The value of simulation models for mine DSM projects

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Abstract

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Energy shortage, escalation of energy cost and climate change have led to an increased focus on energy conservation worldwide. In order to curb the increase in electricity demand, Eskom has introduced demand-side management (DSM) to improve energy efficiency and to shift peak-time load to off-peak periods in order to postpone additional capacity requirements. In the past, several mine DSM projects have been implemented without the use of system simulations as part of the analysis of project planning. Many of these projects are characterised by contractual energy saving targets that have not been met, projects that are delayed, potential energy savings projects that have been overlooked and additional savings that have not realised.

This study demonstrates the potential of simulations to plan new and correct implemented DSM solutions. This is done by allowing analysis of energy consumption in complex technical systems and quantification of the savings potential of DSM interventions to inform design changes in order to attain energy savings.

In applying simulations to a well-instrumented compressed air system, it was possible to compare the theoretical and measured values for system parameters. The simulation was fine-tuned for low-pressure operation (with the system operating well within design constraints) by incorporating estimated flow losses. By simulating high-pressure operation in which the system operates closer to design limits, the constraints that were experienced, were revealed. This application exemplifies the approach that has been adopted in the case studies to follow.

Simulations that have been applied to four case studies demonstrate the use in improving existing DSM projects as well as in planning new DSM projects. Two case studies demonstrate the use of simulations in rectifying problems that have been encountered during the implementation of existing mine DSM projects. Simulations have been employed to propose corrections to these project implementations; this demonstrates significant value for the customer.

In two additional case studies, the value of simulation models is demonstrated where simulations have been developed prior to the implementation of DSM projects. It demonstrates that projects can be implemented with less effort, in a shorter time span and at a reduced cost (both capital and man-hours) by using simulations in the planning phases of DSM projects.

Samevatting

Titel: Die waarde van simulasiemodelle vir DSM-projekte van myne
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Studieleier: Prof M Kleingeld
Graad: Magister in Ingenieurswese (Meganies)

Sleutelwoorde: Waarde van simulasiemodelle, Druklugstelsels, Waternetwerkstelsels, Simulasiesagteware

Energietekort, stygende energiekoste en klimaatsverandering het wêreldwyd tot ‘n toenemende fokus op energiebesparing gelei. Om die verhoging in elektrisiteitsaanvraag aan bande te lê het Eskom aanvraagbestuurstrategie (DSM-strategie) in gebruik geneem om energiedoeltreffendheid te verbeter en energieaanvraag tydens piektye te verskuif na tye van die dag wanneer die aanvraag laer is. Hierdie strategie is daarop gemik om die voorsiening van bykomende kapasiteit vir elektrisiteitsvoorsiening uit te stel [1]. In die verlede is verskeie DSM-projekte van myne geïmplementeer sonder dat simulasiemodelle as deel van die analise van projekbeplanning gebruik is. Baie van hierdie projekte word gekenmerk deur die feit dat kontraktuele teikens vir energiebesparing nie gehaal is nie, vertragings plaasgevind het, potensiële energiebesparingsprojekte misgekyk is en bykomende besparings nie verwesenlik is nie.

Hierdie studie demonstreer die potensiaal van simulasiemodelle om nuwe DSM-projekte te beplan en om reeds geïmplementeerde DSM-oplossings te verbeter. Dit word gedoen deur die ontleding van energieverbruik in komplekse tegniese stelsels en die kwantifisering van die besparingspotensiaal van DSM-oplossings wat op ontwerphersienings gemik is om energiebesparing te bewerkstellig.

Deur simulasiemodelle op ‘n goed geïnstrumenteerde druklugstelsel toe te pas was dit moontlik om die teoretiese en gemete waardes vir stelselparameters te vergelyk. Die simulasiemodel is noukeurig vir laedrukwerking ingestel (met die stelsel wat heeltemal binne die ontwerpbeperkinge funksioneer) deur geraamde vloeiverliese daarby te inkorporeer. Deur hoëdrukwerking te simuleer (waarin die stelsel nader aan ontwerpbeperkinge funksioneer) is die beperkinge wat ondervind is, blootgelê. Hierdie toepassing illustreer die benadering wat in die gevallestudies gebruik is.

Simulasies wat in vier gevallestudies toegepas is, illustreer die gebruik daarvan in die verbetering van bestaande DSM-projekte, sowel as in die beplanning van nuwe DSM-projekte. Twee van hierdie gevallestudies demonstreer die gebruik van simulasies om probleme reg te stel wat tydens die implementering van bestaande DSM–projekte in myne teëgekom is. Simulasies is gebruik om ontwerpregstellings vir hierdie projekimplementering voor te stel; dit illustreer beduidende waarde vir die kliënt.

In twee bykomende gevallestudies word die waarde van simulasiemodelle geïllustreer waar simulasies ontwikkel is voor die implementering van DSM-projekte. Daar word in hierdie gevallestudies aangetoon dat projekte met minder moeite, in ‘n korter tydperk en teen ‘n verminderde koste (wat kapitaal en man-ure betref) geïmplementeer kan word deur simulasies gedurende die beplanningsfases van DSM-projekte te gebruik.

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Nomenclature

BAC	Bulk air cooler/cooling
°C	Degrees centigrade
DBSA	Development Bank of South Africa
DSM	Demand-side management
EE	Energy efficiency
EEDSM	Energy efficiency demand-side management
Esco	Energy service company
Eskom	National electricity supplier
GDP	Gross domestic product
GW	Gigawatt
IMC	Inter-Ministerial Committee
IRP	Integrated resource plan
kPa	kiloPascal
kW	Kilowatt
L	Level
LS	Load shifting
MVA	Megavolt-ampere
MW	Megawatt
MWh	Megawatt-hour
NMD	Notified maximum demand
PC	Peak clip
PCT	Pre-cooling tower
PRV	Pressure reducing valve
3-CPFS	Three chamber pipe feeder system
TOU	Time of use

1 Introduction

1.1 Energy in South Africa

The shortage of energy resources, escalation of energy cost and climate change have led to an increased focus on energy conservation worldwide. In South Africa, the cost of electricity has increased drastically during the past years [2] [1]. The national electricity supplier, now named Eskom, was established in 1923 and generates approximately 95% of the electricity that is used in South Africa. The total installed capacity of Eskom is presently approximately 41 gigawatt (GW) [1].

In 2008, South Africa's electricity supply system became unreliable due to the fact that, among other reasons, the growth of consumer electricity demand exceeded growth in electricity supply, thereby reducing the reserve margin to unacceptably low values. In order to curb the increase in electricity demand, Eskom introduced Demand-side management (DSM) to improve energy efficiency and to shift peak-time load to off-peak periods in order to delay additional capacity requirements [1].

In 2011, Government approved the Integrated Resource Plan (IRP) that was recommended by the Inter-Ministerial Committee (IMC), drawn from a scenario modelling process, as well as the Policy-Adjusted IRP, based on the Revised Balanced Scenario (for more information, please refer to reference 3) [3]. In the Policy-Adjusted Scenario, the South African gross domestic product (GDP) is expected to grow over the next 20 years at an average of 4,6% annually [3]. Given this growth scenario and taking the decommissioning of aging plants into consideration, Eskom has estimated that in excess of 58 GW of new generation capacity will be required in order to meet the projected demand while ensuring an adequate reserve margin [3]. Included in this requirement for the new generation capacity, 3,4 GW is allocated to be obtained from effective demand-side management and other efficiencies and diversifications[3].

The significance of DSM projects (the percentage efficiency gained) is emphasised in Figure 1. The black dotted line indicates the projected demand line without implemented energy initiatives. The red line indicates the efficiency gained as a result of the inherent reduced energy intensity of the consumers. The projected demand is dependent on the improved efficiency of Eskom's clients.

Several energy saving projects have been implemented to prevent load shedding which is similar to those that were experienced in 2008 and 2009 [4]. DSM alone will, however, not solve Eskom's electricity supply shortage problem, but it is providing a short-term solution to the electricity supply shortfall [5]. The goal of DSM is to encourage electricity users to reduce energy consumption and to shift peak power consumption to the time of day when total demand in the RSA is lower.

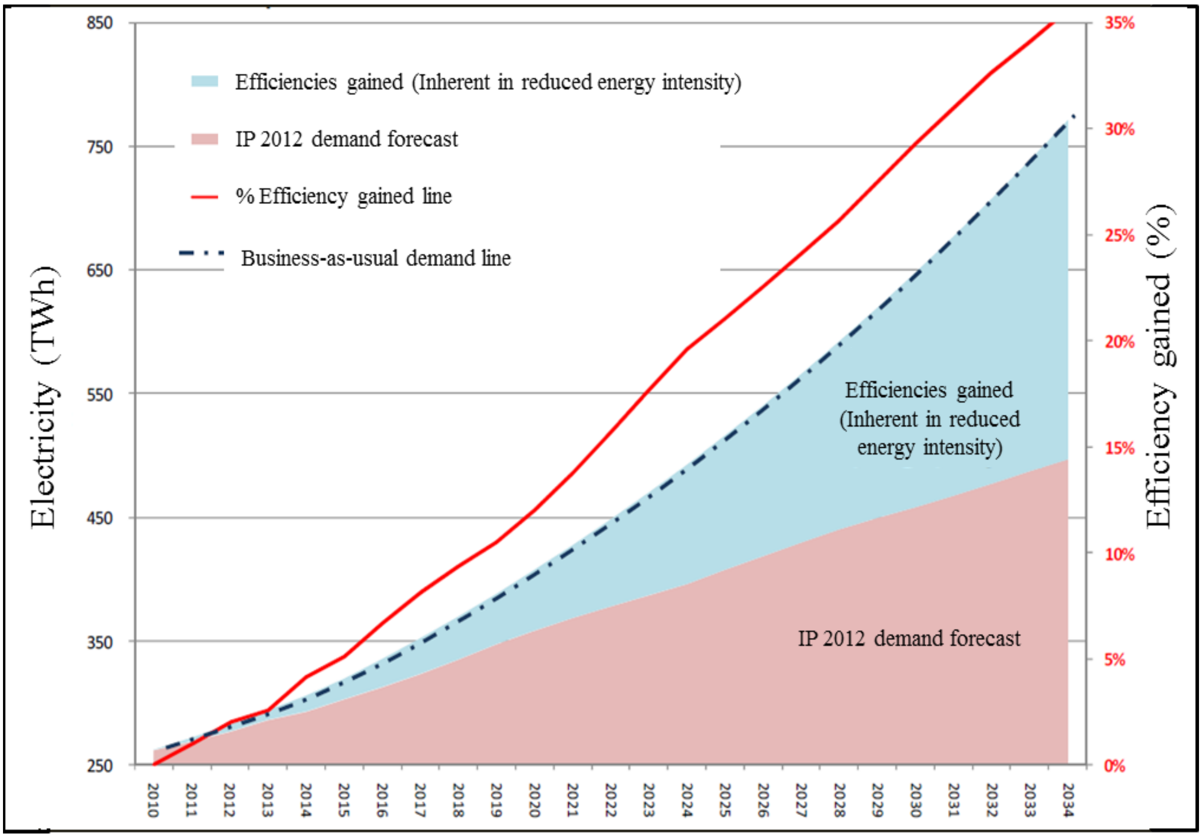

Figure 1: The expected impact of efficiency improvements in the IRP, Balanced Scenario [3]

1.2 South Africa's major energy users

Eskom's combined electricity sales at the end of March 2011 are shown in Figure 2. South African municipalities and the industrial sector consume 40,8% and 26,6% respectively of Eskom's generated electricity, based on Eskom's electricity sales. The South African mining sector consumes 15% of Eskom's total generated electricity, based on Eskom's electricity sales [1].

The mining sector is not the largest electricity consumer, but it consists of approximately 1 000 customers, as opposed to the more than 4 000 000 municipal consumers [1]; it is thus possible to achieve higher electricity savings per customer when focusing on the mining sector instead of the municipal sector. It also has the technical and management expertise to implement cost effective DSM solutions and maintain them in effective operation.

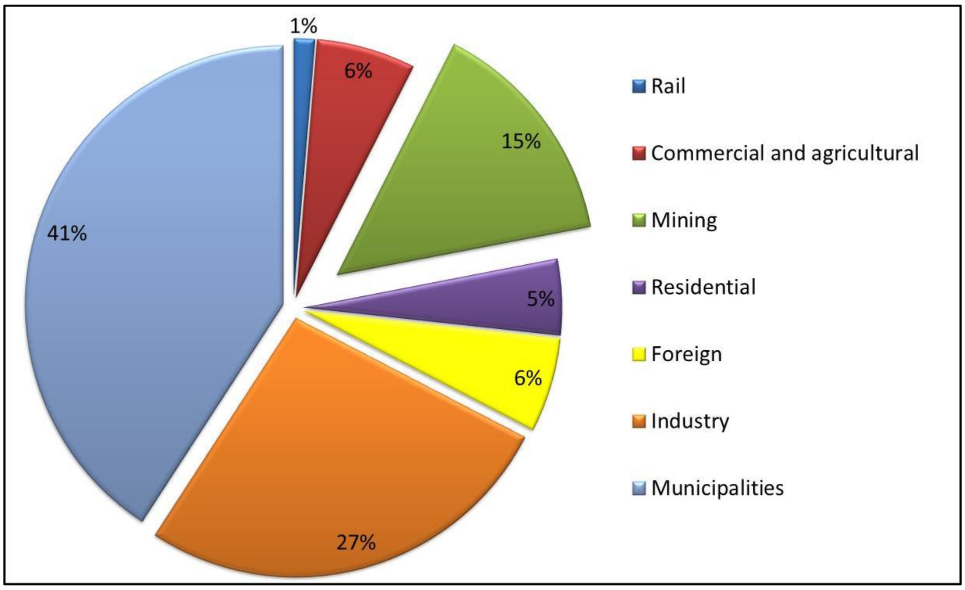

Figure 2: Eskom's total electricity sales for the year ending 31 March 2011 [1]

Gold and platinum mines consume respectively 47% and 33% of the energy in the mining sector. Compressed air systems account for 17% of the total energy that is consumed in the mining sector, industrial cooling for 5% and pumping systems consume 14%, as shown in Figure 3 [6].

Processing and materials handling respectively consume 19% and 23% of the electricity in the mining sector. The electricity consumers in the processing and materials handling sections of mines consist of many smaller electricity consumers compared to compressed air, pumping and industrial cooling systems. For this reason, using the same methodology as explained in the above paragraph, larger electricity savings per consumer could be achieved on the latter three systems. Processing and materials handling are therefore not included in the scope of this study.

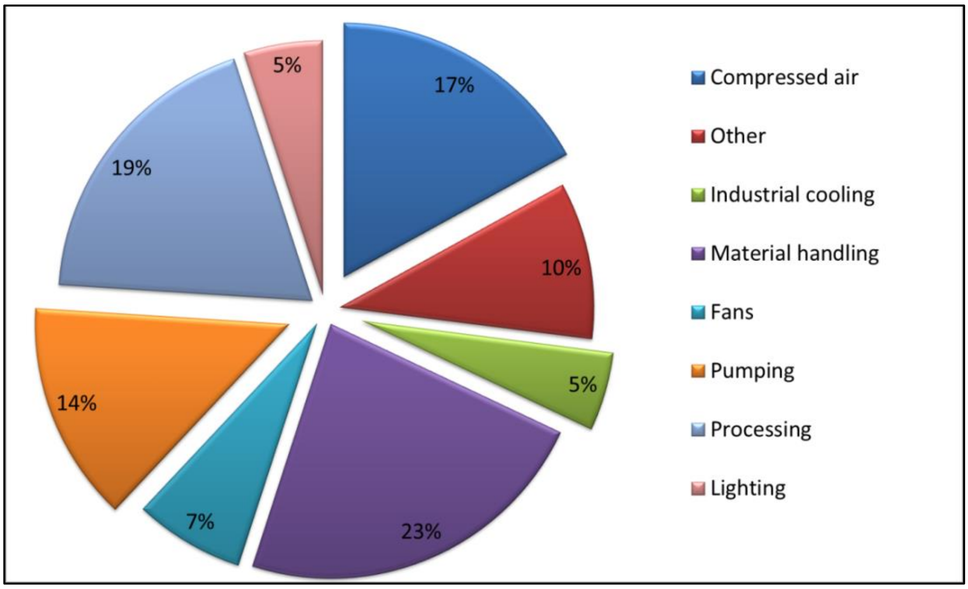

Figure 3: Electricity users in the mining sector [6]

1.3 Eskom’s time-of-use tariff structures

Eskom introduced a time-of-use (TOU) tariff structure to provide appropriate and cost based economic signals to consumers in order to move away from Eskom’s peak demand periods.

Mega Flex is a tariff structure that has been developed by Eskom for urban, industrial and mining clients with a notified maximum demand (NMD) that is greater than 1 MVA. It consists of three different tariff pricing periods [7]. The tariffs are divided into peak, standard and off-peak periods for both the high- and low-demand seasons, as illustrated in Figure 4 [2].

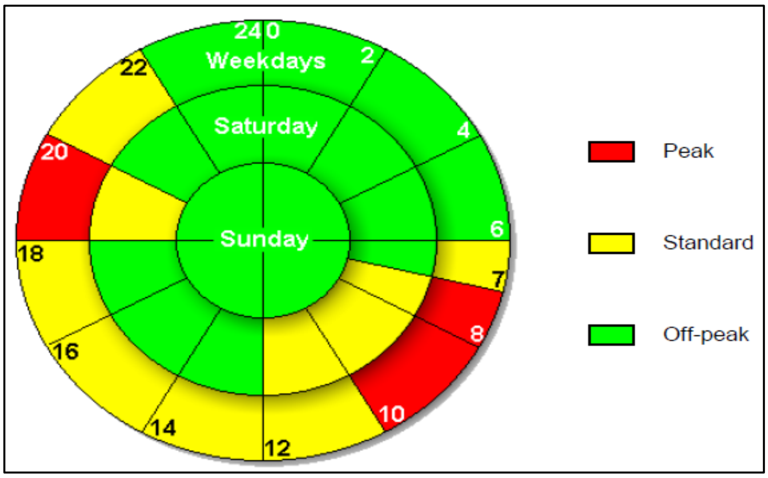

Figure 4: Eskom's time-of-use pricing chart for both the high- and low-demand seasons [2]

Table 1 presents a summary of Eskom’s TOU tariffs. Eskom’s high-demand season includes June, July and August. During the winter months, the electricity demand during evening peak hours increases significantly with a subsequent increase in cost. The tariffs shown in Table 1 are measured in cent per kilowatt-hour.

Table 1: Eskom's Mega Flex TOU tariff structure for 2012/2013 in c/kWh [2]

	High-demand season			**Low-demand season**		
Transmission zone	Peak	Standard	Off-peak	Peak	Standard	Off-peak
< 300 km	247,85	64,36	34,34	69,14	42,34	29,58

1.3.1 Demand-side management

Eskom introduced the TOU pricing structure in combination with the DSM programme as mechanism to regulate energy consumption [7]. In the mining sector, DSM projects consist of energy efficiency, load shifting and peak clipping projects. Energy efficiency demand-side management (EEDSM) programmes are mainly implemented through: [3]

- Eskom's funded programme, where Eskom sponsors or subsidises the complete DSM intervention;
- Standard Offers, where the implementer pays for the initial installations but is repaid by Eskom, based on the sustainable performance of the implemented project; or
- alternative mechanisms to motivate electricity consumption savings.

1.3.1.1 Energy efficiency

This strategy will reduce the end user's overall energy usage. Figure 5 illustrates the results of a typical energy efficiency DSM intervention. The blue graph represents the original power profile prior to the energy efficiency intervention. The red graph illustrates a reduced power profile after the DSM intervention.

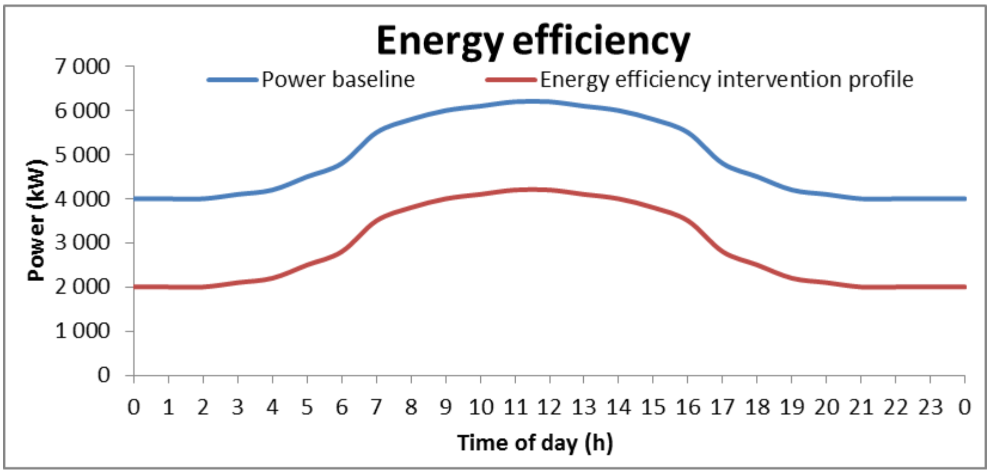

Figure 5: Illustration of a typical energy efficiency DSM intervention baseline

1.3.1.2 Load shifting

Load shifting (LS) strategies will only shift the load out of peak periods to a lower demand period and do not result in energy efficiency improvements. This strategy is implemented to reduce power supply during peak periods when reserve margins are reduced. Total energy consumption for the day will be unchanged.

