air projects South African mining industry, with a cost saving potential of R61 million. Available electricity cost savings has the potential to compensate for a rise of up to 100% in yearly maintenance cost.

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## 5 Conclusion and recommendations

### 5.1 Conclusion

Due to the high electrical energy usage on mines, Eskom focused part of their DSM programme on gold and platinum mines. A particular rewarding area regarding energy savings is CANs. Numerous strategies have been implemented since the start of the DSM programme, focusing on both supply and demand side initiatives. The problem with previous DSM initiatives implemented was that although effective, the static nature of the technologies resulted in missed savings opportunities [12], [13], [14].

Compressor control is not a new phenomenon, and a vast number of control philosophies have been developed over the years. Capacity controllers focusing on the ability of a compressor to reduce its delivery flow, is one of the focus areas explored. System controllers have also been developed to stop/start compressors according to a fluctuating demand. Within the South African mining industry as well, ample evidence of these control strategies has been found.

Literature and experience gained from implementing compressed air optimisation projects proved the need for a dynamically adaptable compressor controller. Static control inputs into both manual and automatic compressor controllers resulted in missed saving opportunities. This is largely attributed to outdated control philosophies on these control systems, with control room operators not always equipped to make informed decisions. By dynamically incorporating all of the necessary system feedback, a fully comprehensive dynamic controller was developed.

The controller mathematical modelling was done by Venter in his preceding study [18] and software development was done by Van Heerden [22]. Theoretically, their controller delivered accurate results when compared with other simulation software. By combining the preceding work done on this controller with other compressed air best practice models developed over the duration of the DSM program, the DCS controller was commissioned in industry. A full evaluation of the system was done to determine if missed savings opportunities could be eliminated.

This study aimed to combine the various technologies by addressing the very static nature of the standard, outdated control philosophies. Focus was shifted to larger CANs with installed capacities in excess of 10 MW. Building on previous technologies developed by Venter [18] and Van Heerden [22], this study added the following to the DCS development:

- analyses of the financial benefit of automatically controlling compressor compressors,

- 
- combination of the best practice models developed throughout the DSM programme into a unique comprehensive solution,
  - developed a compressor efficiency selection criteria model to embed into a fully dynamic compressor controller,
  - implementation and testing of the dynamic CAN controller by evaluating energy efficiency, compressor priorities and characteristics of a CAN, and
  - tested the built-in simulation model using real-time system data. Proposed control philosophies were tested manually to evaluate the potential savings in a CAN.

The system was implemented on a gold and a platinum mine for evaluation. Gold and platinum mines are the sectors where large amounts of compressed air are consumed as an integral part of daily operations. Although the mines are very different in production methods, the results obtained were fairly similar. Both case studies resulted in an energy efficiency component of approximately 5% over a 24-hour period. Energy efficiency was realised without affecting production negatively.

The financial cost benefit of the DCS system was R5.3 million and R11.3 million annually on a typical gold and platinum mine, respectively. If these savings were extrapolated to the 22 mines already subjected to other DSM projects, a R61 million savings could be realised. Savings were achieved by dynamically matching varying flow demand with the corresponding supply. Real-time system data enabled control parameters to be updated continuously to ensure an up-to-date control philosophy at all times.

The impact automated compressor control has on maintenance is a reoccurring concern from clients where DSM projects are implemented. Upon investigation, data available showed a decline in compressor maintenance occurrences when automatic control had been implemented. According to interviews held with compressor departmental managers at platinum mines, no real increase in compressor maintenance was experienced.

The maintenance on electrical switching contactors and motors brushes did increase, but the numbers were negligent when compared to the energy savings achieved. With a compressor maintenance budget of 5% of the electricity bill, compressor maintenance should more than double before financial viability would be void. According to the mine personnel, this is very unlikely to happen.

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## 5.2 Recommendation for future work

Moving from a theoretical design to practical implementation of the DCS system proved challenging during the course of this study. Various additions to the software were required before the system was able to provide adequate results. With the addition of capability to the software and limited time, some of the features of the system were omitted from the results. This was due to insufficient hardware being available on the testing sites at the time of completion of this study.

One of the features that will require extensive testing is the efficiency selection of compressors based on power required per volume of compressed air generated. Although this study did focus on limiting wastages by selecting optimal compressors based on system demand, compressor location versus power versus flow was not evaluated. Adequate power meter readings were not available at the sites in real time for the controller used and historical data was used instead. Testing of this feature using real-time data is recommended for a follow-up to this study. Increased energy savings are expected.

The implementation of the DCS system was only completed on one of the three compressed air rings at Mine A. Although the methodology was manually expanded to the rest of the system, it is recommended that the system also be installed and commissioned at the remaining two shafts. At the time of completion of this study, hardware requirements on these two rings still prevented the automation of these two rings. Compressor upgrades is required on two compressors per network before flow, pressure and power requirements of DCS will be met. Financial constraints at the particular client resulted in these upgrades being postponed until further notice.

A report has been written to Mine B suggesting the installation of smaller compressors to allow closer supply-to-demand matching. The final decision is still to be made on the acquisition of the proposed infrastructure. Comparing the theoretical savings with actual savings achieved will be valuable in the development of the DCS controller. Implementation of DCS should also be evaluated over longer periods at this site in conjunction with a holistic optimisation project. Implementation should preferably be after the upgrade of compressor control on one of the large compressors.