Figure 6 illustrates a typical LS intervention. The blue graph represents the original power profile prior to the load shift intervention and the red graph illustrates a typical optimised load shift profile after DSM intervention.

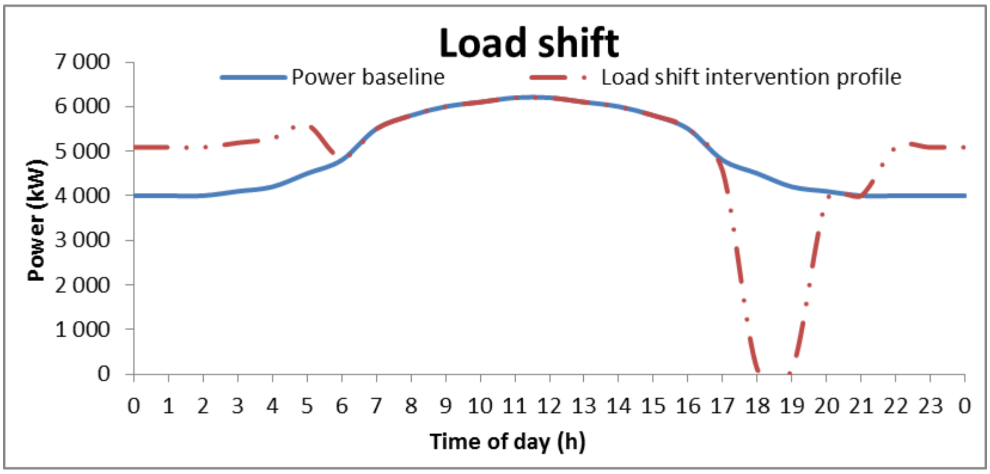

Figure 6: Illustration of a typical load shift DSM intervention baseline

1.3.1.3 Peak clip

This strategy entails the reduction of the end user’s power consumption during Eskom’s peak periods. A peak clip can potentially result in lost production, because no provision is made to compensate for the reduced consumption during non-peak hours; the total weekday energy consumption will thus be reduced.

Figure 7 illustrates the results of a typical peak clip DSM intervention. The blue graph represents the original power profile. The red graph illustrates an optimised peak clip profile, following DSM intervention.

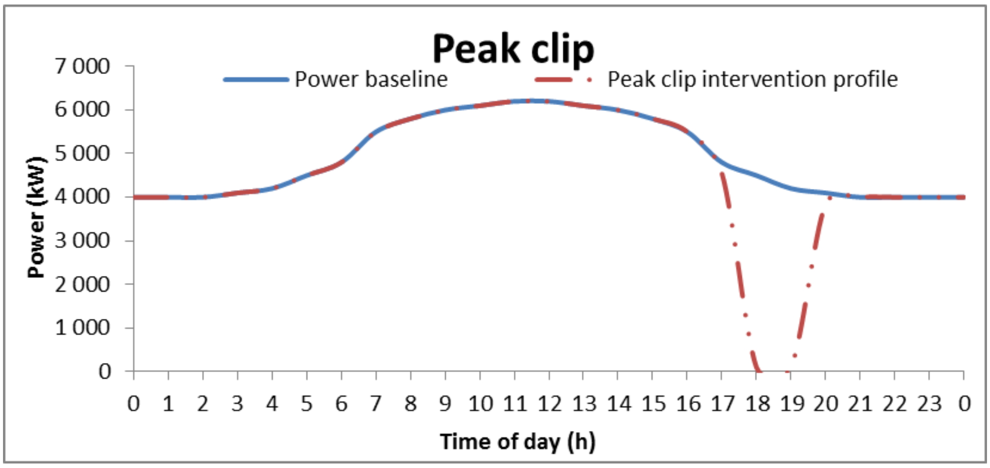

Figure 7: Illustration of a typical peak clip DSM intervention baseline

1.4 Simulation and DSM in the mining environment

Mines in South Africa reach depths of up to 4 000 metres below surface [8]. At 4 000 metres, virgin rock face temperatures of up to 65 °C have been recorded [9]. Blasted ore that bears rock is cooled by spraying it with cold water [10]. The cooling is necessary to ensure that working conditions are held within acceptable limits [11].

Traditionally, mines were cooled by using ventilation air. Due to increasing mine depth, air ventilation cooling became insufficient and alternative cooling methods had to be implemented. These include surface bulk air cooling (BAC), underground station bulk air cooling, chilled service water and crosscut coolers (spot coolers)[8]. When cooling techniques are compared and cost, reliability and safety are taken into consideration, the use of refrigeration plants has been shown to be the best cooling technique [12]. Refrigeration plants are, therefore, widely used to cool water that is used for mine cooling purposes.

In addition to the energy intensive cooling systems, dewatering systems pump water continuously from the various mining levels to the surface to ensure that mining levels are not flooded. Mine water reticulation and cooling systems can in specific instances consume up to 42% of a deep mine’s energy use [13].

Compressed air systems in the mining sector are also large energy consuming systems and consist of compressors that supply compressed air to complex networks. These networks consist typically of surface compressed air pipelines of several kilometres long. Compressed air is supplied to production components that are operating at up to 4 000 metres below the surface [14]. Typically, these systems contribute as much as 20% of the mine's total electricity cost [15].

Energy saving initiatives include the installation of compressor controllers, compressed air valves, cooling system controllers, cooling system water valves and pumping system controllers. Due to unforeseen circumstances, the implementation of some of these initiatives is often delayed. In many cases, additional energy savings could be realised if simulations had been developed and used prior to implementation.

1.5 Objectives of this study

Many examples are documented of DSM projects that were implemented in the past, but did not attain their contractual energy saving targets, were delayed due to improper implementation, or in which additional savings were overlooked [14] [16] [17] [18] [19] [20] [5] [21] [22]. In these cases, simulations had not been employed prior to the planning and implementation of some of these DSM projects. This study will demonstrate the capability of simulations to provide a viable and cost-effective approach for techno-economic assessments of potential mine DSM projects. The significance of simulation models will be illustrated through application in a number of case studies, both retrospectively and prior to DSM project implementation. Four case studies will be evaluated, based on:

- project implementation cost;
- project implementation period;
- project feasibility;
- project design; and
- component design.

Although simulation models can be used on various mine systems, the study will be limited to the evaluation of compressed air and dewatering systems, because the energy that is consumed by these systems accounts for 31% of the energy that is consumed by mines.

1.6 Outline of this document

In this chapter, an overview of South Africa's energy needs and planning is given. The need for energy savings and the rationale for focusing on mine DSM projects are presented. A number of DSM concepts are discussed.

In Chapter 2, an overview of typical compressed air and water reticulation systems is presented. A number of implemented energy saving solutions are discussed in order to demonstrate the nature of energy saving interventions and the use of simulation models in planning and implementing DSM projects. A number of different software simulation packages for use in the mining industry are discussed. A literature survey of simulations that are used in mine DSM projects is presented.

In Chapter 3, the simulation package that has been chosen to use in this study is discussed. The verification and validation processes that have been followed to develop simulations in this study is also discussed.

In Chapter 4, four case studies are used to demonstrate the value of simulations. Two case studies are used to demonstrate the value of simulations in circumventing constraints and obstacles in the implementation of DSM projects. Two other case studies demonstrate the value of simulation as analysis and planning tool prior to the implementation of DSM projects. It is illustrated that simulation models provide an elegant and cost-effective method to optimise DSM projects and that correct use of simulation models circumvent post-implementation re-design and corrections.

In Chapter 5, conclusions and recommendations for future studies are presented. The outcome of this study indicates that simulations have a significant value when mine DSM projects are implemented, upgraded or planned for implementation.

2 System simulation models and their implementation to the mining sector

2.1 Introduction

Since 2005, an accumulative power saving of 2 717 MW has been achieved through the implementation of DSM projects [1]. During 2011, compressed air systems and industrial process optimisation accounted for 115 MW of the total 354 MW power savings that were realised from implemented DSM projects (from the source it is unclear whether these savings were only realised on efficiency optimisation projects on mines and if the industrial sector is included) [1].

Simulation is a powerful tool that is used inter alia by energy service companies (Escos) to establish the viability of a proposed DSM project. However, the significance of using simulation models is often underestimated. In this chapter, various techniques that have been used by Escos to implement DSM projects will be discussed.

2.2 Water reticulation system

2.2.1 Water refrigeration

Refrigeration plants are used to cool water that is to be used underground for cooling purposes. Due to the extreme depths of many South African mines, refrigeration plants are sometimes situated at mining levels below the surface [7]. Water that is used in refrigeration plants is in most cases recirculated continuously.

Water refrigeration is an energy intensive process and including water refrigeration in energy savings simulation should render additional savings (typically about 5%, as illustrated in Figure 3). Water refrigeration is not included in the scope of this study and will therefore not be investigated.

2.2.2 Dewatering

After chilled water has been used in the mining section, it is transferred to underground water dams [7]. The amount of water that can be pumped back to the surface is dependent on the number and size of dewatering pumps, the number and availability of dewatering columns, and the minimum and maximum allowable dam levels [23]. These components all play an important role in DSM strategies.

Successful DSM interventions require surface dam levels to be at a maximum and underground dam levels at a minimum just before commencement of Eskom’s evening peak periods. This will ensure the availability of sufficient surface water for the refrigeration system.

2.2.3 Automation of pumping systems

Substantial energy savings can be realised if proper automation and control philosophies are employed. Kleingeld *et al.* describe the control philosophy of implemented projects that is aimed at reaping the benefit of Eskom’s TOU tariffs [24]. The control philosophy of Kleingeld, developed without making use of simulations, requires the water levels of the underground dewatering dams to be at their minimum setpoint just before Eskom’s peak periods. At the same time, surface dam levels are programmed to be at their maximum setpoints. Large capacity underground dewatering dams will prevent mine flooding and surface dams will ensure that sufficient hot water is available for the refrigeration plants [24].

Kleingeld has implemented eight DSM projects with an average achieved peak load reduction of 41,8 MW successfully. The contractual target was 31,2 MW, which means that the achieved load reduction was 34% higher than the contractual target [18]. DSM project funding is dependent on the projected amount of energy that is saved at the time of contracting. Figure 8 indicates the achieved load shift, compared to the contractual target load shift for the period June 2004 to February 2006.

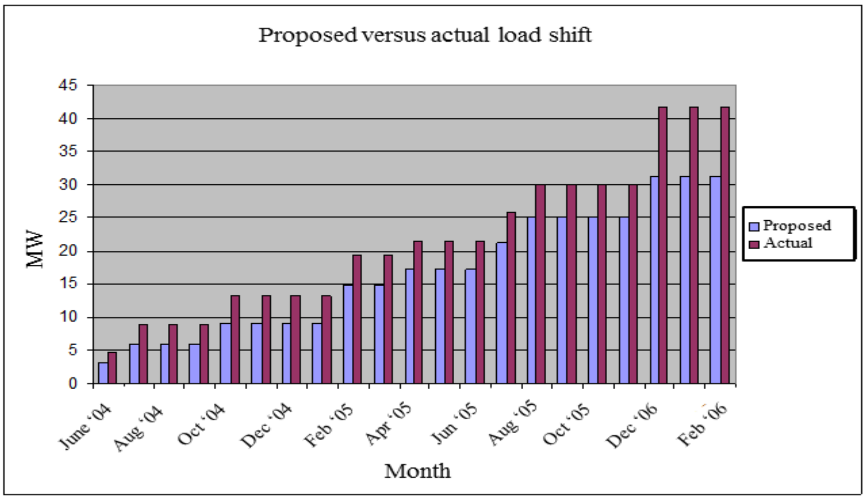

Figure 8: Cumulative load shift that was proposed and achieved [18]

The remuneration of the Esco was based only on the projected savings as contracted. If the contractual savings had been predicted more accurately, the Esco could have received greater remuneration. In this particular case, the over performance of 34% can be attributed to the fact that simulations were not used to assess the possible energy savings.

2.2.4 Energy savings as a result of improved control

In a study that has been conducted by Van Rensburg *et al.*, additional average power savings of 600 kW were achieved through improved pump selection and control philosophies that were obtained by performing simulations. A daily energy saving of 14,4 MWh realised an annual electricity cost saving of R800 000 **[20]**.

Alperovits *et al.* showed that when more than one pump is utilised in a column, pump efficiencies decrease **[25]**. Van Rensburg concluded that a 6,2% reduction in pump efficiency resulted when two pumps were utilised in a single column. Other results indicated that pump efficiencies were reduced by 14% when three pumps instead of a single pump were utilised per column **[20]**. The results of the study also showed that an energy saving, equivalent to 17% of its baseline, could be realised if more efficient pumping scheduling would have been used **[20]**.

In addition to Van Rensburg's study, Schoeman *et al.* developed simulations after a load shift DSM project had been implemented. Based on Schoeman's results, an average additional 5,8 MW load was shifted during Eskom's evening peak period **[26]**.

2.2.5 Energy savings as a result of water demand control

A number of studies have indicated that energy efficiency could be achieved by implementing techniques such as leak management, stope isolation control and automatic supply pressure water control [**16**]. Of these techniques, leak management is directly associated with maintenance and stope isolation control with employee negligence. These techniques will ensure large energy savings, but are not sustainable, unless automated control systems are introduced.

Vosloo *et al.* have conducted a study to calculate the electrical energy savings when implementing an isolating and pressure control valve in series at the point where water from the column entered each mining level. The valves were controlled according to each level's specific pressure setpoints. The average downstream pressure of multiple mining levels was reduced from 1 200 kPa to 1 070 kPa between 16:00 and 20:00. This resulted in a reduction of 90,4 litres per second (l/s) of water that was supplied to the mining levels and consequently 90,4 l/s less water had to be pumped. A daily energy efficiency saving of 10,78 MWh and an annual electricity cost saving of R600 000 were achieved. According to Vosloo, a possible energy saving of 100 MWh per day could be realised if proper water pressure control were to be implemented on deep level mines throughout South Africa [**17**].

Correct control valve selection is important, as the water requirements of the mine have to be matched to the performance characteristics of a valve. Booysen *et al.* describe the selection of an ideal control valve as a compromise between various sets of constraints. These include flow characteristics of the valve, control range of the actuator, cavitation, flashing, water hammer, valve body size, actuator type, safety rating, control speed, after-sales supplier service and valve assembly maintenance [**27**].

Booysen considered a variety of valve types, after which a simulation was developed. Results from this simulation indicated that two control valves had to be installed in series. The first in-line valve had to have a fixed orifice opening in order to reduce the column pressure. This would reduce the pressure to within the pressure control ranges of the second valve. The second installed valve had an electric actuator that was installed to control the downstream water pressure and flow according to the demand.

2.3 Compressed air systems

2.3.1 Introduction

Typical South African mines utilise multi-shaft compressed air systems with complex pipe networks. These compressed air systems operate at pressures of up to 580 kPa and are driven by compressors with installed electric motor capacities of up to 15 MW [22].

Figure 9 illustrates a typical compressed air system [28]. Traditionally, compressed air is supplied at higher pressures than would normally be required. This is done as a safety measure to compensate for potential system pressure losses [29]. Random system pressure losses, resulting from leaks, are often experienced. Rust build-up on the inside walls of supply pipelines will increase the flow friction. This gradual increase in flow resistance leads to a gradual decrease in underground air pressure over time [30].

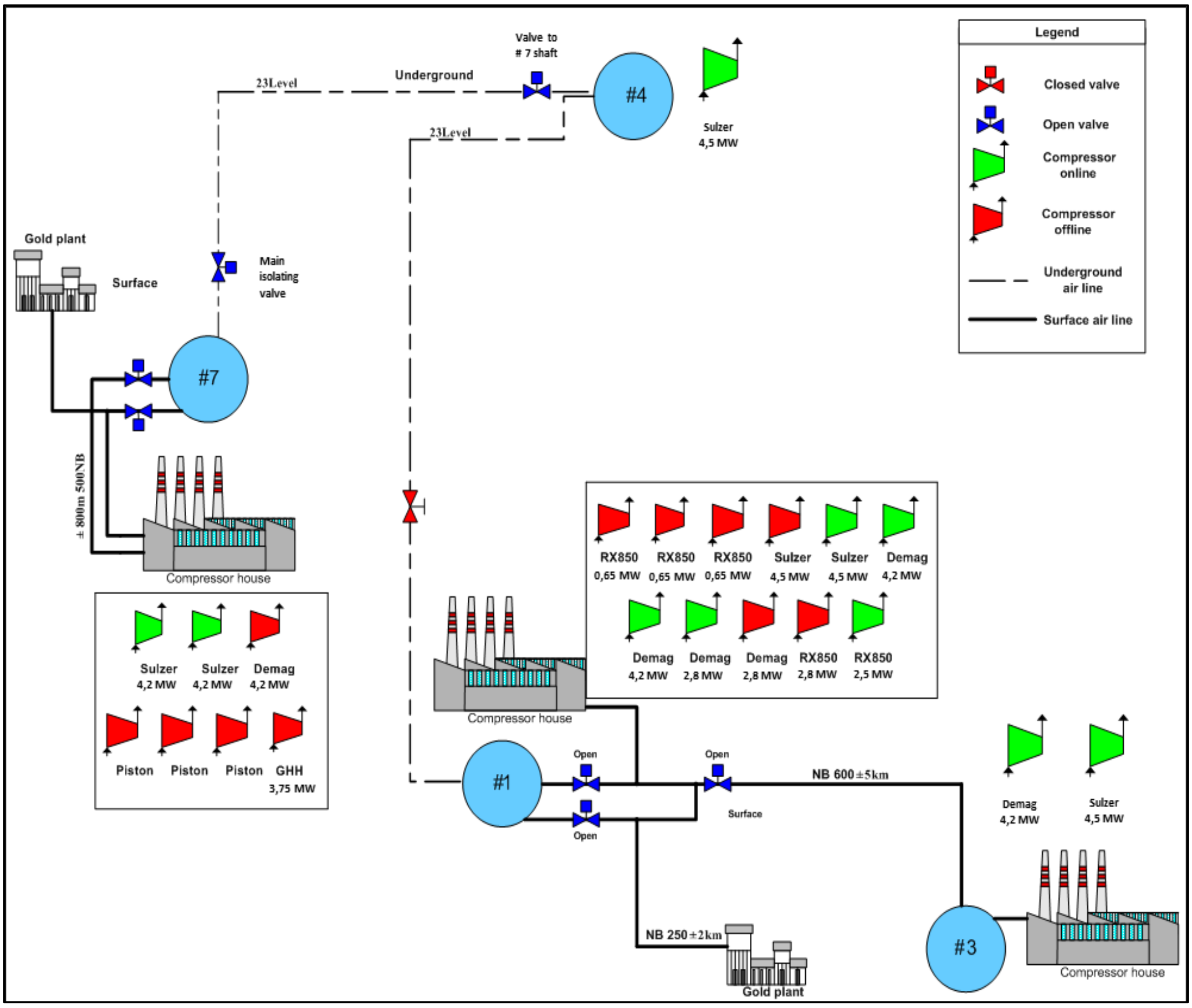

Figure 9: A typical large mine compressed air network [28]

Typical underground compressed air systems are characterised by multiple bypasses and multiple valve configuration splits. Compressed air usage in gold mines varies from air that is used for agitation to compressed air that is used to power pneumatic rock drills. Most of the compressed air equipment require a compressed air delivery pressure of more than 350 kPa in order to function properly [30]. Compressed air is required near the shaft barrel as well as at the stopes, where it is used for various pneumatically operated equipment [30].

2.3.2 Energy optimisation of compressed air systems

Numerous techniques are implemented in order to achieve electrical energy savings on compressed air systems. These techniques include the installation of pressure and mass flow control valves.

The implementation of the different techniques reduces the compressed air usage. With the lowered pressure and flow, less power is needed to keep the system pressurised. Power consumption by a compressor to compress a system can be expressed in terms of the air mass flow and pressure ratio [31].

Equation 1 [32] represents the power input by a compressor in order to generate compressed air:

$$W_{theoretical} = \frac{W_{comp}}{\eta_{comp}} = \dot{m}\,\frac{C_p T_1}{\eta_{comp}}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \qquad 1$$

with

- $W_{theoretical}$ = theoretical compressor power, measured in watt;
- W_{comp} = compressor power input, measured in watt;
- $\dot{m}$ = mass flow of compressed air in kg/s;
- η_{comp} = compressor efficiency;
- n = polytropic constant of air, taken as 1,4 in this study;
- C_p = constant pressure specific heat in J/kg-K;
- T_1 = temperature of air flowing into compressor in Kelvin;
- P_2 = discharge pressure (absolute pressure) in Pa; and
- P_1 = atmospheric pressure in Pa.

From Equation 1, it follows that if the compressor discharge pressure (P_2) or the compressed air delivery ($\dot{m}$) or both are lowered, the required power to deliver compressed air at the new pressure and flow rate is lowered. Mass flow or pressure reduction or both lead to reduced power usage.

2.3.3 Compressed air system control

Compressed air is extensively used in mines. Numerous control strategies have been developed in an attempt to increase compressed air system efficiencies. Lodewyckx *et al.* describe different methods that are implemented in order to exploit Eskom’s TOU tariffs. Some of these methods include: **[33]**

- the use of stored compressed air during low demand periods;
- lowering the air mass flow, for example by using compressor inlet guide vanes;
- load sharing, for example by using two compressors simultaneously to supply compressed air; and
- compressed air demand-side control to lower the compressed air flow and pressure to equipment. Air use can be minimised by fixing leaks, and by installing surface and underground control valves. Control valves are used to throttle airflow according to pressure and flow setpoints, resulting in an increase in the upstream compressed air system pressure. When system pressure increases, the compressor guide vane controller will start to adjust the compressor inlet guide vane angles, resulting in energy savings.

If, for example, a compressed air system demand-side saving project is implemented, it is necessary to control the compressors within its design limitations. Figure 10 presents an example of a typical compressor performance map. The design point is a function of the compressor pressure ratio (π_C), corrected rotational speed of the shaft (N_C) and the corrected air mass flow rate ($\dot{m}_C$) **[34]**. Due to the fact that VSDs are not considered, the corrected rotational speed will be constant.

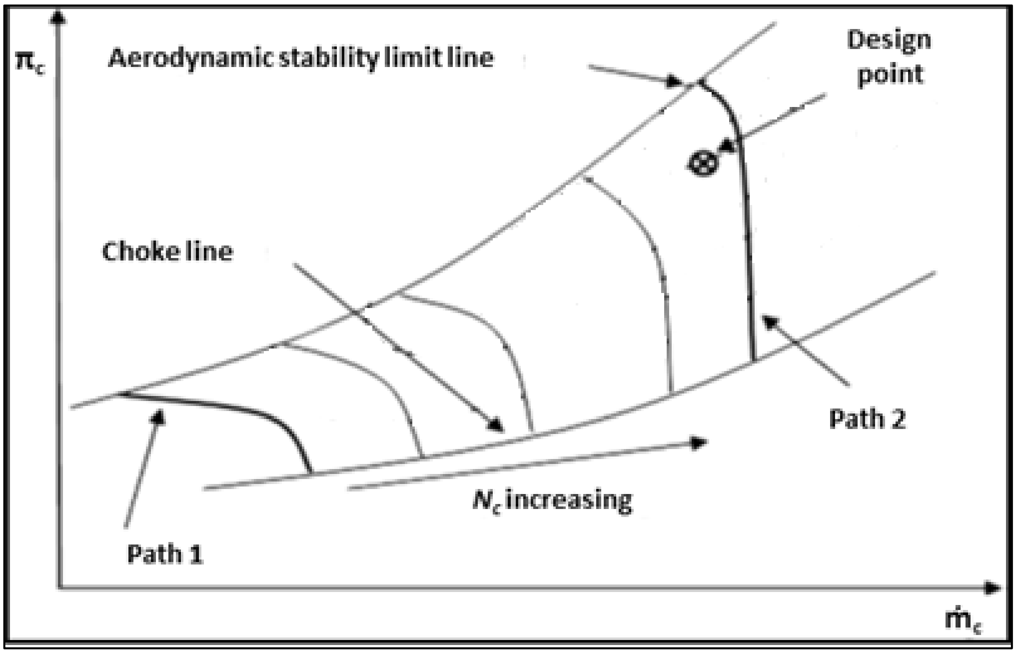

Figure 10: A typical compressor performance map [34]

By installing and optimising the control of the inlet guide vanes and by using the compressor blow-off valve, the compressor can be operated to deliver the optimum amount of air to the system. The addition of guide vanes and the optimised control thereof will yield substantial power savings, while minimising the input cost [35].

Compressor automation plays a critical role in controlling a compressor as close to the design point as possible, as indicated in Figure 10. Figure 11 contains a schematic of the compressor automation setup that is employed at the majority of mines in South Africa [14]. The functioning of guide vanes and blow-off valves plays a critical role in achieving energy savings on a compressor in a compressed air system. A blow-off valve is a pressure relieve valve that mechanically opens when the pressure within the system reaches a certain predetermined pressure [34].

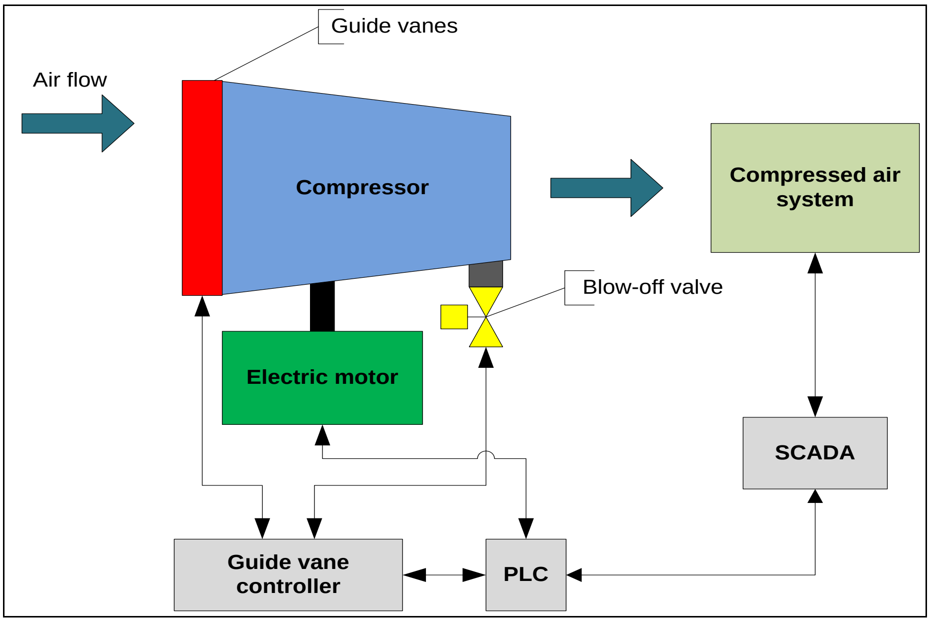

Figure 11: Automated compressor setup [14]

Simulation models can be used to determine the performance of compressors. This study will not focus on compressor optimisation. However, simulations will be used to determine demand optimisation that would lead to supply optimisation. Some of the techniques that will be implemented will lower the compressed air demand. Without proper compressor control, the reduction in compressed air demand will not yield the potential compressor power savings.

2.3.4 Compressed air system supply-side energy optimisation

The majority of compressor applications that are found in mines are operated such that a constant air flow is provided to the mining environment in order to sustain the maximum production pressure requirements. Consequently, few or no compressors are cycled and manually operated at fixed setpoints [35].

Booysen *et al.* conducted a study to determine the effect of system pressure reduction on energy savings. The particular mine’s compressor operational setpoint was set at 600 kPa. Figure 12 represents a weekday pressure baseline for the compressed air system. It is shown that system pressure stayed constant at the 600 kPa, except during peak drilling periods between 06:00 and 10:00 when the pressure was reduced to approximately 560 kPa [35].

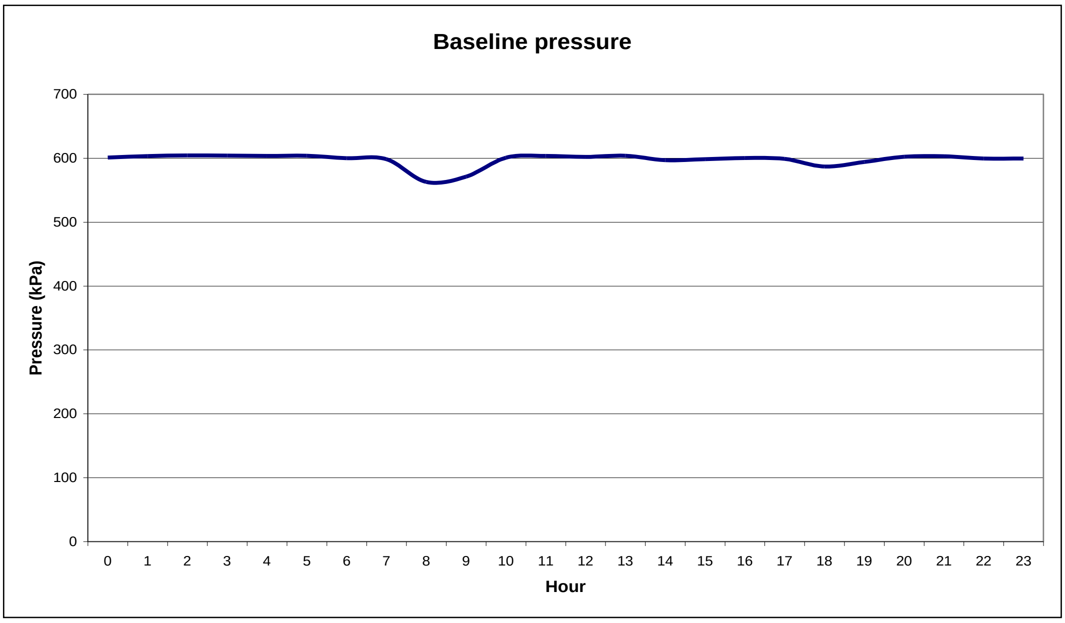

Figure 12: Compressed air system pressure baseline [35]

The pressure reduction is caused by the increased air demand during this period. Booysen concluded that an operational pressure of 480 kPa was sufficient to ensure that production was not influenced. It was calculated that this would be achieved by stopping and starting compressors as needed **[35]**.

A new compressor control philosophy was simulated. The simulation was based on the compressed air demand, as shown in Figure 13. The demand for compressed air is at its peak during the mine's drilling periods between 06:00 and 14:00.

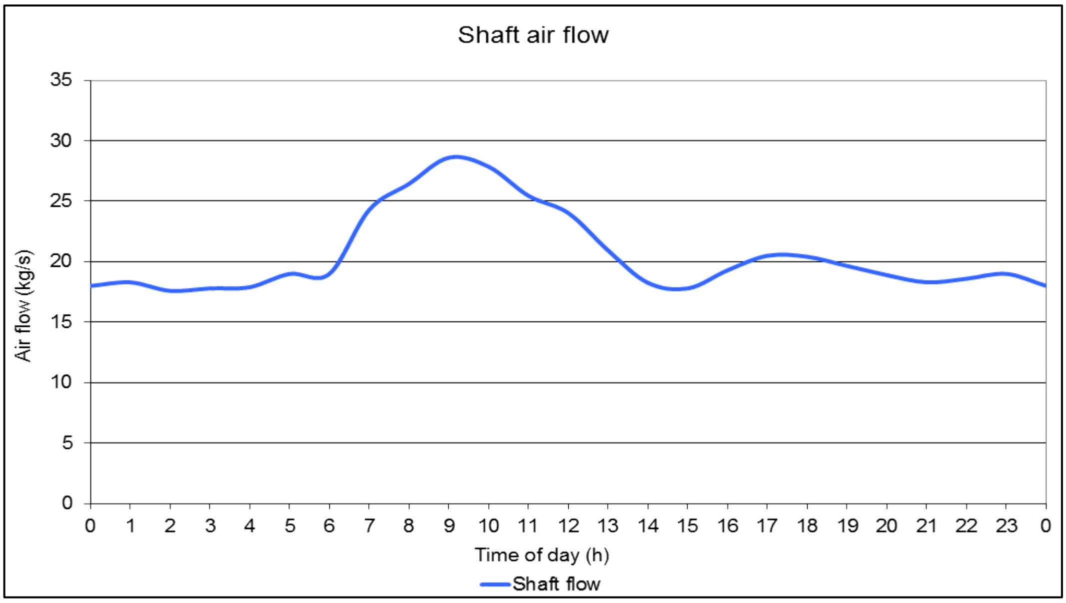

Figure 13: Typical mine air flow demand [35]

The theoretical number of compressors that are necessary to supply the required airflow is shown in Figure 14 [35].

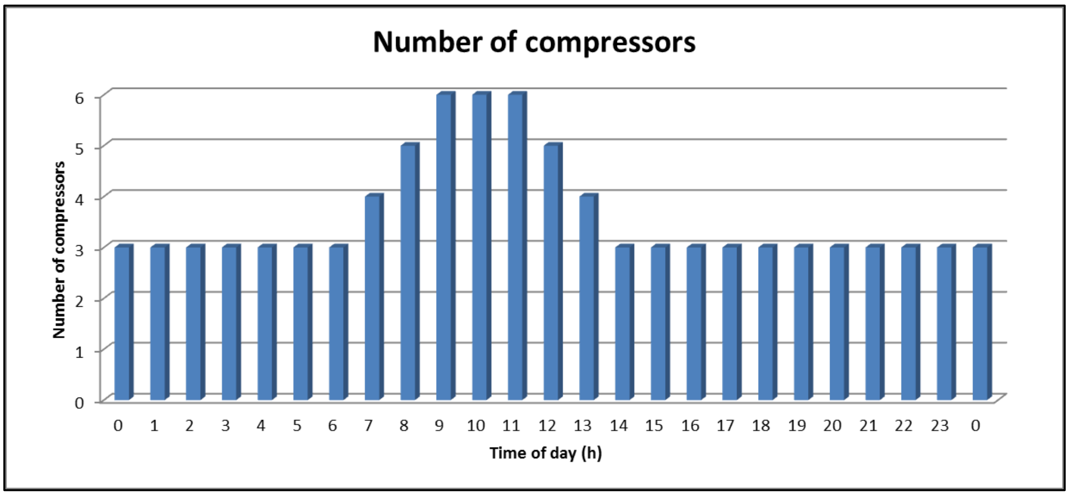

Figure 14: Number of active compressors [35]

Energy savings through supply-side optimisation can be achieved by utilising the compressors, as indicated in Figure 14. However, energy savings that are realised from manual operation of the compressors is not sustainable, as it would be the responsibility of the compressor operators to start and stop the compressors manually when needed. In addition to the possibility of human reference, excessive cycling of compressors increases compressor maintenance and may lead to the mine's notified maximum demand being exceeded [35].

By incorporating guide vane controllers, compressors can be offloaded just before they are shut down [35]. Even though offloaded compressors still consume up to 60% of its installed capacity, compressor offloading remains a viable option to achieve energy savings when shutting down a compressor is not an option.

Through the installation of guide vane controllers, accompanied by a proper control philosophy, Booysen achieved evening peak power savings of 1,25 MW. The energy improvement of 17% that was realised by Booysen's supply side intervention and improved control philosophy yielded an estimated annual electricity cost saving of R 2 750 000 [35].

Simulations can be used to determine the precise compressed air demand, as well as identification of compressors to be utilised and control procedures to be put in place in order to ensure compressed air system energy savings.

2.3.5 Compressed air system demand-side optimisation

The bell-shaped graph that is shown in Figure 13 represents a typical optimised mine compressed air demand profile. If the demand side of a compressed air system is not managed properly, a compressed air flow profile as shown will not necessarily be obtained; instead, a constant high flow will be obtained, as shown in Figure 12. Without proper compressed air demand-side control, the energy savings that are achieved as a result of supply-side management interventions will be limited.

At the majority of mines, prior to employing energy optimisation strategies, compressor setpoints are set equal to the highest required underground pressure demand [**36**]. Compressed air is supplied to all levels at the same pressure. Not all levels have the same pressure requirements, resulting in an unnecessary waste of compressed air and an increase in compressor power consumption. Significant energy savings can be achieved if each mining level is supplied with compressed air that is based on its particular requirements [**19**].

Simulation can be used as a tool to calculate each mining level's specific compressed air demand.

2.3.5.1 Leaks

The majority of South African gold mines are relatively old mines [**29**]. Many undetected compressed air leaks are found in old pipelines, accompanied by poor maintenance [**29**]. Compressed air leaks have been estimated to account for 30% of a compressed air system's compressor output [**31**], [**37**].

Marais *et al*. studied the impact of compressed air leaks on energy consumption [**21**]. It was found that numerous compressed air optimisation projects fail to reach targets as a result of compressed air leaks. Figure 15 indicates the rate at which compressed air, under a constant pressure, would leak out of the compressed air system at varying orifice sizes [**38**].

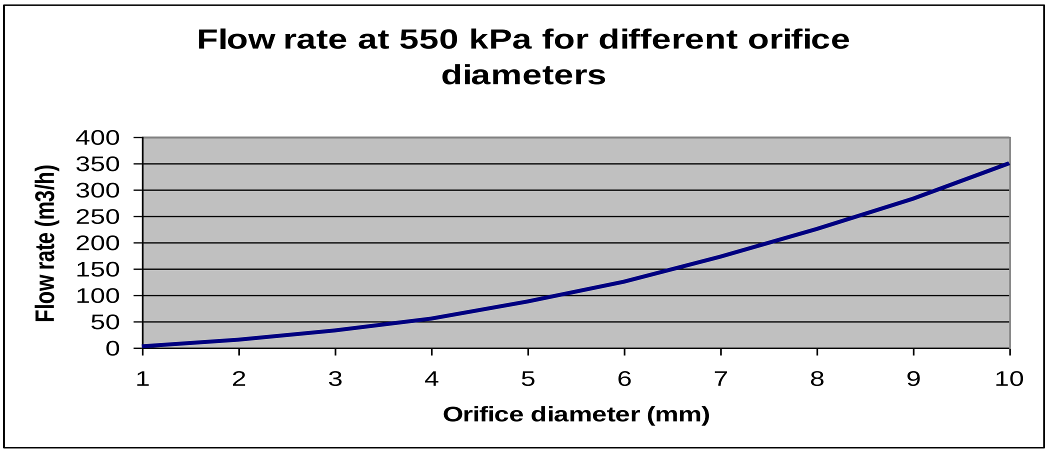

Figure 15: Air flow rate vs. orifice size [38]

The volumetric flow (V_f) rate at which compressed air leaks through an opening can be expressed mathematically in terms of Equation 2 [39]:

$$V_f = \frac{NL \times \frac{(T_i+273)\times P_1}{P_i} \times C_1 \times C_2 \times C_d \times \pi \times \frac{D^2}{4}}{C_3 \times \sqrt{T_1 + 273}} \qquad 2$$

with

- V_f = volumetric flow rate in cubic meters per hour;
- NL = number of air leaks;
- T_i = atmospheric air temperature in degrees centigrade;
- T_1 = line air temperature in degrees centigrade;
- P_1 = line pressure in kilopascal;
- P_i = atmospheric pressure in kilopascal;
- C_1 = isentropic sonic volumetric flow constant (7,3587 m/sK^{0,5});
- C_2 = conversion constant;
- C_d = isentropic coefficient of discharge for square-edged orifices;
- D = leak diameter in millimetres; and
- C_3 = conversion constant.

It is thus clear that the number (NL) and size (D) of leaks have a direct relation to the rate at which compressed air will leak out of a system **[40]**. A five millimetre diameter leak will consume approximately 88 m^3/h of compressed air at 550 kPa **[38]**. Seven kW power is needed additionally to compensate for the air that is lost due to a five millimetre leak **[21]**. In financial terms, such a leak would create a loss of R17 200 per year (based on Mega Flex tariffs) [21].

The most common leaks occur at couplings, hose connectors, tubes and fittings, pressure regulators, shut-off valves and fatigued compressed air pipes [41]. Due to the large number and length of underground passages, many leaks are difficult to detect and therefore remain undetected.

Simulations cannot simulate unknown compressed air leaks, but they can be used to calculate what the ideal compressed air flow rate should be. By comparing the simulated results with actual recorded data, an estimate of compressed air leaks can be made.

Many South African gold mines employ a blasting schedule, called centralised blasting. This entails evacuation of all personnel prior to blasting. In order to exploit Eskom’s TOU tariffs, these blasting periods are scheduled to overlap with Eskom’s evening peak periods. Little to no compressed air is used at the stopes during peak demand periods (18:00 to 20:00); potentially, the entire shaft’s pressure could thus be lowered during these periods by implementing supply-side control [33].

Winders haul skips from the bottom of the shaft to the surface. High-pressure pneumatic loading doors that are situated at the bottom of underground ore silos open and close in order to fill these skips (buckets used to transport the ore vertically form shaft bottom to the surface). The shaft barrel (the vertical space and immediate surroundings wherein the skips operate) needs to be pressurised constantly in order to allow these loading doors to function properly. Compressed air supply-side management alone is, therefore, not a viable option.

2.3.5.2 Valve control

Neser *et al.* have suggested that pressure control valves should be installed on each mining level to throttle the downstream pressure [19]. This will result in an increase in the upstream pressure. Compressed air valve control will not only reduce air leaks, but will also result in the compressor’s guide vane controller adjusting the inlet guide vane angle to reduce the compressor power consumption [42].