Compressor capacity control done at Mine A is very efficient when compared with the control at some of the other mines. There is, however, still room for improvement on the technique used at Mine A due to compressors being idled for at least 10 minutes before being shut down. By allowing other compressors to simultaneously reduce their capacity to maintain the PSP, blow-

off can be eliminated. With the other compressors reducing their capacity efficiently, additional power savings can be realised. The problem, however, is the implementation on the PLC control level has not been explored and tested yet.

By combining DCS with the capacity controllers, compressor location, range, power consumption and efficiency can be used to determine which compressors should be capacity-controlled. As soon as the compressor with the lowest priority approaches blow-off, a signal can be sent to the DCS system. From there, DCS can propose which compressor (or compressors) should be capacity-controlled to prevent inefficient blow-off. With the capacity reduced below the point where a compressor can be switched off, a timer can be activated. Once the DCS system ensures the system pressure can be maintained without the lowest priority compressor, a shutdown command can be issued.

The solution proposed is still theoretical, based on experience obtained while conducting this study. Details of the control need to be discussed with a compressor automation specialist, to obtain the optimal solution. The problem with this approach is, however, that intellectual property is at risk when outside specialists are consulted. Instead, further research into compressor capacity control methodologies using PLCs should be done in order to compile a functional specification list. The functional specification list can then be given to a compressor automation contractor from where it can be implemented without intellectual property being compromised.

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## Appendix A Initial compressor controller

Figure 64 to Figure 69 give the initial compressor controller at Mine A, adapted to integrate with the DCS system. Figure 65 to Figure 67 give the compressor PSP and priorities for a weekday, Saturday and Sunday, respectively. Samples were given where the system inputs were not used for control parameters to indicate the optimisation opportunities.

Intelligent capacity control was done at Mine A. Control was done locally at each compressor, with the data relayed back to the mine's initial controller. Figure 68 and Figure 69 indicate the surge curves of the compressors, as well as the operating point at that given point in time.