Neser implemented level pressure control strategies on three different mines. Specialised control software was used to control the underground compressed air valves according to flow and pressure setpoints. The corresponding energy and annual financial savings are displayed in Table 2 **[19]**.

Table 2: Savings that were achieved as a result of level pressure control [19]

Mine	Daily energy savings (MWh)	Financial savings (R/annum)
Mine A	81,6	R4 080 000
Mine B	9,4	R1 600 000
Mine C	11,5	R2 000 000

Simulation models can be applied to simulate the effect of numerous additions to compressed air networks in order to predict accurately the flow and pressure reductions that can be achieved.

2.4 Simulation software that is used for DSM interventions

Table 3, developed by Vosloo, presents a summary of different water control, as well as management and simulation of software packages, indicating each system's capabilities **[7]** (● indicates a capability).

Table 3: Water control, management and simulation systems [7]

Software capability **Simulation software**	**Pre-Implementation simulation**	**Post-implementation simulation**	**Optimisation**	**Load shifting**	**Energy efficiency**	**Reduce running cost**	**Control**	**Automated operation**	**Monitor**	**Water refrigeration**	**Water pumping**
Motor current monitoring					●				●		●
TASonline			●		●				●		●
Rajan pump performance model					●				●		
A guide to improve energy efficiency			●		●						
Underground pump operator							●		●		●

PLC Programming							●	●		●	●
Adroit							●	●	●	●	●
Wonderware Intouch							●	●	●	●	●
WinCC							●	●	●	●	●
VUMA		●	●	●		●				●	
US Patent No.6366889 by Zalloom		●	●	●		●					●
US Patent No. 6178362 by Woolard *et al*.		●	●	●		●					●
H2ONET Scheduler			●	●		●	●				●
RTP ControlTM by Honeywell Inc.				●		●	●	●			
SA Patent No. 2004/1172 by Temm Int (Pty) Ltd.				●			●		●		●
Real-time Energy Management System (REMS) for Pumps		●	●	●		●	●	●	●		●
Real-time Energy Management System (REMS) for Fridge Plants		●	●	●		●	●	●	●	●	

Based on the criteria that are listed in Table 3, Real-time Energy Management System (REMS) for Pumps is the most advanced water control, management and simulation software system. REMS for Pumps is able to simulate water flow, optimise water networks, assist and automatically perform a load shift, reduce running cost, control water systems, automate operations and monitor water systems.

However, REMS for Pumps does not have a built-in modelling capability to simulate energy efficiency interventions that are implemented on the dewatering systems. It further lacks the capability to model interaction with other systems (that is, other than water pumping systems).

As an update for REMS for Pumps, REMS for Water Supply Optimisation (WSO) has been developed. REMS for WSO includes all the features of REMS for Pumps and, in addition, includes the functionality to manage energy efficiency strategies.

The aforementioned control systems can be used to simulate (or control or both if the capability is provided) energy saving initiatives that have already been implemented. None of these systems can predict the effect of system design changes that are external to the simulated system. The REMS software collects data from installed infrastructure and, by using the system's control setpoints, manipulates and controls the system in order to obtain

TOU energy savings. Although REMS for WSO has the functionality to simulate implemented systems retrospectively, it is not able to predict the influence of system changes on an existing water system. REMS is merely a set of control rules that utilises installed instrumentation in order to control the specific system within its control boundaries, which are preprogrammed.

In many cases, however, water valves are used to throttle water flow that is delivered to mining sections. A valve's specific flow coefficient (CV) severely effects the downstream flow and pressure of water flowing in a pipe [43]. The aforementioned control software does not have the built-in functionality to predict flow and pressure losses that occur as a result of the addition of valves to the existing infrastructure.

KYPipe's steady state software package incorporates the solving of steady state problems [44]. Pumps, junctions, variable pressure supply, regulators, active valves, turbines, on/off valves and different meters can be included in plant simulation models [44]. KYPipe can be used to perform pre-implementation simulations in conjunction with REMS for control purposes.

In addition to REMS for WSO and REMS for Pumps, REMS for OAN (Optimisation of Air Networks), REMS for CM (Compressor Manager) and REMS for DCS (Dynamic Compressor Selection) have been developed [36]. These software packages have capabilities that are similar to REMS for WSO and Pumps, except that REMS for OAN and REMS for DCS are used to realise energy efficiency savings and REMS for CM is used to realise peak clip energy savings on compressed air systems. Both REMS for OAN and CM are static monitor and control systems with built-in, preprogrammed PID controllers. REMS for DCS has a built-in processing capability that enables it to receive data, analyse the received data and make active control decisions that are based on the actual received data. Similar to REMS, KYPipe has a steady state, one-dimensional, isothermal flow simulation package for ideal and non-ideal variable density gasses.

KYPipe was chosen as a simulation package to perform various pre-implementation as well as post-implementation simulations for this study. It is a relatively inexpensive and far less complicated alternative to software such as Flownex and is a validated and verified simulation package [45] [46]. KYPipe can be used in conjunction with in-house-designed REMS software to simulate and control implemented DSM projects. Table 4 presents a summary of the software which have been used to simulate and control DSM projects that were discussed in this study.

Table 4: Summary of simulation software

Software capability **Simulation software**	**Pre-implementation simulation**	**Post-implementation simulation**	**Optimisation**	**Load shifting**	**Energy efficiency**	**Peak clipping**	**Reduce running cost**	**Control**	**Automated operation**	**Compressed air**	**Water pumping**
KYPipe	●	●	●		●					●	●
REMS for DCS		●	●		●	●	●	●	●	●	
REMS for OAN		●	●		●	●	●	●	●		●
REMS for CM		●				●	●	●	●	●	
REMS for WSO		●	●	●	●	●	●	●	●	●	

A pre-implementation simulation is defined as a simulation model that simulates and predicts a system’s behaviour prior to the design and installation of such a system; simulations are completed prior to commencement of any site-specific planning or plant modifications or both.

2.5 Conclusion

In this chapter, various strategies to achieve energy savings on mine dewatering and compressed air systems have been discussed. Based on a literature survey of mine DSM projects, it has been indicated that simulations were not sufficiently used prior to project planning and implementation.

Simulation models can be employed to explore the additional energy saving potential, based on improved control of valves, pumps and compressors for improved supply and demand management. When planning to implement DSM projects, a complex plant layout and the influence of pipe diameter, length and roughness on compressed air system design can be simulated, resulting in optimised energy saving interventions. The influence of auto-compression, valve choice, pipe network layout and so forth can be simulated, and the results can be used and implemented in actual systems to optimise energy saving potential.

Simulation models can also assist in the determination of leaks in pipe systems: Although the modelling or accurate measurement of leaks in dewatering and compressed air systems is difficult, the ideal pressure and flow can be attained by assuming that no leaks can be simulated. The difference in the simulated and measured values can be attributed to leaks. This can be a valuable indication to plant managers.

If simulations were developed prior to or in conjunction with the implementation of the DSM projects, more funds could have been available to implement the proposed projects, more clients could have reaped the benefit of electricity cost savings and Eskom could also have benefited from the reduced load on its electricity distribution system.

Simulation models are ideal tools to explore the energy saving potential of different plant design configurations as well as supply and demand control strategies. These simulations can circumvent expensive trial and error interventions that are based on an incomplete understanding of plant design.

3 Simulation software and simulation methodology

3.1 KYPipe's gas simulation engine

3.1.1 Introduction

The user interface, as well as the methods that are used to calculate variables of the gas and water systems of KYPipe, is similar. Mathematical equations that are used to iterate and calculate the unknown variables of gas and water systems are different, since water is considered to be an incompressible fluid. Because of the generic similarities, only the gas simulation engine for KYPipe will be discussed.

3.1.2 KYPipe's gas simulation engine

KYPipe's gas simulation engine (GAS) consists of various built-in functions that are capable of analysing large and complex pipe networks by calculating the flow and pressure distribution of a pipe network. Unless the user specifies temperature variations, isothermal flow is assumed [47].

Within GAS, an on-scale simulation model can be developed that represents the compressed air network. The simulations include a description of the network configuration, including pipe length, diameter, roughness, elevation change of lines, location of demands or inflow points, and the location of compressors, valves and other fittings [47].

In this study, GAS is primarily used to determine the effect of demand and load changes on the overall operation of compressed air networks. In most cases, the values for pipe roughness are unknown [47].

The simulation needs to characterise the actual system; it is thus necessary to describe elements that are used in the simulation model. Different geometric features are used within the simulation environment. Of these features, the main geometric feature is constant diameter pipe section. Different pipe sections can be specified to have different diameters within the same network. Fittings such as bends, valves and compressors that are found in compressed air systems can be added to a pipe network. The end point of a pipe section is referred to as either a junction node or a fixed pressure node [47].

A junction node is the point where two or more pipes are joined, or where flow is removed or supplied to the system. A junction node also refers to the point in the system where a pipe diameter is changed, or to a component, such as a valve or a compressor, as demonstrated by the green arrows in Figure 16 [47].

A fixed pressure node refers to a node in the system where the pressure is known. This is usually a connection to a storage tank, reservoir or source of specified pressure. The red arrows in Figure 16 point towards fixed pressure nodes. Only one compressor can be added to a compressed air network in GAS. In systems where more than one compressor is used, a constant pressure source with a fixed compressed air delivery rate is used. Equation 1 is used to calculate the compressor power.

To simulate and solve the complex mathematical equations that are used to describe the simulation, GAS requires the appropriate data for at least one fixed pressure node [47].

In addition to the pipes and nodes, a primary loop is defined as a pipe circuit that contains closed pipe circuits [47]. The black and orange pipe section in Figure 16 represents a primary loop.

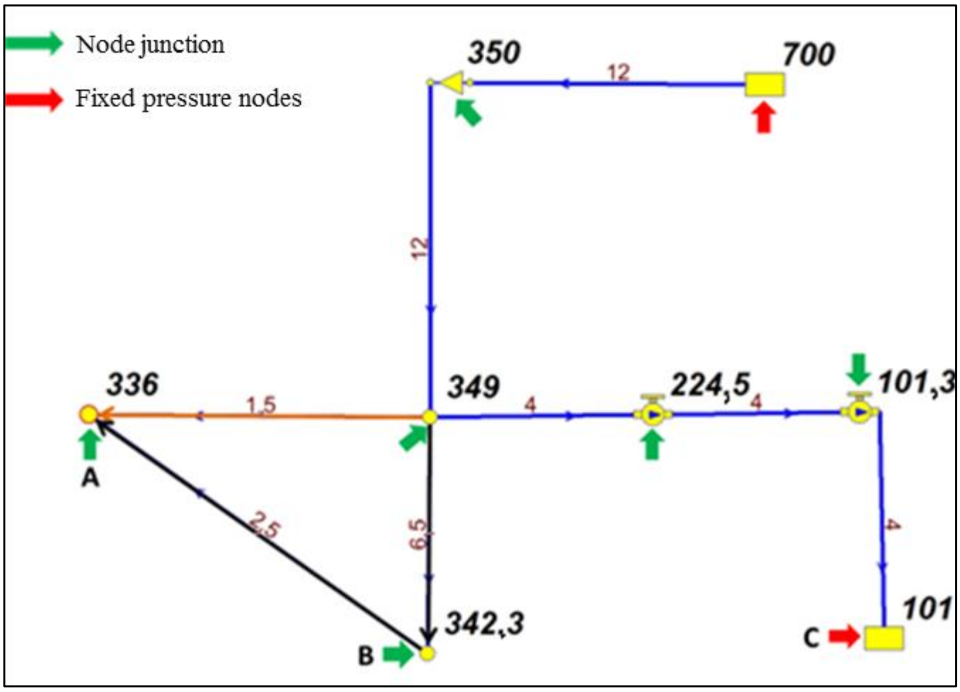

Figure 16: GAS simplified layout

Using these definitions for a junction, fixed pressure node and primary loop, and with reference to Figure 16, any number of pipe sections, nodes and fixed pressure nodes can be defined in terms of Equation 3 [**47**]:

$$p = j + l + f - 1 \qquad 3$$

with

- p = number of pipe sections (8);
- j = number of junction nodes (6);
- l = number of primary loops (1); and
- f = number of fixed pressure nodes (2).

The nodes, pipe section numbers and fixed pressure node labels are automatically assigned as the system is modelled in the GAS environment. These equations are then solved in order to compile a list of pressure and flow results.

In GAS, the total pipe length, inside diameter and pipe roughness of each pipe section are required and have to be entered by the user. These three parameters have a crucial effect on the pressure losses when compressed air is transported through a pipeline.

Equation 4 presents the general flow equation for the steady-state isothermal flow of gas in a pipeline [**48**]. The equation is based on the flow of air through a pipe section, as shown in Figure 17. Air will pass through the pipe from point 1 to point 2 in Figure 17. The flow rate at which air passes through the system (Q) is expressed in Equation 4 [**48**]:

$$Q = 1.1494 \times 10^{-3} \left(\frac{T_b}{P_b}\right) \left[\frac{\left({P_1}^2 - {P_2}^2\right)}{G T_f L Z f}\right]^{0.5} D^{2.5} \qquad 4$$

with

- Q = gas flow rate measured at standard conditions (m^3/day);
- f = friction factor;
- P_b = base pressure (kPa);
- T_b = base temperature (K);

- P_1 = upstream pressure (kPa);
- P_2 = downstream pressure (kPa);
- G = gas specific gravity (for air = 1);
- T_f = average gas flowing temperature;
- L = pipe segment length (km);
- Z = gas compressibility factor; and
- D = pipe inside diameter (mm).

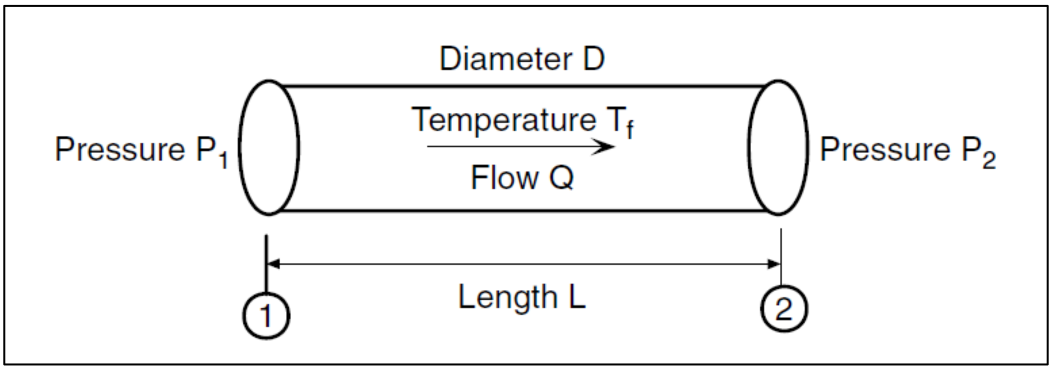

Figure 17: Steady one-dimensional flow in a gas pipeline [48]

In GAS, air flow at the end node will either be set by the user or a forced flow will be calculated as a result of the difference at the fixed pressure nodes. Either P_1 or P_2, as well as the base temperature and pressure, will be supplied by the user as an input to the simulation. The base temperature and pressure are usually taken as the atmospheric pressure and the compressor delivery temperature [50] (101 kPa and 308,75 K respectively).

In the case of mine compressed air systems, it is assumed that the temperature of the gas that is flowing in the pipeline will stay constant. It can thus be assumed that G, being 1 for air, and Z, the gas compressibility factor, will not change, as both are dependent on the temperature. The only unknown variables in Equation 4 are the length of the pipe sections (L) and the friction factor.

The friction factor, also called the Darcy Friction factor [50], is a function of the Reynolds number. The Reynolds number is used to characterise whether the flow in the pipe is laminar, turbulent or critical. The Reynolds number equation [50] is as follows:

$$Re = \frac{uD\rho}{\mu} \qquad 5$$

with

- Re = Reynolds number;
- u = average velocity in the pipe (m/s);
- D = inside diameter of the pipe (m);
- ρ = gas density (kg/m^3); and
- μ = gas viscosity (kg/m-s).

Different relations between the friction factor and the Reynolds number exist, based on the flow type. For laminar flow, the Reynolds number must be equal to or smaller than 2 000; for turbulent flow, the Reynolds number must be greater than 4 000, with critical flow in-between. It is assumed that, for mine compressed air systems, the flow in pipelines will be turbulent [**50**].

Turbulent flows in pipes can be subdivided into three regions: turbulent flow in smooth pipes, turbulent flow in fully rough pipes, and transition flow between the smooth and rough pipes. The friction factor is only dependent on the Reynolds number when smooth pipes are used. When fully rough pipes are used, the internal pipe roughness has a larger influence on the friction factor than the Reynolds number. For transition flow between smooth and rough pipes, as found in mine compressed air systems, the friction factor is dependent on the Reynolds number, pipe roughness and the pipe inside diameter [**50**].

The Colebrook-White equation defines the relationship between the friction factor, Reynolds number, pipe roughness and inside diameter of a pipe. This equation is used to calculate the friction factor in gas pipelines with turbulent flow [**50**]:

$$\frac{1}{\sqrt{f}} = -2Log_{10}\left(\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \qquad 6$$

with

- f = dimensionless friction factor;

- D = inside diameter of the pipe (mm);
- e = absolute pipe roughness (mm); and
- Re = Reynolds number.

The relative roughness of a pipe is the ratio between the absolute pipe roughness and the inside diameter of a pipe $\left(\frac{e}{D}\right)$ [50].

When modelling DSM projects, it is evident from the above equations that pipe diameter, length and roughness have a large influence on the accuracy of a simulation, as shown in the mass flow of each pipe (indicated in red) in Figure 16. Each pipe section between the nodes in Figure 16 has the same length. Nodes A, B and C have the same compressed air demand. The pipe section that is indicated in orange, however, has an inside diameter of 350 mm and the rest of the pipe sections have inside diameters of 500 mm. As a result of the smaller inside diameter, the friction factor is too high and air is transported through point B, the pipe sections with a larger pipe diameter and a lower pipe friction.

According to Garbers *et al.* [51], 'auto–compression' is the term which is used when referring to air that is compressed by its own weight. The pressure of the air (P) can be expressed in terms of air gravitational acceleration (g) and a reference height (H), as shown in Equation 7 [52]:

$$P = P_0 \times (\frac{HL}{T_o + 1})^{\frac{-LR}{g}} \qquad 7$$

with

- P_0 = atmospheric pressure (Pa);
- T_o = atmospheric temperature (K);
- L = lapse rate of air (K/m);
- g = gravitational acceleration (m/s^2);
- R = gas constant for air (J/kg K); and
- H = reference height (m).

Pipe friction is proportional to the square of the air velocity within the pipe. A too high air velocity may result in a sudden and large pressure drop [51].

The beneficial effect of auto-compression on vertical pipes is never lost. However, the friction losses in pipes could exceed the additional pressure that was obtained from auto–compression, resulting in lowered pressures at production levels [51]. As a result of the lowered pressure, workers who are drilling at the rock-face will need to spend more time to complete work when inadequate pressure is supplied [51].

Table 5 shows the average drill times in relation to the pressure that is supplied to the pneumatic drills that are used for drilling in these specific cases[51]:

Table 5: Drill time, compared to supply pressure [51]

Drill time for a Seco 215 pneumatic drill			
Pressure	350 kPa	450 kPa	550 kPa
Drill time	0,18 m/min	0,28 m/min	0,64 m/min
40 holes (1,8 m)	6,6 hours	4,28 hours	1,88 hours

In order to mitigate pressure-related problems, especially when a loss of auto-compression occurs, the surface pressure will have to be increased. An increase in surface pressure will result in higher power consumption. The effect of auto-compression and losses as a result of air flow can be simulated by using GAS [51].

3.2 Verification and validation process that has been followed in this study

3.2.1 Introduction

KYPipe is a validated and verified simulation package [45] [46]. The process which has been followed to validate and verify simulations that were developed in KYPipe is illustrated through an application in this section. A similar validation and verification process has been followed to prove the validity and accuracy of KYPipe's water engine. For demonstration purposes, only the gas validation process is presented.

This case study has been performed on a well instrumented, compressed air network, allowing a comparison of theoretical/simulated data with measured data.

3.2.2 Specifications that are needed in order to develop a simulation

Various constraints and parameters have to be considered when developing accurate simulations. Some of these constraints include the following:

- Accurate verified simulations with the applicable capabilities (as demonstrated in Table 3);
- accurate design configuration data at DSM implementation sites;
- accurate assumptions;
- sufficient knowledge of the system where DSM projects are proposed to be implemented;
- the ability to identify various alternative strategies and to simulate the alternatives with reasonable accuracy;
- external factors that have an influence on the simulation model, like unscheduled production changes; and
- sufficient communication with site personnel in order to obtain relevant knowledge of the actual system in cases where documentation is incomplete.

3.2.3 Application: System background

Mine A is a platinum mine with 10 shafts of which all but one shaft are supplied with compressed air from seven different compressor houses. As mining activity at mine A gradually increased, the pipe network was expanded without keeping growth in future demand in mind. Consequently, newly developed shafts were not supplied with compressed air at the required flow rate and pressure.

Engineers at mine A planned to install a new compressor closer to the main production shafts in order to increase the delivery pressure. To circumvent compressed air friction losses that are associated with long pipes, the engineers planned to install a new compressor closer to the production shafts, allowing the shutdown of remote compressors. Three adequate sites for the installation of the compressor were identified, based on the availability of existing infrastructure to accommodate additional compressors. By doing this, it was hoped that energy savings would be achieved and pressure delivery at the production shafts would be increased.

A simulation was developed to analyse the energy saving potential of the planned plant design changes. This was done not only to determine the most feasible location for the mine's proposed new compressor, but also to evaluate the financial benefits and possible rebates from Eskom through their DSM mechanism, thereby determining the techno-economic feasibility of the proposed solution.

3.2.4 Simulation model setup and verification

Information regarding the pipe network was obtained from mine personnel. Relevant data of the mine's compressed air pipeline was captured, including intersections, bends, pipe lengths, pipe diameters and GPS co-ordinates. This information was used to plot the compressed air pipe network on Google Earth™. A satellite view of the plotted pipeline is shown in Figure 18:

Figure 18: Satellite view of compressed air pipe network

A simplified simulation model, including all the variables, was developed from the pipe network that was plotted on the satellite picture. All parameters of the compressed air reticulation system were taken into consideration.

The following simulation assumptions are applicable to this simulation model:

- Pipe reference roughness is assumed to be 4,5 µm, as derived from the Engineering ToolBox for commercial steel pipes [53];
- the average compressed air temperature within the pipes is 30 °C;

- the pipe lengths are assumed to be equal to the measurable lengths of the pipes, derived graphically by using satellite images (Google Earth™); and
- the number of bends within the compressed air pipelines was determined by following the plotted pipe networks on the satellite images.

Data from the mine's Supervisory Control and Data Acquisition (SCADA) system was used to compile a 24-hour weekday baseline. Given the fact that KYPipe can only solve static problems, the simulation model was verified for low-, medium- and high-demand scenarios. In a typical mine production day, the compressed air demand is

- low at 17:00;
- medium at 02:00; and
- high at 12:00.

Data for each demand scenario from the SCADA included

- power consumption for each compressor;
- delivery pressure setpoints of each compressor;
- compressor compressed air delivery;
- compressed air flow at each shaft; and
- compressed air pressure at each shaft.

The accuracy of the simulation of the compressed air that was delivered to each reference point in the simulation was verified by comparing simulation results to the actual data during a low-flow scenario: During a low-flow scenario, flow losses are limited, as the system is designed for high flow. If the pressure or flow of a certain node within the simulation model did not correspond with the recorded data, the simulation model was adapted by adding or removing simulated compressed air losses due to pipe friction, bends, CV of valves and so forth. The complete simulation model is shown in Figure 19:

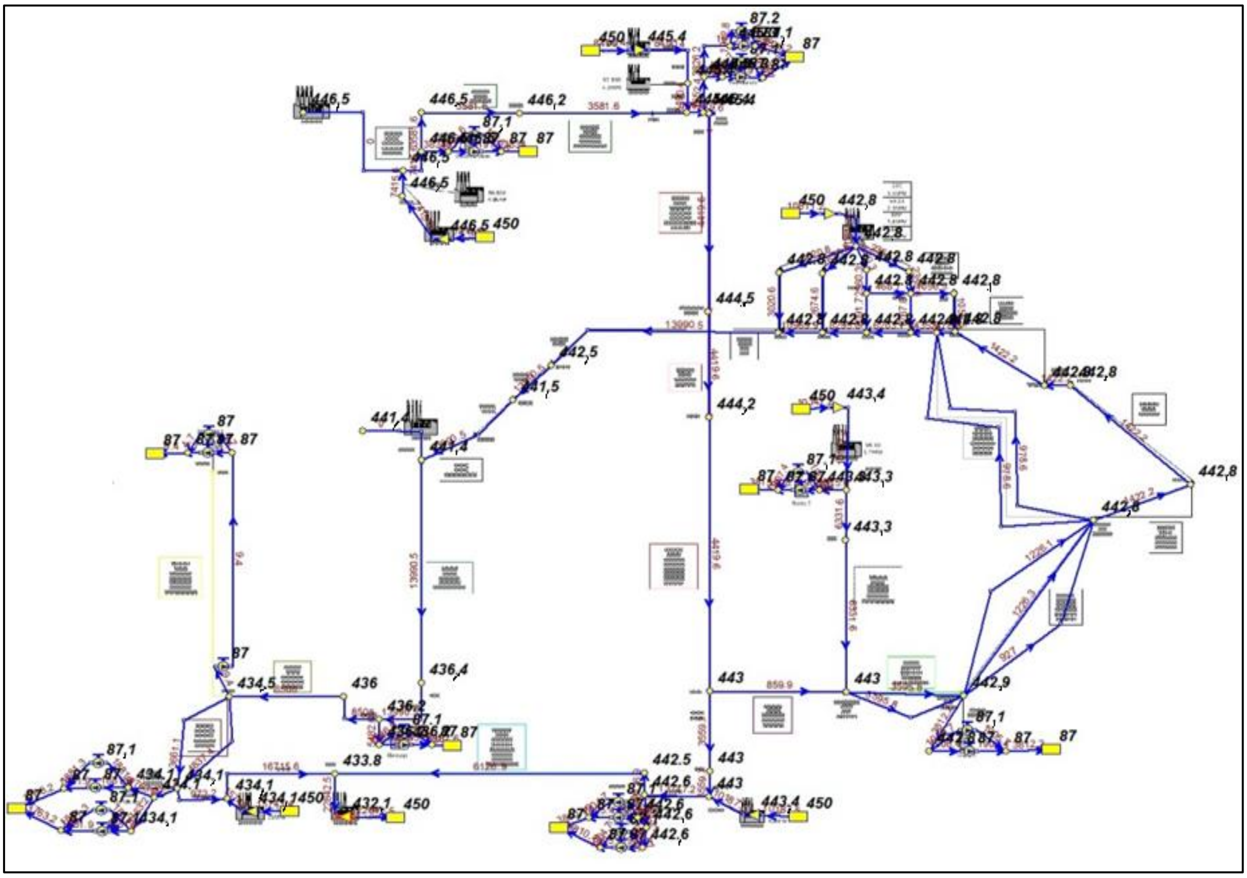

Figure 19: GAS – verified simulation model

3.2.5 Verification of the simulation model

The results obtained from the simulation were compared to data from the SCADA. The comparisons between the simulation's low-, medium- and high-demand values and the actual data at critical shafts are shown in Table 6:

Table 6: Compressor placement results

Simulation results	**High-flow shaft pressure (kPa)**			**Medium-flow shaft pressure (kPa)**			**Low-flow shaft pressure (kPa)**		
Shafts	Actual	Simulated	Difference	Actual	Simulated	Difference	Actual	Simulated	Difference
Shaft A 1	499	530	6%	554	526	-5%	497	496	0%
Shaft B 1	468	482	3%	486	472	-3%	453	462	2%
Shaft B 2	474	467	-1%	503	468	-7%	460	460	0%
Shaft C 1	480	520	8%	522	527	1%	474	518	8%
Shaft C 2	456	531	14%	568	545	-4%	554	518	-6%
Shaft D 1	484	517	6%	524	500	-5%	475	481	1%
Average difference %			6%			-4%			3%

The simulated results for the low-flow scenario fell within 3% of the measured data. The difference between the actual and simulated results can be attributed to

- incorrect data from the actual system instrumentation due to inter alia calibration errors;
- simulation data assumptions, such as pipe roughness – many of the compressed air pipes that are used in the actual system are old. The reference roughness of pipes could be greater than the assumed reference roughness values, which are based on aging steel pipes; and
- inaccuracies in simulating pipe geometry – the simulation model is based on the graphical representation of satellite images.

3.2.6 Application: Simulation outcome

The unexpected large difference in the measured and simulated pressures during the high-flow simulation, especially at shafts C_1 and C_2, led to an investigation into the cause of the measured pressure drop. A flow restriction between the compressors and the delivery points was found to be the cause of the pressure drop: three pipes with the same diameter were joined into a section with the diameter of only one pipe. The pressure drop only manifested as a result of the higher flow demand of the new shafts. Removal of this bottleneck, which was a relatively inexpensive exercise (the approximate cost was R60 000), circumvented the purchase and installation of a new compressor which had been estimated to cost in excess of R20 million.

3.3 Conclusion

In this case study, a comprehensive, complex compressed air network was simulated. The value of simulation was demonstrated by simulating the planned DSM interventions. A design/constriction error manifested when flow demand increased as a result of the extended mining operations. The use of simulations led to the identification of the design/construction error and circumvented the unnecessary expenditure of R20 million.

4 Simulation modelling for DSM project design corrections and planning

4.1 Introduction

DSM projects that are implemented without using simulation models are often characterised by technical problems, resulting in project delays or failure to comply with contractual targets or both, as will be demonstrated in this chapter. The first two case studies in the chapter will demonstrate the value of simulation by using it as a tool to rectify DSM projects during various stages of implementation.

In the last two case studies, the value of simulation will be demonstrated by using it as a tool to plan an entire project prior to project implementation. It will be demonstrated that simulations will not only be valuable when equipment is specified, but also when project techno-economic feasibility is assessed.

4.2 Case study one – Design optimisation to achieve energy savings in a compressed air network

4.2.1 Introduction

A surface compressed air pipeline of more than 40 km supplies compressed air throughout the network. Compressors that are located throughout the network operate at the same pressure setpoint. Mine A and mine B are connected on level 70 and 76 by underground compressed air pipes, as shown in Figure 20:

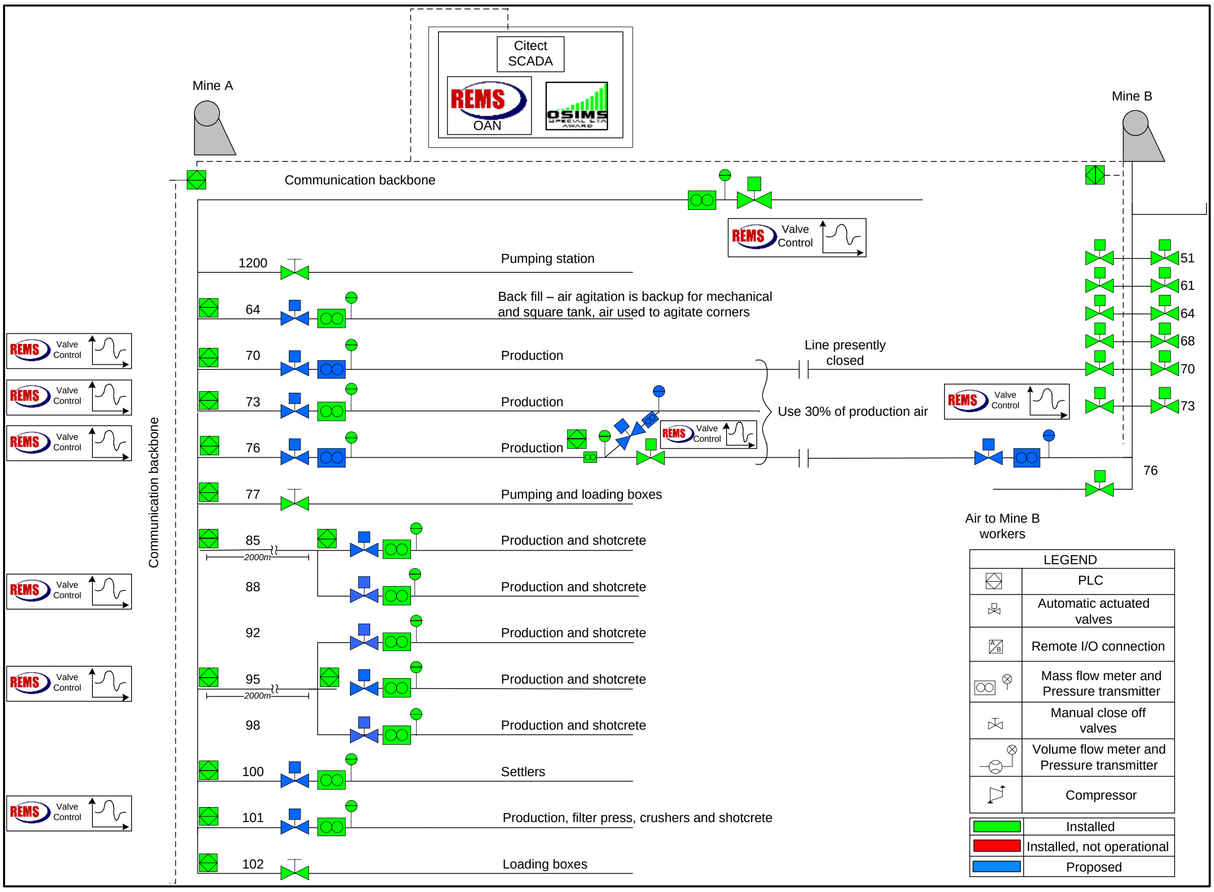

Figure 20: Control and hardware installation at mine A and mine B

4.2.2 Problem statement

Production at mine A increased after a production section of a nearby mine had been reallocated to be accessed from mine A, resulting in a significant increase of compressed air demand at mine A during the drilling shift between 06:00 and 14:00, as indicated with the blue line in Figure 21. With increased demand, the delivery pressure fell to below the acceptable level of 480 kPa. In Figure 20, equipment (highlighted in green) indicates the original design of the compressed air system.

Whenever the compressed air flow exceeded 24 kg/s, the delivery pressure at the rock-face was too low to sustain normal mining operations. The flow rate at mine A only exceeded 24 kg/s during mine A’s peak production period, as indicated with the red line in Figure 21.

In order to compensate for mine A’s pressure supply problem, the setpoints of all compressors in the network had to be increased during mine A’s peak drilling period, resulting in higher compressor power consumption.

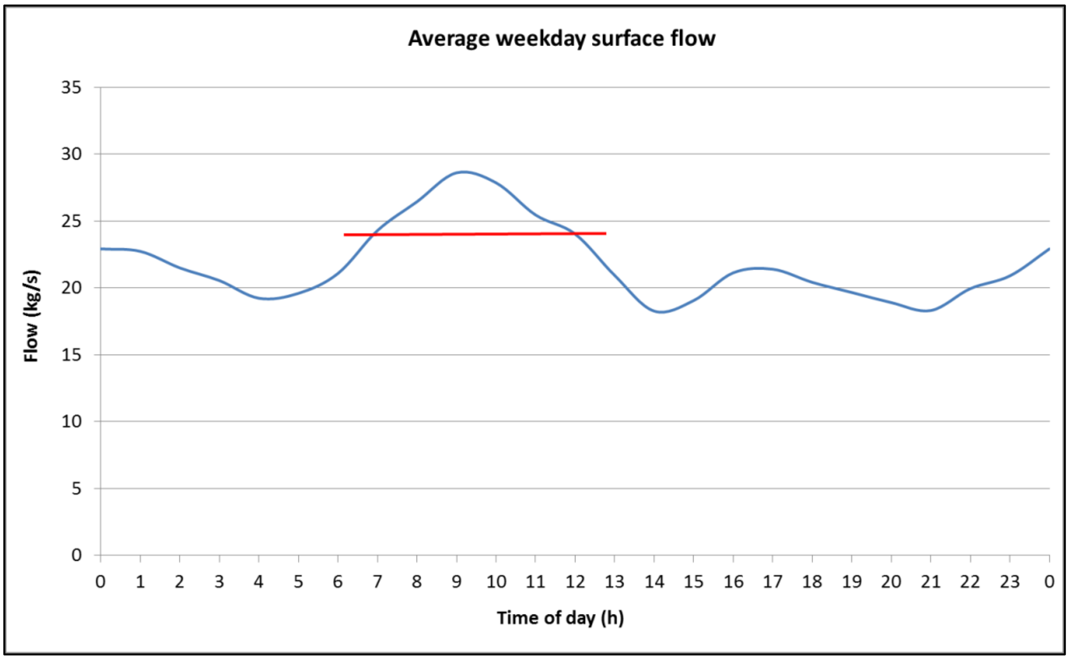

Figure 21: Average weekday surface flow

4.2.3 Initial solution

Prior to the study, Eskom approved two energy optimisation projects on this compressed air network. The first project included retrofitting of mechanical guide vanes on the existing compressors. An average peak clip power saving of 12,7 MW was achieved as a result of the implemented project. REMS for CM was used as control system after the implementation of the first project. The second project was aimed at lowering the network’s overall power consumption by 2,2 MW. REMS for OAN was used as control system during the implementation of the second project. However, the project did not reach the contractual power saving target.

No simulations were used in either of the two projects to estimate the potential savings. The expected energy saving was based on a basic Excel flow and pressure calculation: The actual pressure that was delivered to each level was compared to the delivery setpoint on each level. A percentage oversupply was then calculated and used to calculate flow savings. The resultant flow and pressure reductions were intended to result in compressor power savings. The values in Table 7 illustrate the technique:

Table 7: Project energy savings

	Baseline				**Optimised 95 level kPa**			**Optimised 85 level**		
Time of day	Flow at 95 level in kg/s	Pressure at 95 level in kPa	Flow at 85 level in kg/s	Pressure at 85 level in kPa	Pressure set point (kPa)	Actual pressure % above set point	Flow saving (kg/s)	Pressure set point (kPa)	Actual pressure % above set point	Flow saving (kg/s)
12:00	8,1	568,5	2,1	558,5	520,0	9%	0,7	520,0	7%	0,2
13:00	7,2	677,1	2,2	661,1	520,0	23%	1,7	520,0	27%	0,6
Average	8,0	622,5	3,5	609,0	487,5	20%	1,5	487,5	25%	0,7

Based on the calculations (using Equation 1), a power saving of 2,2 MW was expected. The implemented project, however, only managed to save 1,3 MW.

It was proposed that the equipment (highlighted in blue) in Figure 20 should be installed as part of the scope of the second DSM project. The old valves had a limited control range and had to be serviced regularly. New 100 mm valves were specified and bought as part of the control redesign; they had improved reliability. However, after installation of the valves, the pressure at mining levels was found to be too low to sustain mining operations. Based on their own calculations, mine personnel concluded that these valves were too small.

4.2.4 Proposed solution

In section 2.3.2, the influence of pressure and flow on the compressor power was discussed (refer to Equation 1). The compressor power consumption would be lowered if either the system pressure is lowered or the compressed air demand is lowered (a reduction in flow rate), or both are lowered.

In order to lower compressor setpoints, an attempt was made to lower the compressed air flow on the mining levels by installing control valves. Because the procured 100 mm control valves were too small, it was proposed that these valves should be placed in a parallel configuration with larger open/close valves. With both old and new valves being placed in an open position, enough compressed air would hypothetically be delivered to the mining equipment without adversely lowering the delivery pressure.

Compressed air connections on levels 70 and 76 between mine A and mine B had been closed in the past. By reopening these connections, air could hypothetically be exported from mine B to mine A. This would allow less air to be supplied through the compressed air pipeline of mine A to mine A’s mining levels. Less flow losses would occur and the compressor’s pressure set point could be lowered.

In 2008, as a consequence of the decision to suspend access to large production sections of mine B and to allow access from nearby shafts, production at mine B decreased by 28%. This resulted in the decrease of compressed air demand to 23 kg/s. By analysing data that was acquired by using the REMS systems, it was concluded that it was feasible to export compressed air from mine B to mine A if the compressed air flow rate at mine B did not exceed 33 kg/s.

4.2.5 Simulation setup

The layout of each mining level was obtained from drawings that were supplied by mine personnel. As discussed in Chapter 3, the simulation assumptions, as well as the verification and validation process, were followed.

The simulation model was developed in order to characterise the actual mine compressed air system. The rationale was to reduce air flow through mine A by importing air from mine B without exceeding the allowable air flow rate. The proposed design changes are discussed below and are shown in Figure 22:

A. The parallel valve configuration on each level was included in the simulation model in order to enhance controllability.
B. The pipe sections between mine A and mine B were simulated to be open in order to import air from mine A to mine B.
C. Two control valves were placed in the pipelines between mine A and mine B in order to control the flow actively.
D. During peak drilling periods, the surface compressed air pressure was lowered from 570 kPA to 540 kPa in order to achieve power savings.
E. All other control valves at mine A were placed in a fully open position due to the reported unreliability of the valves.
F. A pipe section between levels 76 and 85 at mine A was added in order to supply compressed air to level 85 from mine B. This would reduce the amount of compressed air flowing through mine A.

G. The flow on level 70 from mine B was throttled to deliver only 0,8 kg/s compressed air to mine A. Mine A subsequently delivered 1,7 kg/s compressed air to the mining sections on level 70. The sum of the air flow of G and H may not surpass 10 kg/s in order not to surpass mine B's maximum allowable air flow rate.

H. 8,7 kg/s compressed air was supplied to level 76 from mine B, of which 3,6 kg/s was supplied to level 85. Compressed air was not supplied to levels 76, 73 or 85 from mine A.