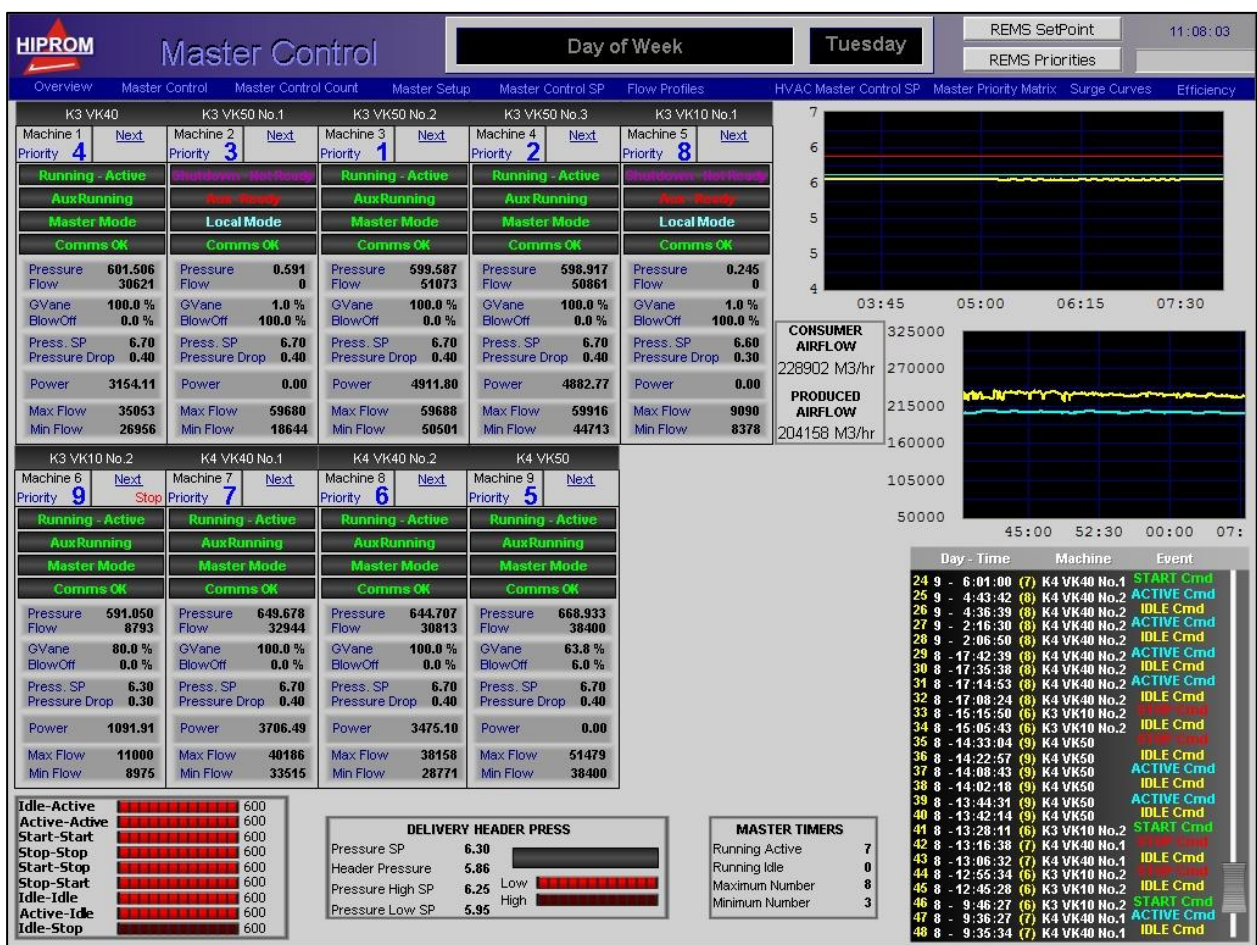


Figure 64: Initial compressor controller at Mine A

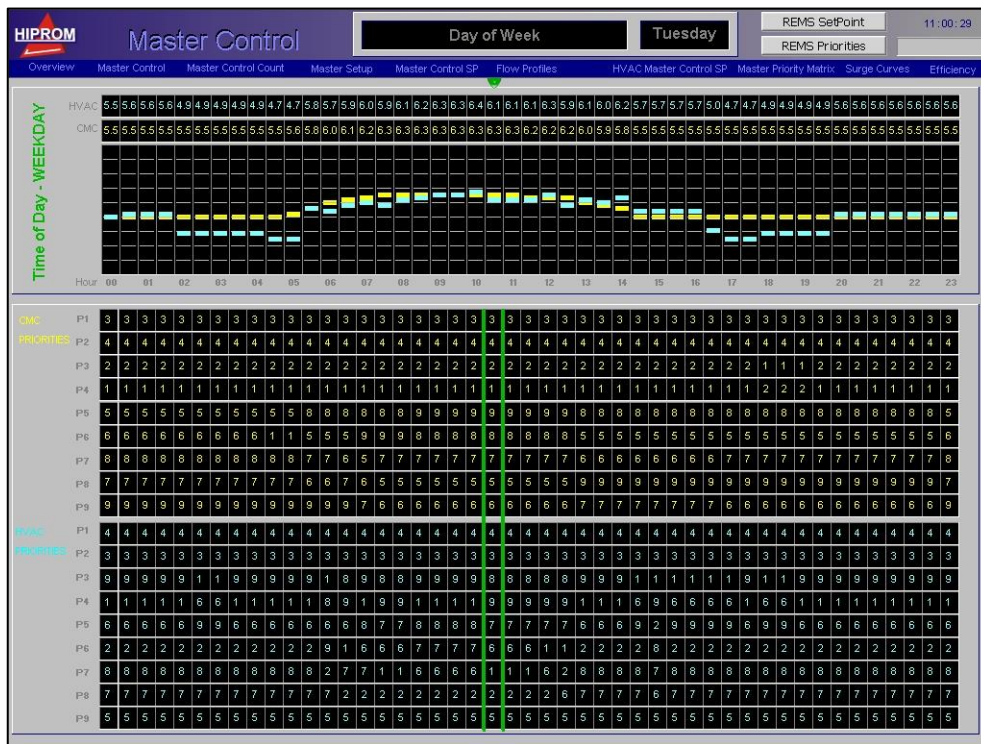


Figure 65: Mine compressor controller for Ring A-1 indicating weekday set points and priorities

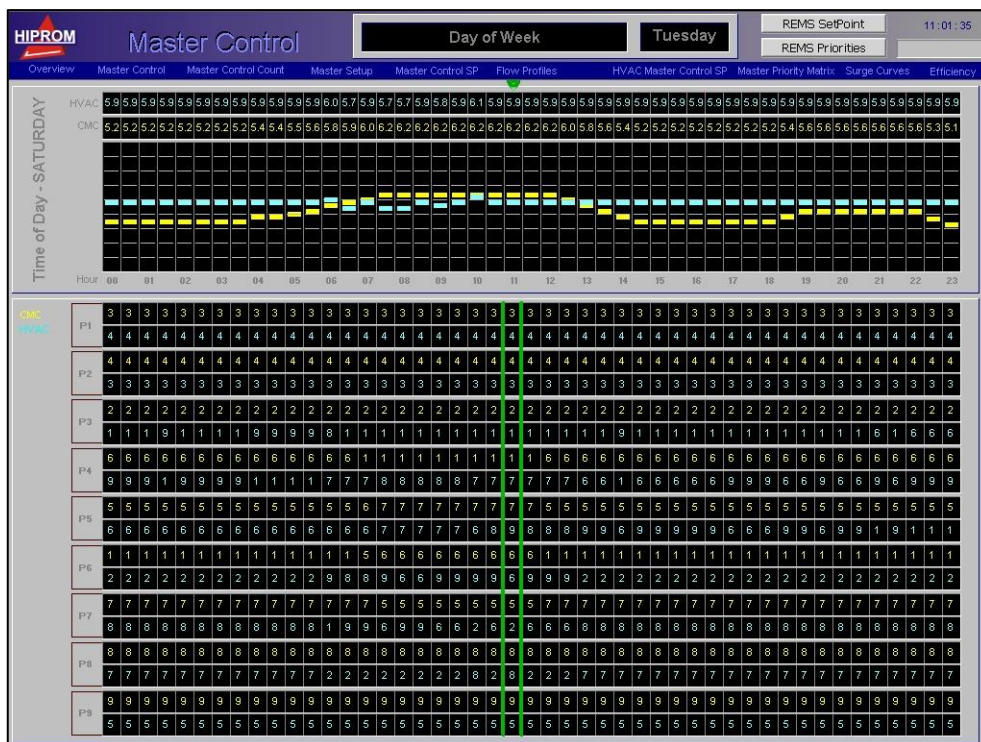


Figure 66: Mine compressor controller for Ring A-1 indicating Saturday set points and priorities