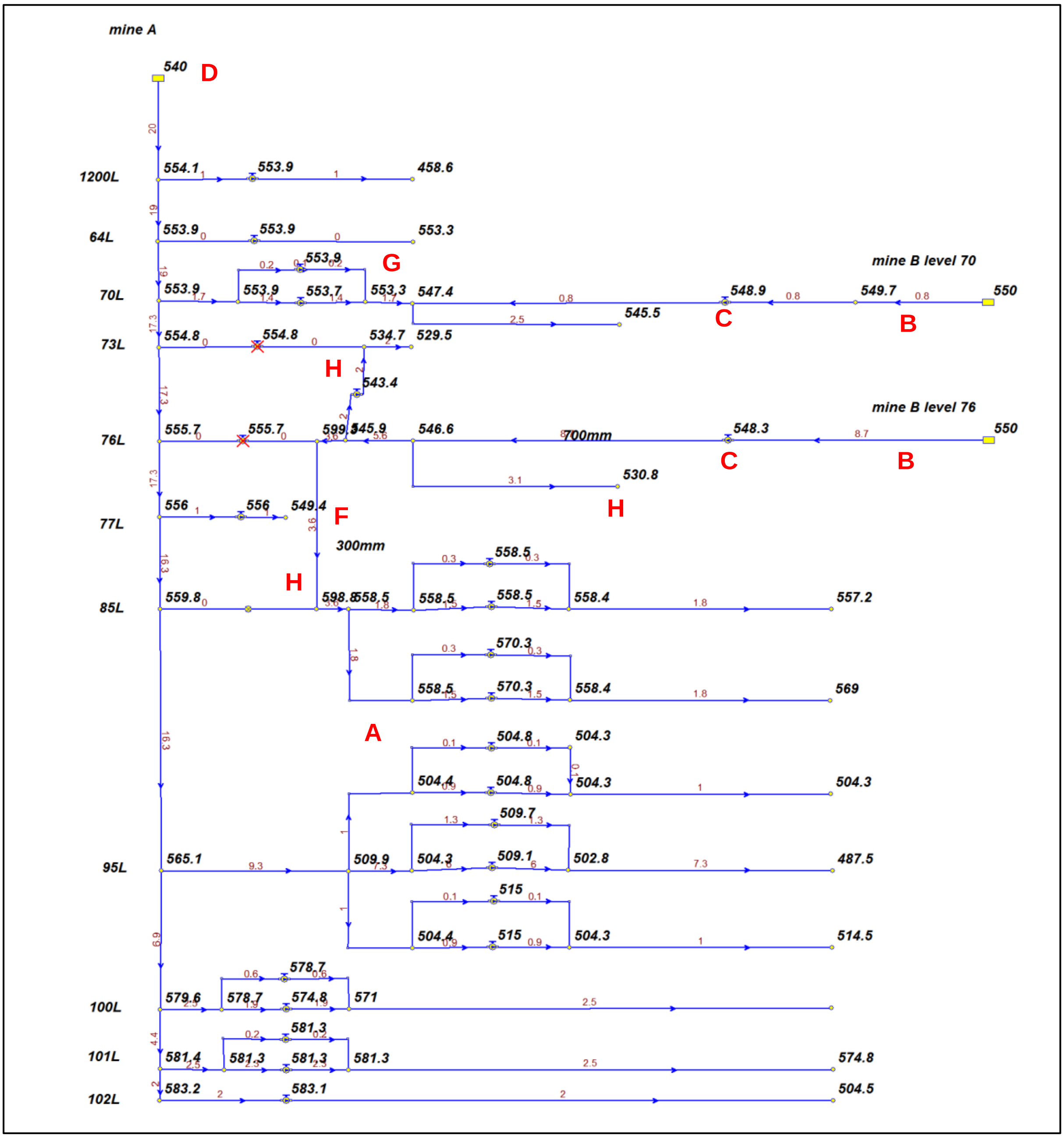

Figure 22: Final simulation – Import air from mine B

From the results of the simulation, it could be established that the reduction in the compressed air flow rate at mine A resulted in a reduction in pressure losses.

4.2.6 Design change results

By installing the proposed valve configuration and by importing air from mine B, less air had to be supplied by mine A to mine A’s mining levels. With mine A’s compressed air flow rate reduced to lower than 24 kg/s, the compressor’s set point could be lowered from 570 kPa to 540 kPa.

In the initial project, only 1,3 MW power saving was achieved. Through implementing the propositions as simulated above, an additional power saving of 2,2 MW was achieved, resulting in a total power saving of 3,5 MW. Figure 23 illustrates the power savings that were achieved through the different steps of the implemented project:

A. Project commencement with an average power consumption of 30 MW.
B. Continued project implementation.
C. Installation of initial 100 mm control valves.
D. Removal of valves by mine personnel.
E. Installation of parallel valve configuration; compressed air is still not imported from mine B.
F. Air is imported from mine B, but the additional pipework between levels 76 and 85 is not completed.
G. Continuation of pipework between level 76 and level 85.
H. Air is imported from mine A, with the additional pipework completed as demonstrated in the simulation. After the implemented solution, the average power consumption is approximately 25 MW.

In Figure 23, the red curve indicates the power baseline, which is defined as the average of three months’ power baselines and which is a contractual requirement to be used in subsequent power savings verification.

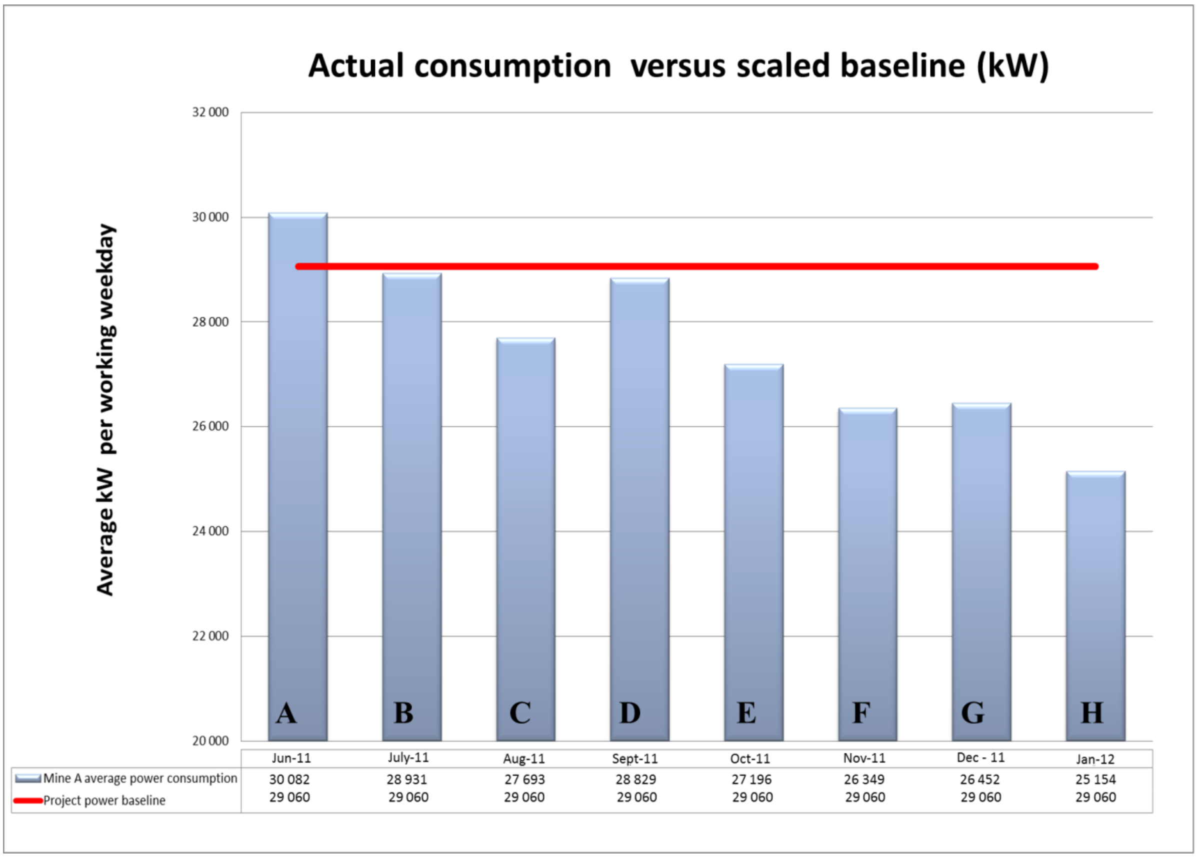

Figure 23: Mine A's compressor power savings

4.2.7 Conclusions

This case study illustrates the value of using simulation models for the implementation of DSM projects on mine compressed air networks. A previous DSM project, which had been implemented without the benefit of using simulations, predicted that a power saving of 2,2 MW was achievable. Due to the complexity of the system and the lack of simulation to analyse the proposed design changes and to predict the impact thereof more accurately, the implemented solution did not yield the required power savings.

Subsequently, as part of this study, a simulation model was developed. The simulation results indicated that a parallel valve configuration would yield the required flow and pressure. The simulation also predicted that additional pipework between mine A and mine B, and at mine A between levels 76 and 85, would lower the air supplied at mine A, resulting in reduced flow losses. With reduced flow losses and the appropriate flow and pressure control, the compressor's pressure setpoints could be lowered, resulting in a power saving of 3,5 MW.

The additional power saving justified the insignificant cost that was associated with the proposed solution by circumventing the payment of penalties that were associated with the underperformance of the initial solution. The lack of using simulation in the initial solution resulted in additional cost as well as a loss of income, which was not included in the contractual phase. This case study exemplifies the value of simulations for determining the feasibility of design changes to achieve power savings on mine compressed air systems.

4.3 Case study two – Design optimisation to achieve energy savings in a high-pressure water reticulation system

4.3.1 Introduction

Mine A is a deep-level gold mine, requiring chilled water for mining purposes. A DSM project, aimed at reducing the overall energy that is needed for pumping, was scheduled to be completed during 2010/2011, based on a techno-economic proposal. The aim of the project was to obtain energy savings by reducing the amount of water that had to be pumped to the surface by reducing the amount of water that was fed to underground levels.

On each mining level, NGD control valves were used in the water reticulation system. The NGD control valves were used to reduce water pressure in order to protect underground equipment. These valves had limited control and had to be serviced or replaced regularly due to a high wear rate that was caused by cavitation. As part of a DSM project to reduce power consumption, the old 200 mm NGD control valves were to be decommissioned and new 100 mm globe valves were to be installed. The initial project implementation phases went according to plan until the first control valve was installed.

In an attempt to find a solution to the pressure problem, a simulation model was developed as part of this study and data that were obtained from the model calculations were compared with data that were collected from the mine's SCADA system.

4.3.2 Mine A's layout and proposed control

Figure 24 represents a simplified layout of the water reticulation system of mine A. The PRVs (indicated in blue) are used to lower the downstream water pressure to within allowable parameters (below 1 500 kPa for this mine). New globe valves were proposed to be installed in order to control the water flow and pressure that were delivered to each mining level.

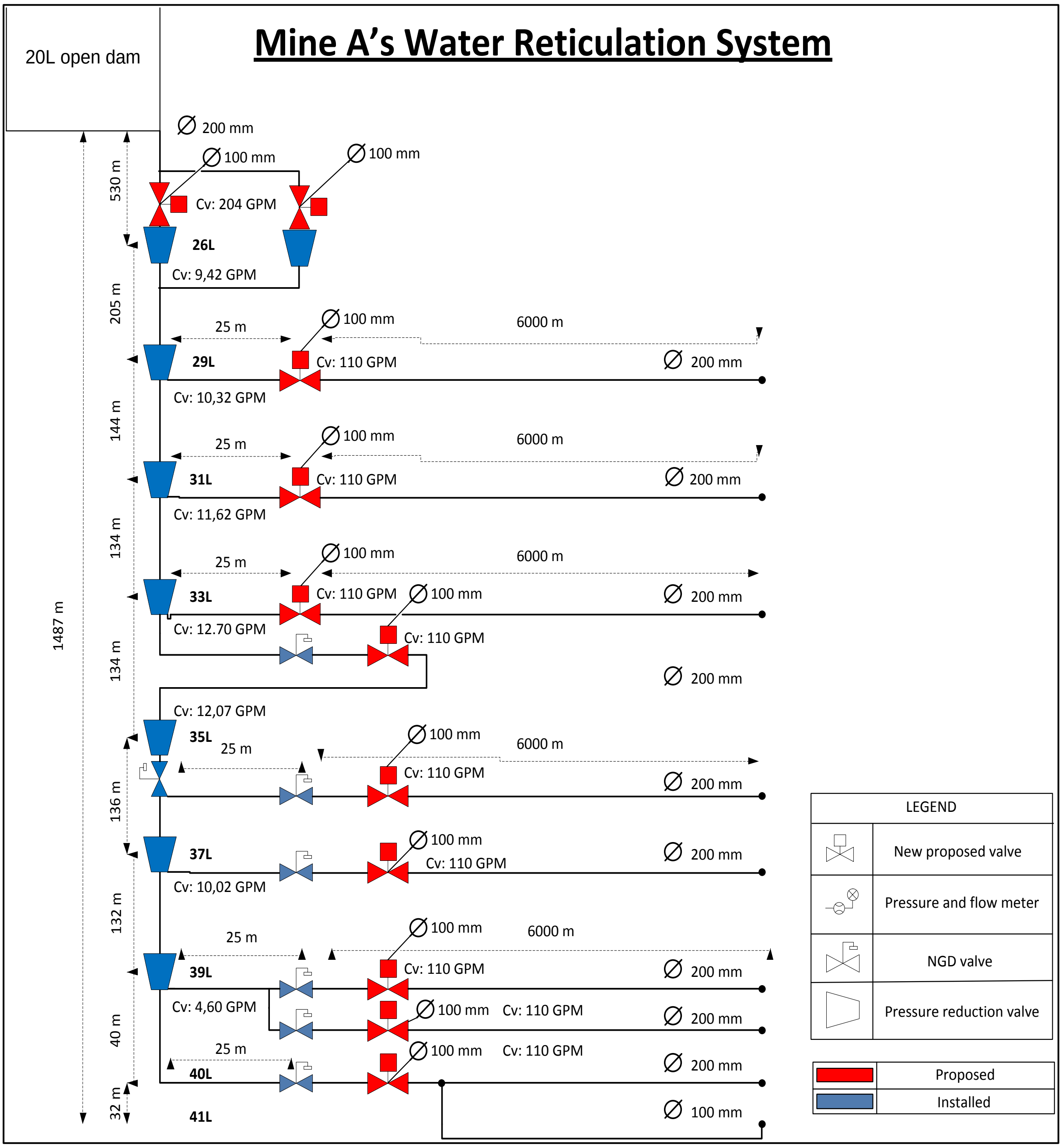

Figure 24: Layout of mine A's water reticulation system

Only one of the two PRVs in the main water column above level 29 was in use. An existing NGD valve (which was installed in series with a PRV) malfunctioned continuously due to the high water pressure and was subsequently removed.

4.3.3 DSM design without using simulation models

The initial project plan was to reduce the amount of water that was used underground and to reduce the amount of water to be pumped back to the surface thereby.

The scope of the initial proposed project was limited to

- replacing the NGD valves with more durable control valves to regulate the water pressure on the underground mining levels. The old NGD valves would not be removed, but would be placed in a fully open position, while the new valves would be controlled; and
- installing two additional control valves with an orifice diameter of 100 mm on each bypass line in the main water column above level 29. The new, more robust valves would be used to control the flow of water that was supplied to the mine.

During the commissioning of the first control valve, the downstream water pressure dropped unacceptably low at the rock-face. Subsequently, mine personnel removed the valve and suspended the installation of other similar control valves. The proposed DSM project was, therefore, not completed within the contractual period. The cause of the pressure drop at the rock-face was unknown. It was thought to be due to insufficient valve size.

4.3.4 Simulation setup

A simulation development process, similar to the procedure that has been discussed in Chapter 3, was followed.

The simplified simulation model is presented in Figure 25. The nodes at the end of each level represent a specific water flow demand, based on actual recorded data. A 24-hour flow demand profile for each level was entered into the simulation model. The simulation results and measured data were obtained at 11:00 am, prior to proposed changes, as discussed in section 4.3.3.

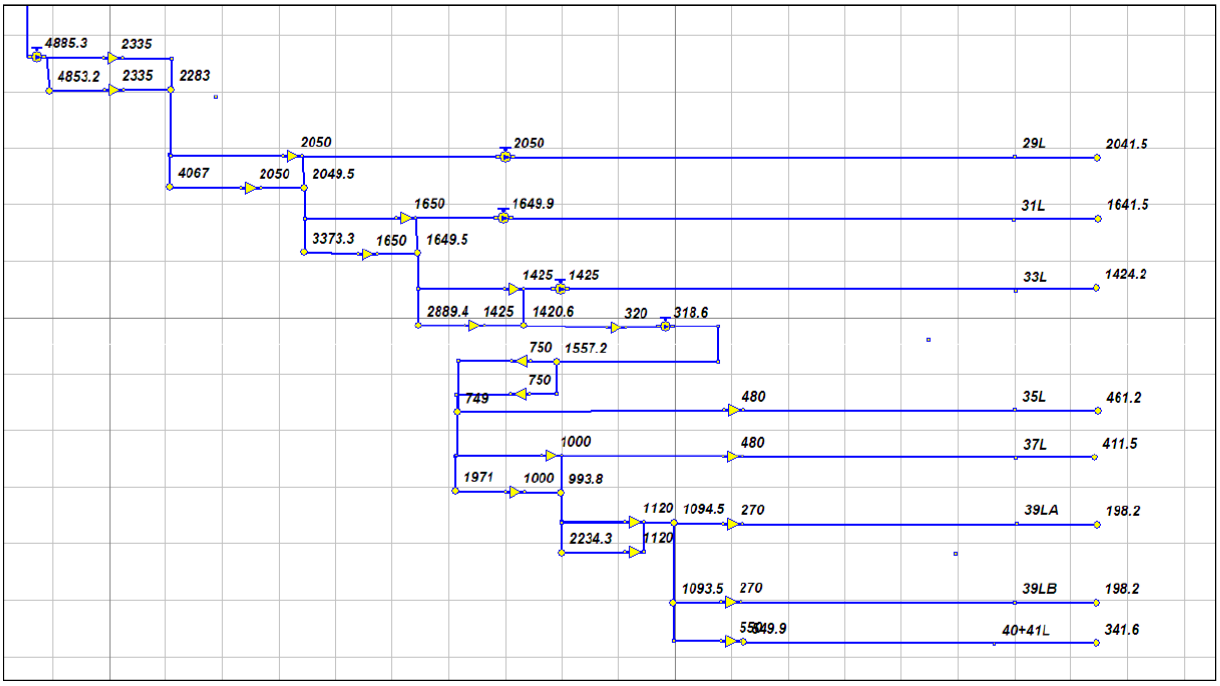

Figure 25: Simulation model of the water reticulation system of mine A, indicating mine levels and pressure during drilling periods

4.3.5 Simulated performance of the proposed new solution

The simulation that is shown in Figure 25 was adapted to include the new proposed globe valves. The NGD valves were placed in a fully open position. In the simulation, the globe valves' orifice openings were varied to determine whether the valves would be able to control the required downstream pressure.

Personnel at mine A argued that the pressure reduction, following the installation of the first valve on level 29, was a result of the fact that the orifice openings of the new valves were too small. Results from the simulation indicated that the pressure drop should not have occurred. The results that were obtained for the other levels verified that the simulation results were within 5% of the recorded data. It could therefore be assumed that the new valves would not cause a pressure drop if the simulation variables and boundaries were correct.

If the mine's demand for water would increase, the pressure within the system would theoretically drop and vice versa. In order to verify correct valve functioning under extreme high- or low-flow scenarios, the simulation was extended by simulating maximum and minimum flow and pressure conditions.

In order to determine the flow at which high pressure losses would occur, a scenario was simulated in which the demand on levels 37 to 40 was individually increased. The flow was increased until a substantial pressure drop was present. The level and theoretical maximum allowable flow is illustrated in Table 8:

Table 8: Maximum allowable flow and corresponding pressure

Level	Maximum allowable flow	Simulated pressure
37 L	50 l/sec	500 kPa
39 LA	55 l/sec	551 kPa
39 LB	50 l/sec	566 kPa
40 L	70 l/sec	545 kPa

The maximum allowable flow for each level was compared to recorded data. At neither of the levels had a flow been recorded that exceeded the simulated maximum allowable flow; it was thus assumed that the valves would not be the cause of a pressure drop if the system were operated within its operational boundaries.

If the water flow rate through the system decreased, a hypothetical increase in system pressure would be expected. Another simulation was developed to determine whether the proposed control valves would be able to reduce the delivery pressure in order to protect equipment.

From the simulation results, it was concluded that the proposed valves were able to restrict the high input pressure effectively to below 1 500 kPa.