Figure 67: Mine compressor controller for Ring A-1 indicating Sunday set points and priorities

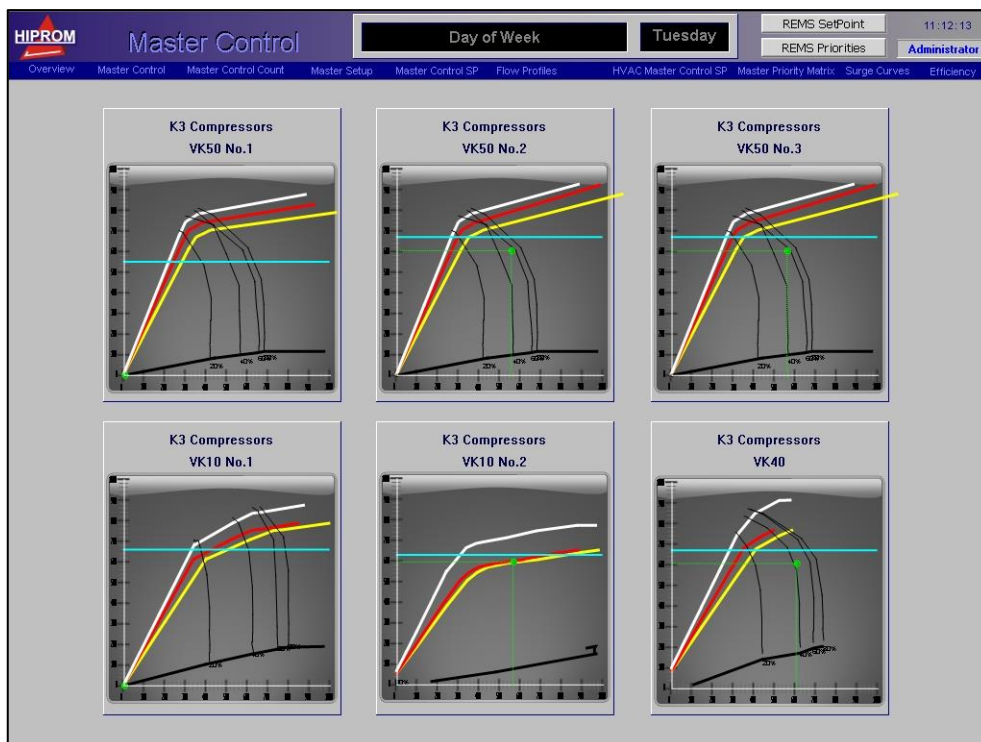


Figure 68: Compressor 1 to Compressor 6 surge curves and capacity control

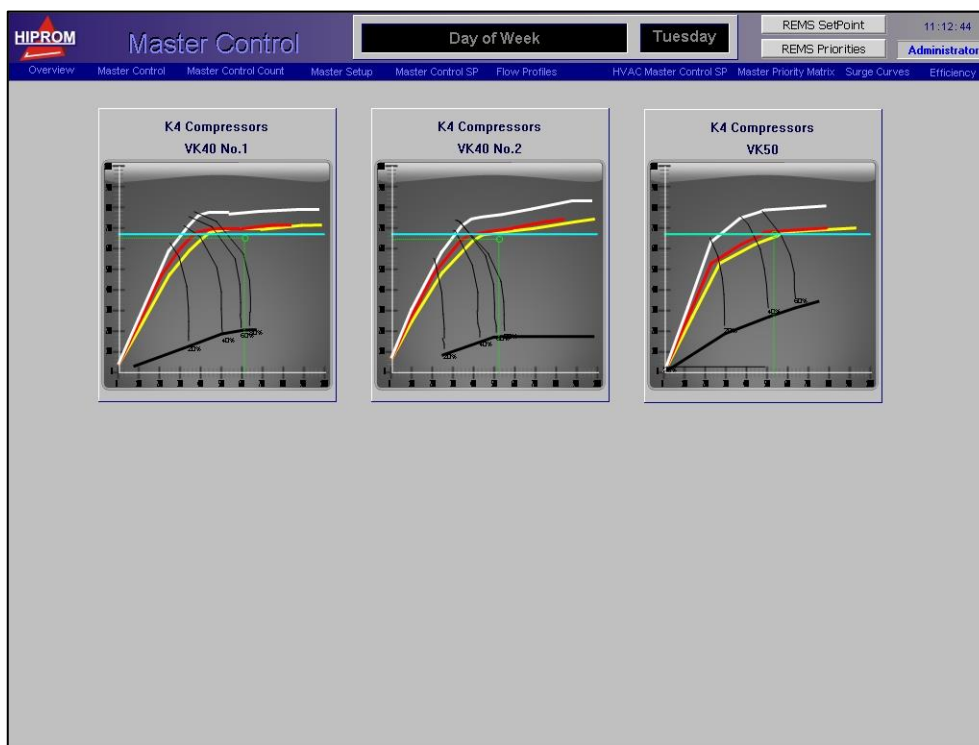


Figure 69: Compressor 7 to Compressor 9 surge curves and capacity control

## Appendix B Mine A compressed air ring set-up in software

Figure 70 to Figure 78 give the set-up tables of each compressor of Mine A as captured in the DCS system. Due to the power data not being consistent and accurate, these values were not used in the calculation of the priorities at Mine A, and can be ignored. Flow ranges at the various pressure ranges were used to match demand and supply flow in the network.