4.3.6 Simulated performance of the proposed mid-shaft control valve

A simulation was developed in order to assess the feasibility to supply water through the two proposed globe valves without adversely affecting the delivery pressure. From the simulation results it was concluded that the valves were too small – even when the valves were placed in a fully open position, the delivery flow was too low. It was, therefore, not feasible to install two 100 mm diameter globe control valves.

Further simulations indicated that the placement of 200 mm diameter globe and gate valves in parallel, each in series with a PRV (Philmac), would result in enough water being supplied to the mine, even if one control valve would malfunction. The proposed valve configuration is shown in Figure 26:

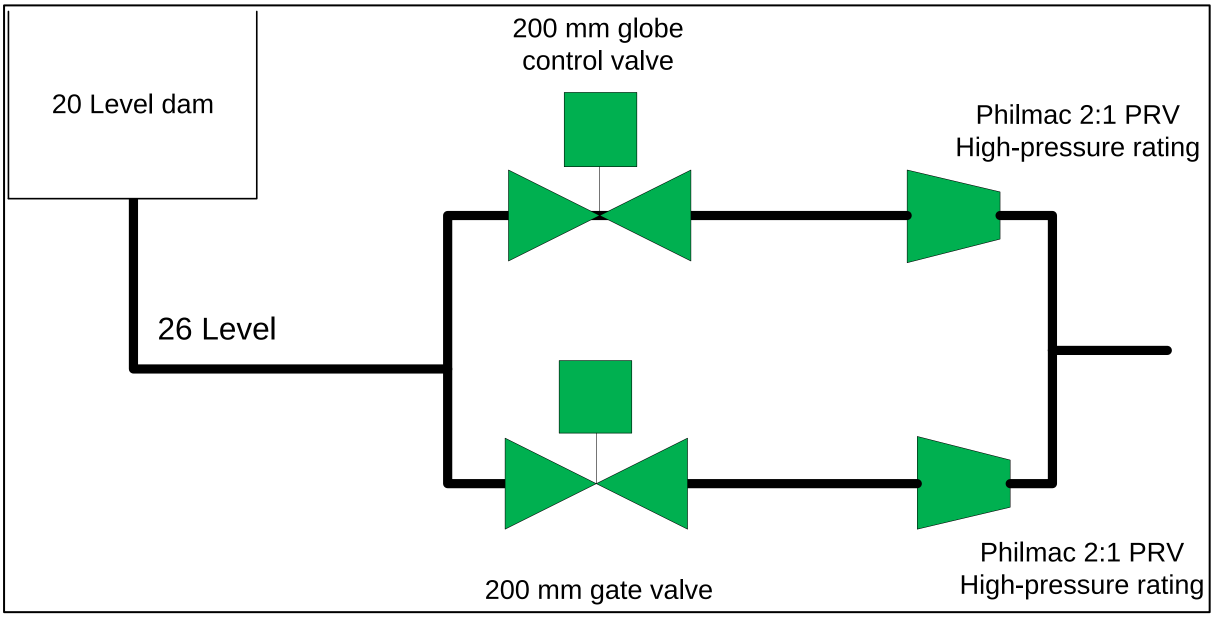

Figure 26: Proposed valve configuration for mine A's main water column

4.3.7 Design change results

The proposed control valves on the mining levels were installed and the valves performed as had been predicted in the simulations. The performance of the valve on level 37 is shown in Figure 27: The ability of the valves to control the delivery pressure (purple line) to within 10% of the pressure set point (red line) is indicated.

The relationship between flow increase and pressure decrease, as predicted and simulated, is demonstrated in Figure 27. The data in Figure 27 was obtained by measurements after the valves had been installed: As the water flow rate increases (blue line), pressure decreases (green line) and vice versa.

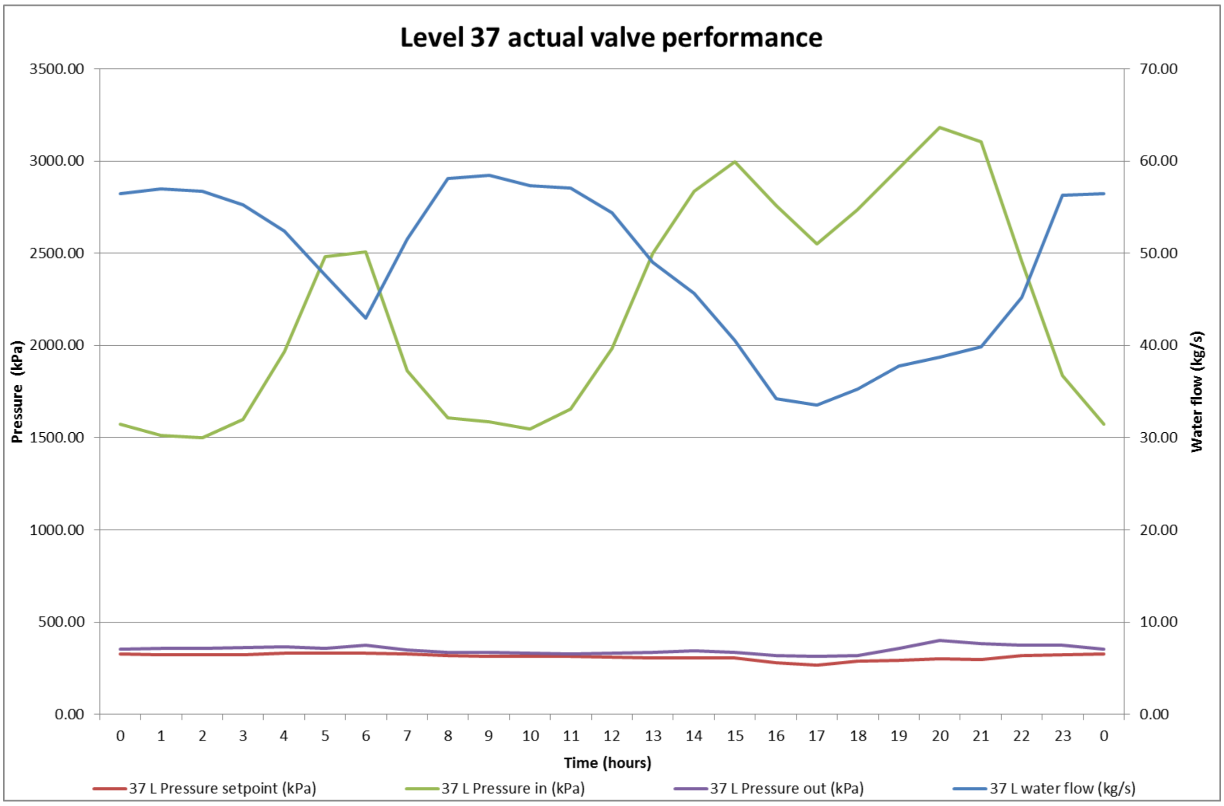

Figure 27: Actual performance of the control valves that were installed on level 37

By installing and controlling valves to deliver the required flow at the required pressure, 5,8 Ml less water per day was allowed to flow to underground levels from the surface, which resulted in a power saving of 3,7 MW.

4.3.8 Conclusions

This case study illustrates the value of simulations when implementing DSM projects for power savings on mine water reticulation systems. A previous DSM project, which had been implemented without using simulations, resulted in project delays and failure to meet contractual deadlines. Due to the complexity of the system and the lack of using simulations to analyse the proposed design change and to predict its impact more accurately, project delays resulted in lost man-hours, penalties being paid and energy savings not being achieved.

Subsequently, as part of this study, a simulation model was developed to analyse two proposed design changes to the installed solutions. The simulation results indicated that the reported pressure drop was not attributable to the installed control valve. The simulation also predicted that the installation of the proposed mid-shaft valves would render an insufficient flow. A new design, including a valve configuration, was simulated and it was found that it achieved the desired flow savings. Appropriate flow and pressure control resulted in a power saving of 3,7 MW, which is in line with the contractual agreement.

This case study exemplifies the value of simulation models for determining the feasibility of design changes, such as improving valve configuration, flow and pressure control in water reticulation systems to achieve energy efficiency improvements.

4.4 Case study three – The value of simulation models in evaluating compressed air delivery solutions

4.4.1 Introduction

Mine A and mine B are two gold mines that are situated in the Free State. Prior to the implementation of a DSM project on a compressed air system, production at both mines had dramatically decreased. The easily accessible pillar reserves had not been extracted and were now being mined. The only mining development was, therefore, done in the pillar area and no longer at the far-reaching tunnels of the old mine. Consequently, compressed air lines, leading to the old mining areas at both shafts, were blanked off to reduce both shafts' compressed air requirements. Due to the reduction in compressed air requirements, an oversupply of compressed air was generated when only the smallest compressors at both shafts were utilised.

When compressors blow off or unnecessary system leakage occurs, energy is wasted. At mine A, the regular compressor blow-off resulted in additional compressor operation problems: The blow-off valve of one of the compressors malfunctioned, resulting in catastrophic failure of the compressor. Mine operators, therefore, opened underground valves in order to alleviate the constant pressure build-up in an attempt to prevent another valve failure; this resulted in energy wastage.

The 3,6 MW compressor that was used at mine A was initially designed to be a base-load compressor and capacity controllers were not included in the initial design. The compressor output could, therefore, not be varied in order to match the compressed air supply with the system demand.

Three different-sized compressors were installed at Mine B. These compressors included a 3 MW, a 3,95 MW and a 4,8 MW compressor. The compressors supplied compressed air to mine B's East and West shafts via a 2 400 metre compressed air pipeline that was installed at ground level. All these compressors had capacity controllers installed, but when utilising the smallest compressor with its capacity controller fully utilised, the compressor continued to blow-off.

A solution had to be found that would address the oversupply of compressed air at both shafts without negatively influencing gold production.

4.4.2 Proposed solution at mine A

Various solutions that were proposed to solve the abovementioned problem had been investigated and pursued by relevant mine personnel. The mine management requested the Esco to investigate and report on various of the proposed solutions. As part of this study, a number of these solutions were investigated and simulations were developed in order to verify the viability of the proposed solutions.

Figure 28 is a representation of the original compressed air layout of mine A and mine B. The flow of air through the pipes is measured in m^3/h.

The maximum flow that was delivered to mine A was 42 500 m^3/h. After consulting the managing engineer at mine A, it was concluded that the planned future maximum number of equipment that should be used was

- 60 drills (at 430 m^3/h per drill) [**30**]; and
- 4 loaders (at 1 000 m^3/h per loader) [**30**].

Using this information, the expected compressed air flow requirement at mine A was calculated to be 29 800 m^3/h. The same simulation development, validation and verification process was followed, with the same assumptions as was discussed in Chapter 3.

The units for the mass flow rates for this case study and the following case studies will vary. This is due to the fact that the different mines have individually standardized on different units to use with their mass flow meters. The temperatures at which these mass flow meters are calibrated are unknown and an accurate conversion to a single unit is therefore not possible.

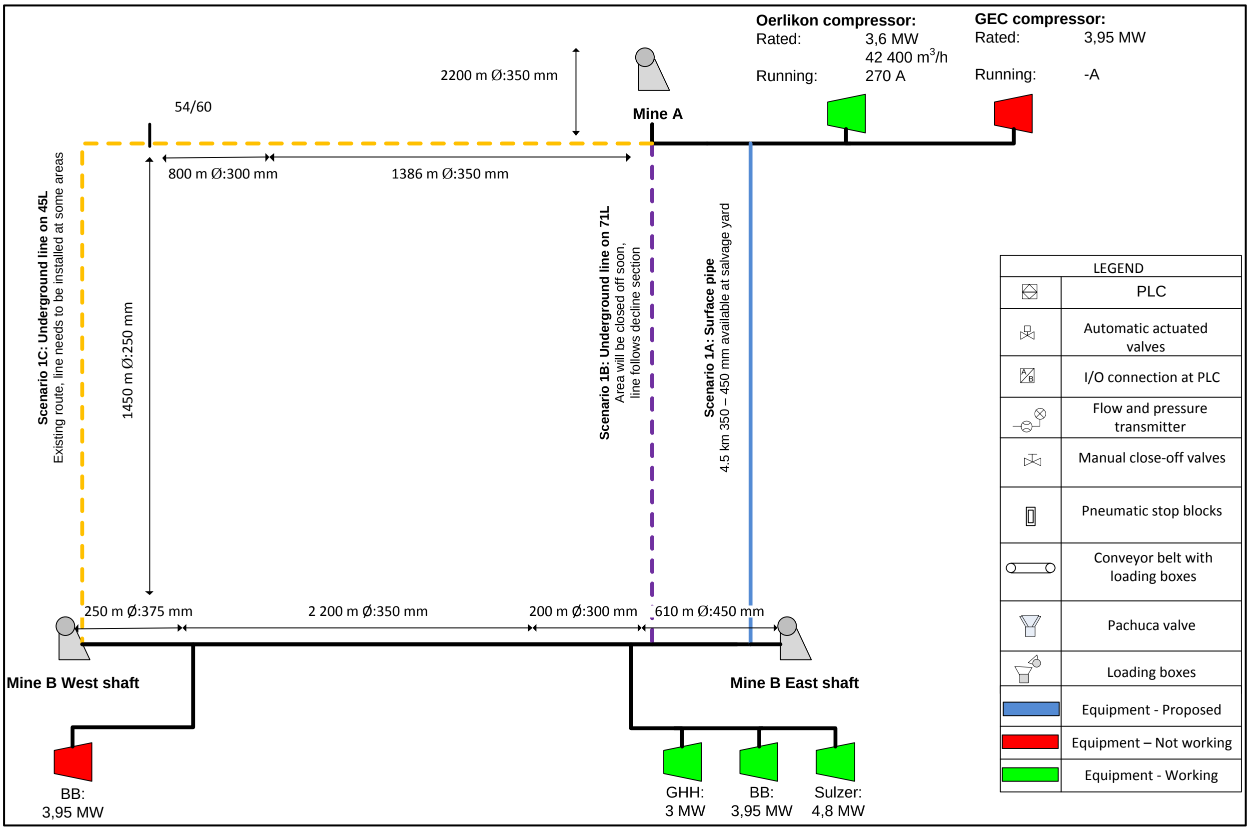

Figure 28: Schematic layout of the proposed solutions for mine A and mine B

4.4.3 Proposed solutions

Personnel from mine A and mine B were consulted to determine practical and viable solutions. The propositions to be investigated included

1) replacement of the existing compressors with stand-alone compressors;
2) upgrading of the existing compressor at mine A with variable output control;
3) supply of compressed air to mine A from mine B via an underground pipeline at mine B West shaft;
4) supply of compressed air to mine A via the decline at mine B East shaft; and
5) supply of compressed air to mine A via a surface pipeline from mine B.

The aforementioned solutions were investigated in techno-economic evaluations in order to find the best solution. In the following sections, the listed propositions will be discussed.

4.4.3.1 Proposition one – Utilising smaller stand-alone compressors at mine A and mine B

This option would enable both mines to supply just enough compressed air to address the particular compressed air demands of each mine.

The solution would be sufficient at mine A, as the compressed air demand was not expected to increase significantly when the development phases would be completed and mining of the pillar would commence. Small stand-alone compressors have sufficient output control in order to match the compressed air supply to the compressed air demand. Stand-alone compressors also do not necessitate the installation of cooling towers. However, the power consumption of the required stand-alone compressors would still be 2 800 kW in order to meet the compressed air demand. An estimated power saving of less than 800 kW (3 600 kW installed – 2 800 kW stand-alone) would be achieved at an estimated installation cost of R2,5 million.

At mine B, production was expected to increase in future. It was expected that the installed compressors would be sufficient to supply the necessary compressed air without blowing off. It would be a waste of capital to buy stand-alone compressors for this mine.

If stand-alone compressors were to be installed at mine A, the compressor blow-off problem at mine B would still need to be addressed. The cost of installing stand-alone compressors with the required combined installed capacity would not be justified by the short expected life of mine A (2,5 years).

4.4.3.2 Proposition two – Upgrading of existing compressors to include vane control

The compressor at mine A had received its scheduled five-year maintenance prior to the scaling down of production at the shaft. The compressor was, therefore, in a good mechanical condition and the proposed retrofitting of capacity control would thus be plausible.

However, if mine A's compressors were to be retrofitted with guide vane controllers, the yielded electrical energy savings would not be comparable with compressors that were designed to include guide vane control. By retrofitting the compressor at mine A, the constant blow-off problem would be solved, but the associated energy savings would be too low to justify a DSM project (power savings are expected to be less than 400 kW).

The proposition to install new compressors with guide vane control at mine A would enable the mine to control the compressed air delivery, but insignificant electrical energy savings would be achieved. The cost of this proposed installation would, therefore, not be justified by the potential savings. In addition, the compressors at mine B already had guide vane control, but the smallest compressor continued to blow off regularly.

4.4.3.3 Proposition three – Installation of an underground bypass pipeline via mine B's West shaft

This section will be discussed with reference to Figure 28. A compressed air pipeline between mine B's West and East shafts already existed. Mine B's West shaft is connected to mine A on level 54/60, making it possible to install an underground compressed air supply pipeline. Compressed air would be supplied to mine A through a pipe network of approximately 8 855 metre from mine B's East shaft.

The underground use of compressed air pipes with a nominal diameter of 250 mm was planned. The pipeline is schematically indicated with the orange-dotted line in Figure 28. Personnel at both mine A and mine B were actively pursuing this proposition prior to the development of simulations.

Figure 29 presents the results that were obtained from the developed simulation. The simulation does not take compressed air demand at mine B's West or East shaft into consideration. The capability of the compressors at mine B's East shaft to supply the required compressed air to all three shafts was not investigated. The simulations were mainly developed in order to determine the feasibility of transferring the required compressed air through the proposed pipe network at the required pressure and flow.

The simulation results are discussed with reference to Figure 29:

A. Mine B's compressor setpoints were set at 450 kPa.

B. The surface compressed air pressure was 320 kPa at mine B's West shaft. The pressure drop is a result of the high flow of compressed air through the narrow 300 mm diameter pipe sections.

C. The air delivery pressure at mine A is 18,8 kPa on level 60. The pressure drop is due to the high flow and resulting pipe friction through the 250 mm diameter pipe sections between mine B's West shaft and mine A.

D. The flow demand on level 60 at mine A was set to be 29 800 m^3/h, which is the maximum expected future demand at mine A.

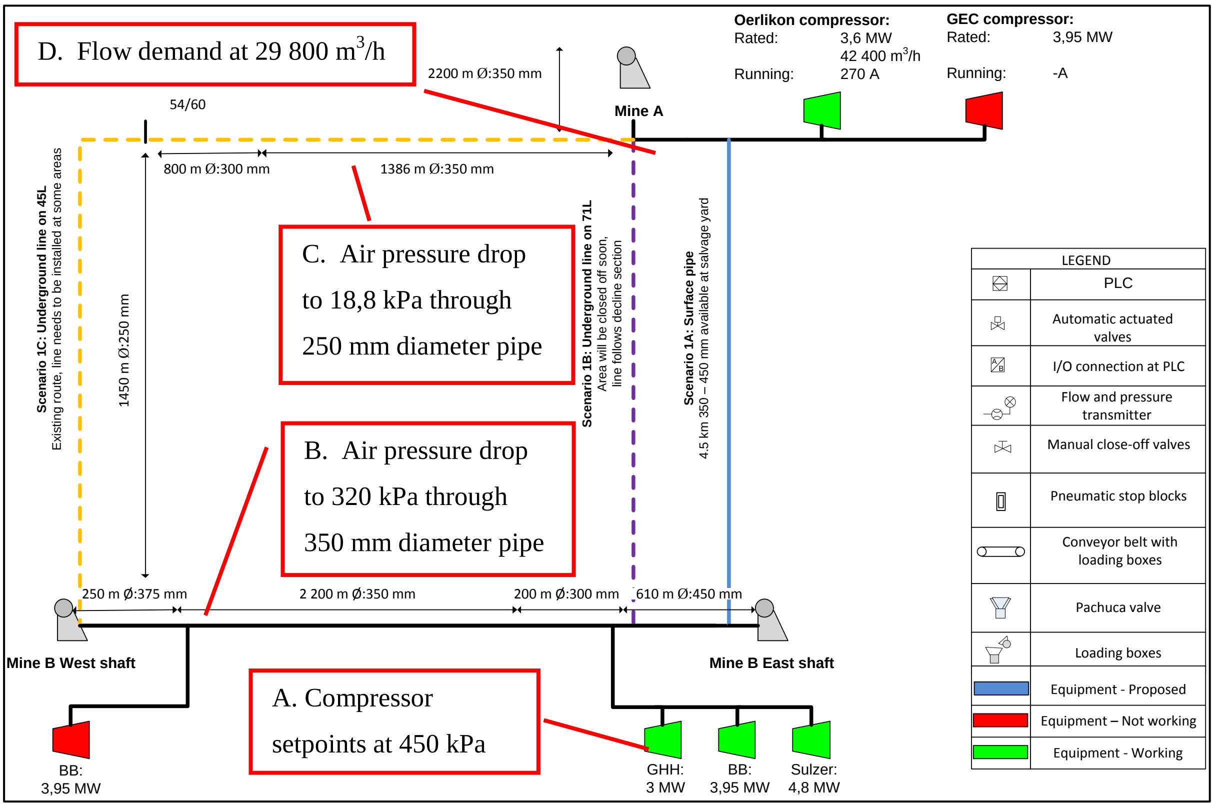

Figure 29: Simulated results for compressed air pipeline bypass at mine B West shaft

It was found that this proposition was not feasible, as it was not possible to supply compressed air to mine A from mine B at the required pressure and flow. The use of simulations in this DSM project proposal resulted in the circumvention of capital expenditure by mine personnel who had actively pursued this proposition which would not have rendered a positive result.