Compressor - [redacted]

Description : [redacted]

Control tags

Hold delay Start [redacted] High Active

Stop [redacted]

Load [redacted]

Unload [redacted]

Pressure set-point Master Controller [redacted] Machine HVAC 1 PressureSP

Priority InternalTag VK40 Priority

Weight InternalTag vk40 weight

Permission tags

Start [redacted] Def TUK

Stop [redacted] Def TUK

Load [redacted] Def TUK

Unload [redacted] Def TUK

Set-point control [redacted] Def TUK

Status tags

Running Master Controller Karee.KCMC.Machine HVAC 1 Running

Loaded [redacted]

Availability InternalTag M1 Availability

Priority InternalTag VK40 Priority

Measurement tags

Power usage Master Controller [redacted] Machine HVAC 1 Power

Delivery volume Master Controller [redacted] Machine HVAC 1 Current m<sup>3</sup>/h

Delivery pressure Master Controller [redacted] Machine HVAC 1 Current kPa

Guide vane position Master Controller [redacted] Machine HVAC 1 CurrentGV Invert

Running hours [redacted]

Efficiency [redacted]

BlowOff Position Master Controller [redacted] Machine HVAC 1 CurrentBO Invert

Efficiency out [redacted]

Flow ranges

Pressure (Pa)	Flow Range (kg/s)
680000	5.63-8.32
660000	5.63-8.01
640000	5.63-8.22
620000	5.63-8.03
600000	5.63-8.16
580000	5.63-8.28
560000	5.63-8.66
540000	5.63-8.68
520000	5.63-8.75
500000	5.63-8.86
480000	5.63-8.78
460000	5.63-8.54
440000	5.63-8.49
420000	5.63-8.38
400000	5.63-8.21
380000	5.63-8.05

Power efficiency

Flow (kg/s)	Power (kw)
0	0
1	0
2	0
3	0
4	0
5	0
6	INF
7	INF
8	2.5492
9	2.6024

Control Parameters

Auto update Flow  Auto update Efficiency

Enable table logging

Min Vain Position 40.00 %

Max Vain Position 100.00 %

Max BlowOff Pos 0 %

Power rating 15000.00 kW

Type -- Make

Baseload Compressor

Reserve Compressor

Max Stops per day 100

OK Cancel

Figure 70: Compressor 1 set-up table

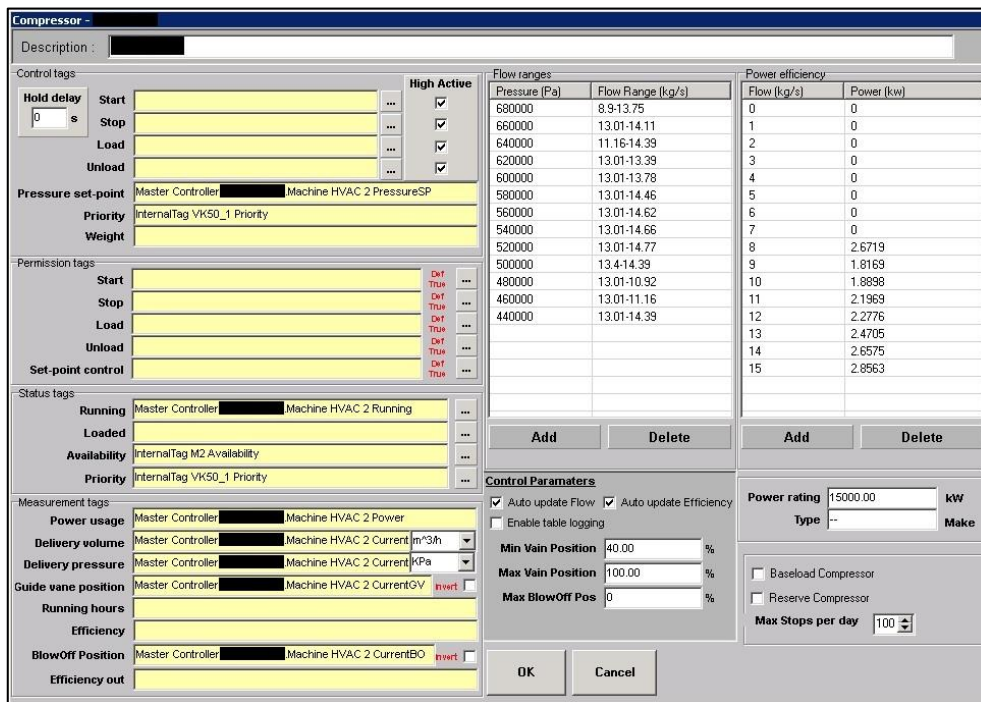


Figure 71: Compressor 2 set-up table

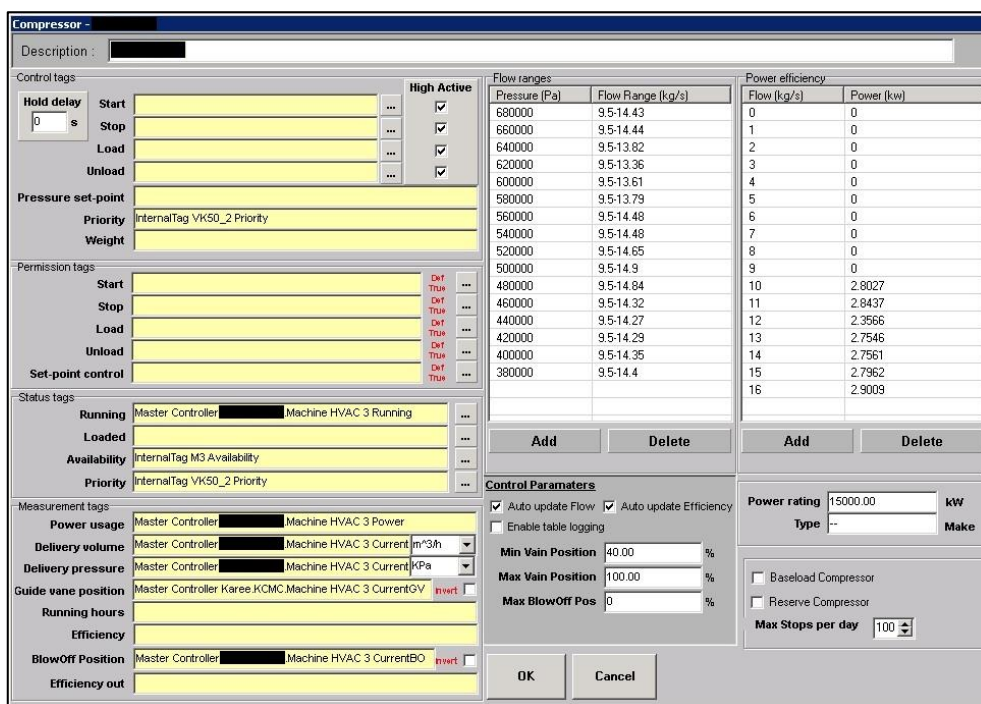


Figure 72: Compressor 3 set-up table

**Compressor -**

Description : [REDACTED]

Control tags: **High Active**

Hold delay: 0 s

Start: [REDACTED]

Stop: [REDACTED]

Load: [REDACTED]

Unload: [REDACTED]

Pressure set-point: Master Controller [REDACTED] Machine HVAC 4 PressureSP

Priority: InternalTag VK50\_3 Priority

Weight: [REDACTED]

Permission tags: Start [REDACTED] Dwt TLUK ...

Stop [REDACTED] Dwt TLUK ...

Load [REDACTED] Dwt TLUK ...

Unload [REDACTED] Dwt TLUK ...

Set-point control [REDACTED] Dwt TLUK ...

Status tags: Running: Master Controller [REDACTED] Machine HVAC 4 Running ...

Loaded: [REDACTED] ...

Availability: InternalTag M4 Availability ...

Priority: InternalTag VK50\_3 Priority ...

Measurement tags: Power usage: Master Controller [REDACTED] Machine HVAC 4 Power

Delivery volume: Master Controller [REDACTED] Machine HVAC 4 Current m<sup>3</sup>/h

Delivery pressure: Master Controller [REDACTED] Machine HVAC 4 Current kPa

Guide vane position: Master Controller [REDACTED] Machine HVAC 4 Current GV *hwrt*

Running hours: [REDACTED]

Efficiency: [REDACTED]

BlowOff Position: Master Controller [REDACTED] Machine HVAC 4 Current BO *hwrt*

Efficiency out: [REDACTED]

Flow ranges		Power efficiency	
Pressure (Pa)	Flow Range (kg/s)	Flow (kg/s)	Power (kw)
680000	9.42-14.4	0	0
660000	9.42-14.39	1	0
640000	9.42-14.25	2	0
620000	9.42-13.24	3	0
600000	9.42-13.36	4	0
580000	9.42-13.63	5	0
560000	9.42-14.48	6	0
540000	9.42-14.44	7	0
520000	9.42-14.59	8	0
500000	9.42-14.84	9	0
480000	9.42-14.49	10	0
460000	9.42-14.62	11	2.2168
440000	9.42-14.7	12	2.3906
420000	9.42-14.78	13	2.7469
400000	9.42-14.83	14	2.7576
		15	2.8031
		16	2.9099

Control Parameters:

Auto update Flow  Auto update Efficiency

Enable table logging

Min Vain Position: 40.00 %

Max Vain Position: 100.00 %

Max BlowOff Pos: 0 %

Power rating: 15000.00 kW

Type: -- Make

Baseload Compressor

Reserve Compressor

Max Stops per day: 100

OK Cancel

Figure 73: Compressor 4 set-up table

**Compressor -**

Description : [REDACTED]

Control tags: **High Active**

Hold delay: 0 s

Start: [REDACTED]

Stop: [REDACTED]

Load: [REDACTED]

Unload: [REDACTED]

Pressure set-point: Master Controller [REDACTED] Machine HVAC 5 PressureSP

Priority: InternalTag VK10\_1 Priority

Weight: [REDACTED]

Permission tags: Start [REDACTED] Dwt TLUK ...

Stop [REDACTED] Dwt TLUK ...

Load [REDACTED] Dwt TLUK ...

Unload [REDACTED] Dwt TLUK ...

Set-point control [REDACTED] Dwt TLUK ...

Status tags: Running: Master Controller [REDACTED] Machine HVAC 5 Running ...

Loaded: [REDACTED] ...

Availability: InternalTag M5 Availability ...

Priority: InternalTag VK10\_1 Priority ...

Measurement tags: Power usage: Master Controller [REDACTED] Machine HVAC 5 Power

Delivery volume: Master Controller [REDACTED] Machine HVAC 5 Current m<sup>3</sup>/h

Delivery pressure: Master Controller [REDACTED] Machine HVAC 5 Current kPa

Guide vane position: Master Controller [REDACTED] Machine HVAC 5 Current GV *hwrt*

Running hours: [REDACTED]

Efficiency: [REDACTED]

BlowOff Position: Master Controller [REDACTED] Machine HVAC 5 Current BO *hwrt*

Efficiency out: [REDACTED]

Flow ranges		Power efficiency	
Pressure (Pa)	Flow Range (kg/s)	Flow (kg/s)	Power (kw)
680000	1.95-2.29	0	0
640000	1.73-2.38	1	0
620000	1.95-2.27	2	1.8983
600000	1.95-2.24		
580000	1.95-2.32		
560000	1.95-2.32		
540000	1.95-2.31		
520000	1.95-2.32		
500000	1.95-2.33		
480000	1.95-2.37		
460000	1.95-2.38		

Control Parameters:

Auto update Flow  Auto update Efficiency

Enable table logging

Min Vain Position: 80.00 %

Max Vain Position: 100.00 %

Max BlowOff Pos: 20 %

Power rating: 15000.00 kW

Type: -- Make

Baseload Compressor

Reserve Compressor

Max Stops per day: 100

OK Cancel

Figure 74: Compressor 5 set-up table

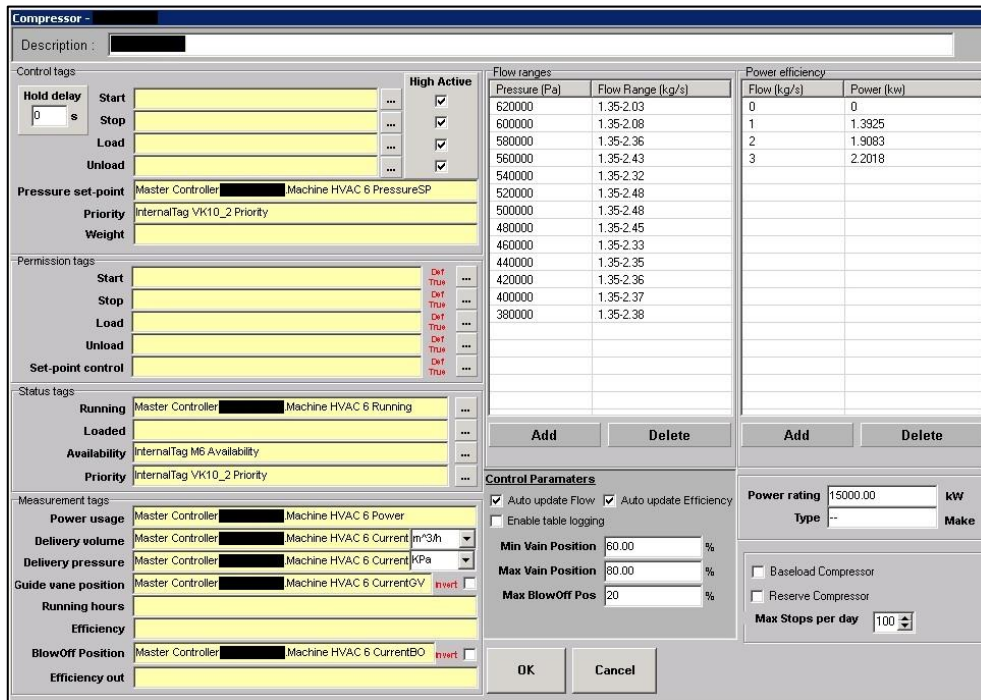


Figure 75: Compressor 6 set-up table

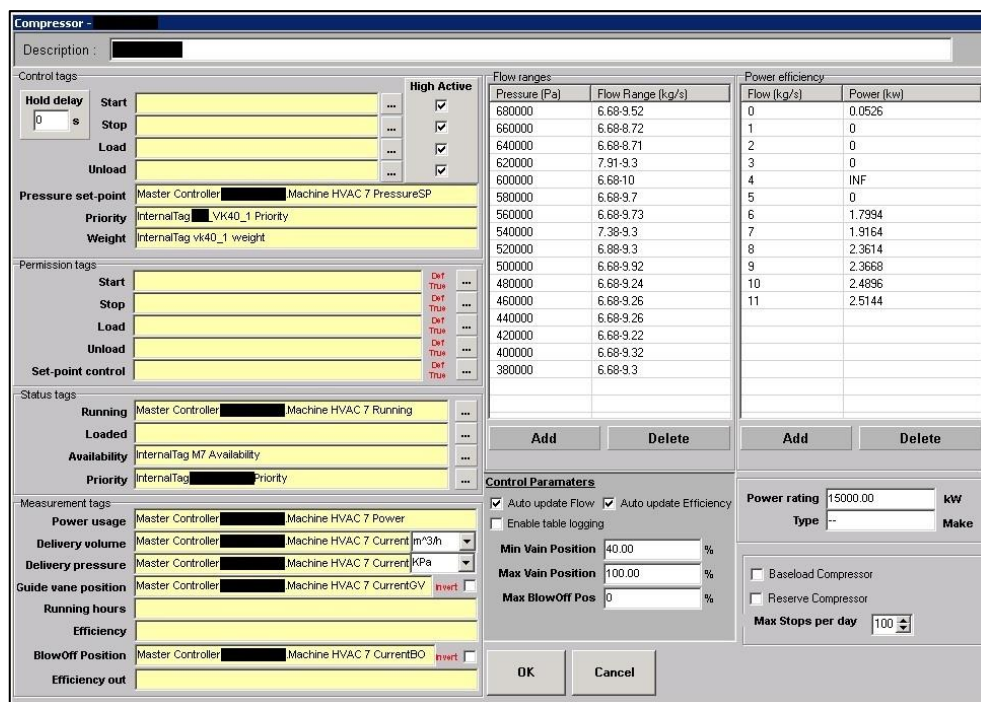


Figure 76: Compressor 7 set-up table



## Appendix C Mine A maintenance occurrences

Maintenance records for maintenance occurrences from 2002 to 2013 as obtained from a platinum mine are recorded in Table 20 to Table 27.

Table 20: Compressor 1 maintenance record

May-02	Recommissioned after major overhaul. Gear set replaced.
Aug-03	Replaced all intercoolers. Cleaned aftercooler.
Oct-03	Replaced oil cooler.
Dec-04	Replaced HP intercooler and aftercooler.
Jul-08	New oil sampling point has been fitted.
Aug-10	Main lube oil pump inspection done by Siemens.
Jun-11	All coolers were reported to be changed.
Nov-11	Manometer readings taken from suction pressure instrument with a manometer.

Table 21: Compressor 2 maintenance record

Mar-10	Control philosophy on lube oil system has been changed by Hiprom to prevent unnecessary starting of the auxiliary lube oil pump.
Nov-10	Motor replaced – tripping on high vibration.
May-11	HP intercooler changed.
Nov-11	Manometer readings taken from suction pressure instrument with a manometer.
Apr-13	HP cooler replaced. Aftercooler replaced – awaiting seals.
May-13	Seals replaced.

Table 22: Compressor 3 maintenance record

Nov-03	Overhauled ± two years ago.
Jun-04	'Cone' type filters installed.
Jan-05	AMOT valve fitted.
May-07	HP intercooler serviced.
Jul-08	New oil sampling point fitted – after oil cooler and before filter.
Mar-10	Control philosophy on lube oil system has been changed by Hiprom to prevent unnecessary starting of the auxiliary lube oil pump.
Oct-10	MP and HP intercoolers and aftercooler changed.
Apr-11	Motor changed.

Nov-11	Manometer readings taken from suction pressure instrument with a manometer.
Jan-12	Oil pump was changed.
Apr-13	LP intercooler and aftercooler replaced. Seals also replaced.
Nov-13	Motor changed.
Not known	Part D8844100501 was taken out and part D004539 installed.

Table 23: Compressor 4 maintenance record

Jul-03	It was reported to us that all of the intercoolers and the aftercooler were replaced. There does not appear to be any improvement in the air temperatures. To be confirmed.
Dec-03	HP and aftercooler seals have been replaced and the cooling water flow rate through these coolers was reduced – interstage air temperatures have improved significantly.
Jun-04	Air filters replaced with 'cone' type filters.
Sep-04	Compressor overhauled.
Jan-05	"Amot" valve fitted.
Jun-05	Drive motor replaced.
Oct-06	Aftercooler change just after we monitored for the November cycle.
Nov-06	Oil cooler replaced.
Sep-09	Air filters serviced.
Mar-10	Control philosophy on lube oil system has been changed by Hiprom to prevent unnecessary starting of the auxiliary lube oil pump.
Nov-11	Manometer readings taken from suction pressure instrument with a manometer.
Apr-13	LP and MP cooler seals replaced.

Table 24: Compressor 5 maintenance record

Jun-04	Suction filters replaced with 'cone' type filters.
Oct-06	Reground gear set installed into this unit. Vibration amplitudes decreased in general throughout with exception of a few positions where the amplitudes only decreased slightly.

Table 25: Compressor 6 maintenance record

Sep-03	It appears as though the suction air filters have been serviced – to be confirmed.
Jun-04	Air filters replaced with 'cone' type filters.
Jun-06	Reground gear set was fitted to this unit.
Dec-10	Bearing inspection done.

Table 26: Compressor 7 maintenance record

Jul-04	This compressor had a new bull gear, new pinion shafts, new 3rd/4th stage impellers and old 1st/2nd stage impellers fitted when commissioned.
Feb-05	Replaced drive motor with No 2 compressor motor.
Jun-05	Replaced drive motor.
Aug-05	Gear and bearing inspection performed. Mesh on the 1st/2nd stage adjusted slightly.
Oct-06	New hole drilled and tapped for suction pressure (manometer) downstream from orifice.
-	Gear set to be sent to Germany for inspection – vibration amplitudes have been high on this unit since it was commissioned.
Jun-09	Gear set replaced (hour meter reading: 7226).
May-11	All intercoolers changed.

Table 27: Compressor 8 maintenance record

Mar-05	Commissioned with new gear set.
Jun-05	Motor overhauled.
Oct-06	New hole drilled and tapped for suction pressure (manometer) upstream from orifice.
Dec-08	Correct oil sample point fitted.
June-10	mmH <sub>2</sub> O reading taken on suction pipe after orifice. No 1 compressor taken before orifice.
Oct-11	Annual to be done.