4.4.3.4 Proposition four – Installation of an underground bypass pipeline via the mine B East shaft decline

This proposition required compressed air to be supplied to mine A via the level 71 decline pipeline from mine B. Discontinued mining of the sections that were accessed from the decline and the proposed pipeline through the decline would require that the decline section would have to be maintained. This proposition was, therefore, not feasible; consequently, simulations for this proposition were not developed.

4.4.3.5 Proposition five – Installation of a surface compressed air pipeline

In the past, a surface compressed air pipeline existed between mine A and mine B’s East shaft, but it was removed to be used at a different mine. The splints of the old pipe network still existed and if the required compressed air pipes were available and/or procured, the installation of such a pipeline could be far less challenging than the installation of underground pipelines.

The schematic representation of the proposed pipeline is indicated with the blue line in Figure 28. The mine had an existing stockpile of reclaimed 450 mm and 350 mm diameter pipes. The compressed air pipe size for the simulation that is shown in Figure 30 was therefore based on the available 450 mm and 350 mm outside diameter pipes. It was estimated that there were enough 400 mm and 350 mm pipes available to span 2 000 metre and 2 500 metre respectively. Should the simulated results indicate that the proposed solution was feasible and larger pipes were to be used during the installation, the compressed air pressure delivery to mine A would be sufficient.

Figure 30 represents the simulation. The following applies to Figure 30

A. The compressor setpoints at mine B’s East shaft were set at 450 kPa.
B. The surface compressed air pressure at mine B’s East shaft was 450 kPa just before the proposed pipeline split to mine A.
C. The compressed air pressure drop near mine A was due to the high flow through the 450 mm diameter pipe sections.
D. The compressed air pressure on the surface at mine A was 187 kPa. The pressure reduction was caused by the high flow through the 350 mm pipes.

E. The flow demand at mine A was set to 29 800 m^3/h.

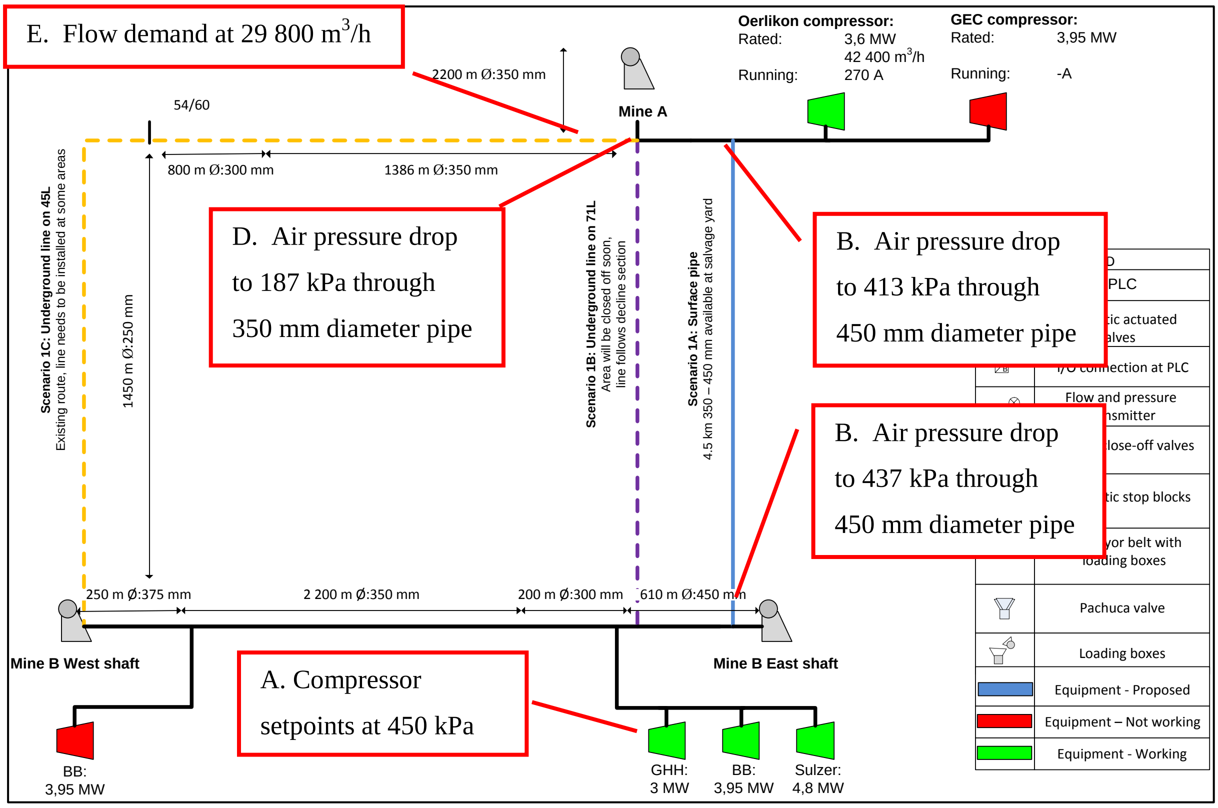

Figure 30: Simulated results for the surface compressed air pipeline with the bulk compressed air demand on surface

If only 450 mm pipes were to be used, a delivery pressure of 358 kPa could be achieved. In the simulation, the specified demand at mine A would not be exceeded in practice and the pressure would, therefore, not drop to below 358 kPa. The installation of a surface compressed air pipeline between both shafts would be technically viable if the delivery pressure of 358 kPa were to be acceptable during peak production periods.

Based on the simulation results, it was shown that if the compressor at mine A and the 3 MW compressor at mine B were to be shut down, and the 4,8 MW compressor at mine B were to be utilised, a 1,8 MW power saving could be realised at an annual electricity cost saving of R6,6 million. The total cost of this implementation would amount to R9,7 million, which would be (partially) borne by Eskom. The payback period was estimated to be approximately 18 months, which is well within the envisaged 2,5 years window for residual mining operations.

Based on the simulation results, it was recommended that the surface compressed air pipe network should be installed. The following suggestions were made:

i. Only 450 mm compressed air pipes should be used for the surface compressed air link between mine A and mine B. The compressed air delivery pressure at mine A would then be sufficient for mining to commence without having pressure-related problems. It was also suggested that the compressed air demand be limited to 16 000 m^3/h if a delivery pressure of 400 kPa is required.

ii. If a combination of 350 mm and 450 mm pipes were to be used, the available 450 mm compressed air pipes should be placed on mine B's side of the pipeline and the remaining 350 mm diameter pipes on mine A's side to complete the pipeline. The maximum expected flow through the pipe combination should be limited to 12 500 m^3/h if a delivery pressure of 400 kPa were required.

iii. If a surface compressed air network were installed as proposed, mine A's compressor should be shut down indefinitely. Only one of mine B's larger compressors can supply both mines with compressed air at the desired pressure and flow.

Figure 31 represents the delivery pressure for the proposed solutions at variable flow:

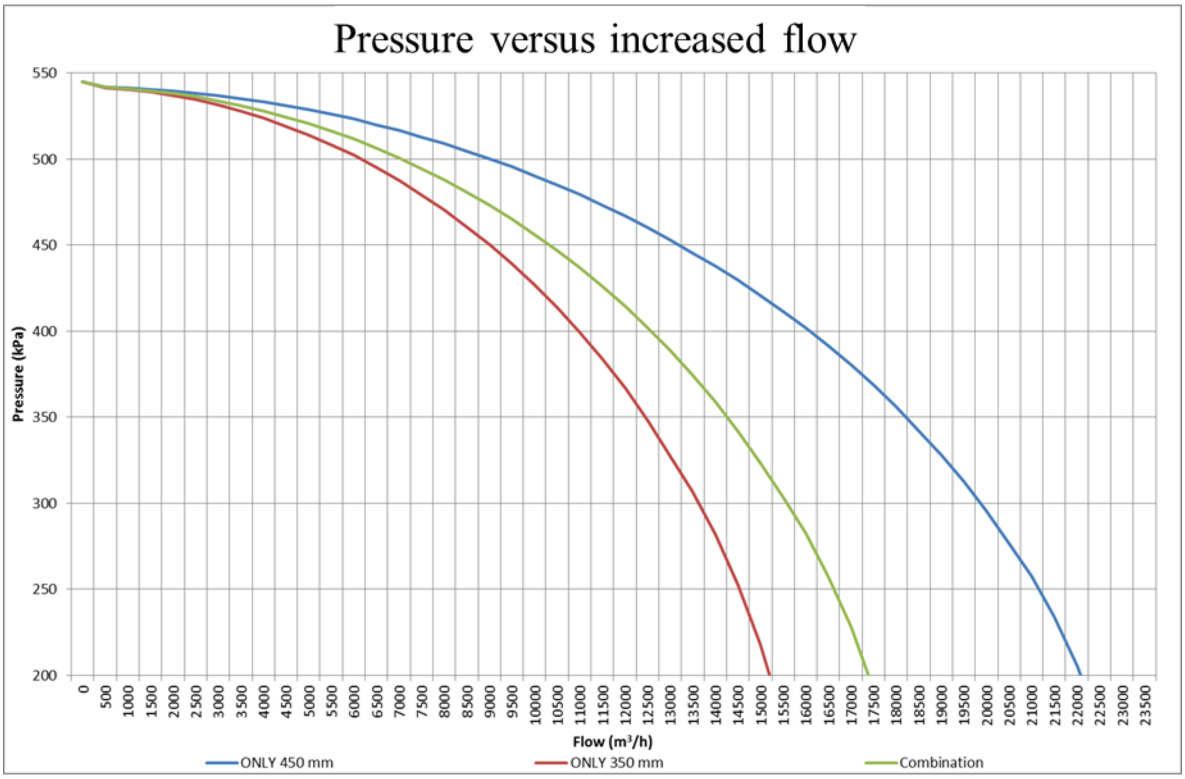

Figure 31: Simulated delivery pressure at various flows for the proposed solutions

The results from the simulations indicated that the mine's chosen solution (to export air to mine A through mine B's West shaft) would not yield the required results. The mine, therefore, cancelled all further installation of underground pipework immediately. From the simulation results and the subsequent summary and suggestions, the mine salvaged old pipes and bought the additional 450 mm diameter pipes to install the proposed surface compressed air pipeline between mine B East shaft and mine A.

4.4.4 Conclusion

Prior to the use of simulations, mine personnel pursued the installation of the underground pipe network as described above and contemplated several other solutions. By using a simulation, the solutions, which personnel at the mine had been working on, were shown to be technically unviable. Both infrastructure and man-hours would have been wasted in an attempt to complete the project.

In this application, the value of simulations in the optimisation of compressed air networks for mine DSM projects is demonstrated. Based on simulation results, it is expected that upon completion of the pipe network, the compressor blow-off problem will be solved. In addition and due to the realised energy saving, this DSM proposal was submitted to and approved by Eskom for funding. Based on this study and the approval and techno-economic evaluation by Eskom, it is expected that the mine will receive a rebate for the cost that was incurred to acquire the necessary pipes for completion of the project.

4.5 Case study four – The value of simulation models in planning the relocation of a large mine compressor

4.5.1 Introduction

Mine A is situated south-east of Welkom in the Free State. Recent development projects at the newest production shaft, shaft number five, resulted in an increased compressed air demand.

4.5.2 System background

Mine A consists of a gold plant and five shafts. Three different compressors feed compressed air to the 16 km long surface compressed air network, of which two compressors are located at shaft number five and one compressor at shaft number three. Figure 32 presents mine A’s compressed air system schematically.

Shaft five is mine A's main production shaft. With the increased production, the two compressors that are located at shaft five no longer supplied the desired compressed air flow at the required pressure. Compressed air had to be supplied from the compressor at shaft three in order to meet the demand. Following this solution, the pressure delivered to shaft five was still too low.

In an attempt to increase the service delivery, mine A planned to relocate an unused, refurbished compressor from another mine to shaft five. Mine personnel expected that the relocation of the compressor would ensure better compressed air service. In addition to the increased service delivery, personnel of mine A wanted to discover whether any energy savings would be achieved that would justify a rebate from the DSM mechanism.

Figure 32 is a schematic layout of mine A's compressed air system. The compressors (marked green in Figure 32) indicate the presently installed compressors, while the pipeline and compressor (marked in blue) represent the mine's proposed compressor installation.

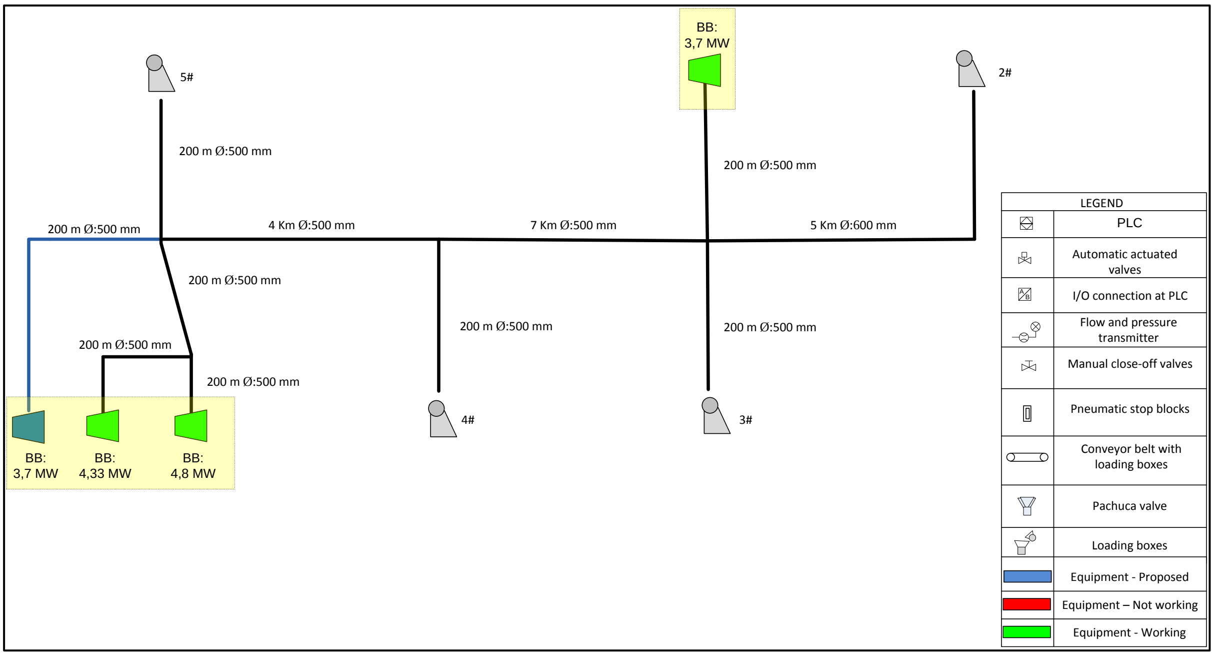

Figure 32: Schematic layout of mine A's compressed air system

Only shaft five is being mined actively. However, all other shafts must remain functional, as they form part of contingency plans if any problems arise at shaft five. All systems that are using compressed air at these shafts must, therefore, be pressurised constantly. In addition to the fact that the shafts form part of a contingency plan, compressors and compressed air pipelines at mine A are continuously pressurised to prevent vandalisation of these systems.

4.5.3 Simulation model

A similar validation, verification and development process was followed with the same assumptions as was discussed in Chapter 3.

The simulation was developed to determine the extent of pressure losses when air is supplied from shaft three to shaft five. The associated energy loss, due to the pressure loss, was determined. The following assumptions were made:

- Due to the lack of instrumentation, compressed air consumption was assumed to be 30 m^3/s at shaft five and 6 m^3/s at shaft four, based on the flow requirements as measured by a portable logger. It was assumed that the compressed air pipelines that are connecting shafts two and three consume 0,1 m^3/s of compressed air, which can be attributed to compressed air leaks. These values were provided by the senior shaft engineer [**54**].
- According to the senior shaft engineer, the compressed air network consists of mainly 500 mm diameter steel pipes, except for the section between shafts two and three, which consists of 600 mm diameter steel pipes.
- The assumption was made that the pipe that delivers compressed air from the relocated compressor to shaft five ties into the main column just before it enters the shaft.
- A 3,7 MW compressor is presently installed at shaft number three. The relocated compressor was assumed to have the same installed capacity as the compressor at shaft number three.
- The different flow and pressure variables that were used throughout the simulation is based on the mine’s maximum peak drilling compressed air demand from 07:00 to 12:00.

The electrical energy savings that were realised, was determined by using Equation 1, as well as the pressure losses over the pipe sections and flow of compressed air between the shafts.

4.5.4 Simulation one: Present configuration

Simulation one represents the compressor configuration as it was usually operated: two compressors at shaft five (5#) and one compressor at shaft three (3#). Figure 33 is a schematic representation of simulation one. Note that pressure values are indicated in black (kPa) and the flow is indicated in red (m^3/min).

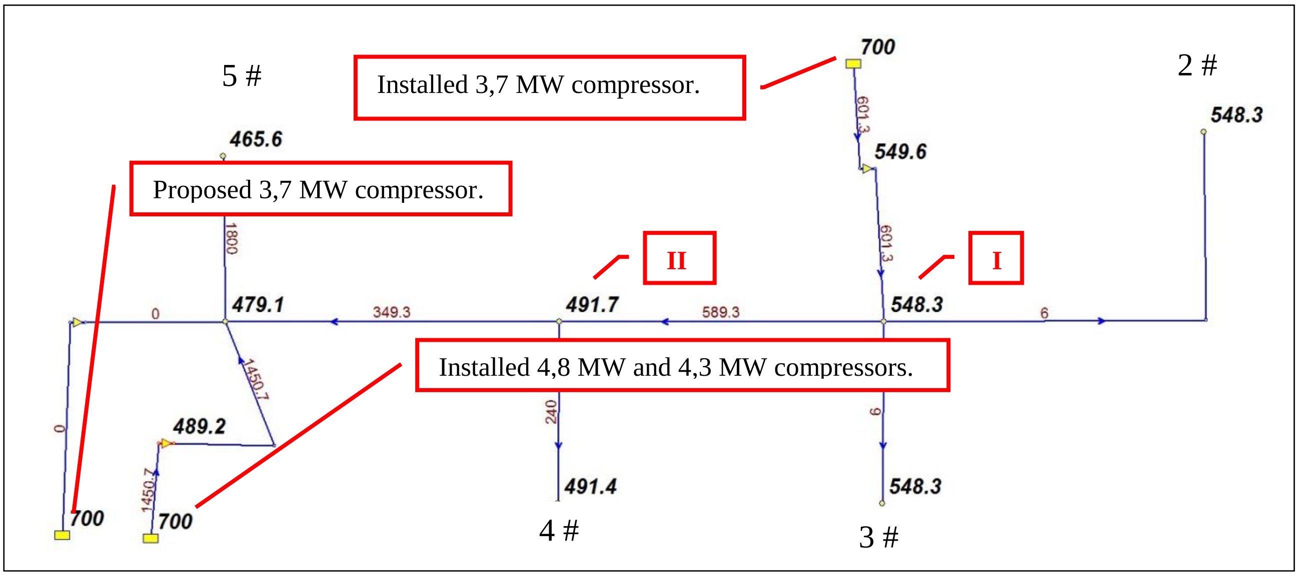

Figure 33: Simulation one – Present configuration

In simulation one, the installed 3,7 MW compressor delivers 601,3 m^3/min (13,3 kg/s) compressed air to the compressed air network at 550 kPa, as recorded from the SCADA system. In this simulation, the proposed new 3,7 MW compressor is simulated to deliver no compressed air to the network. The two existing compressors at shaft five deliver a combined flow of 1 450,7 m^3/min (31,4 kg/s) to the existing network. The compressor delivery flow rates are based on the actual measured flow.

The major pressure loss in the compressed air network between the pipe intersections at shaft three (indicated with the red roman I) and the intersection at shaft four (indicated with the red roman II) is illustrated in Figure 33.

By using this Equation 1, the theoretical power needed to compress air to 548,3 kPa with a flow rate of 589,3 m^3/min (12,8 kg/s) is 2 664 kW (I). The theoretical power needed to compress air to 491 kPa with a flow rate of 589,3 m^3/min (12,8 kg/s) is 2 462 kW (II). The theoretical electrical energy loss due to pipe friction and leaks is therefore 202 kW (I minus II).

4.5.4.1 Simulation two: Relocated compressor

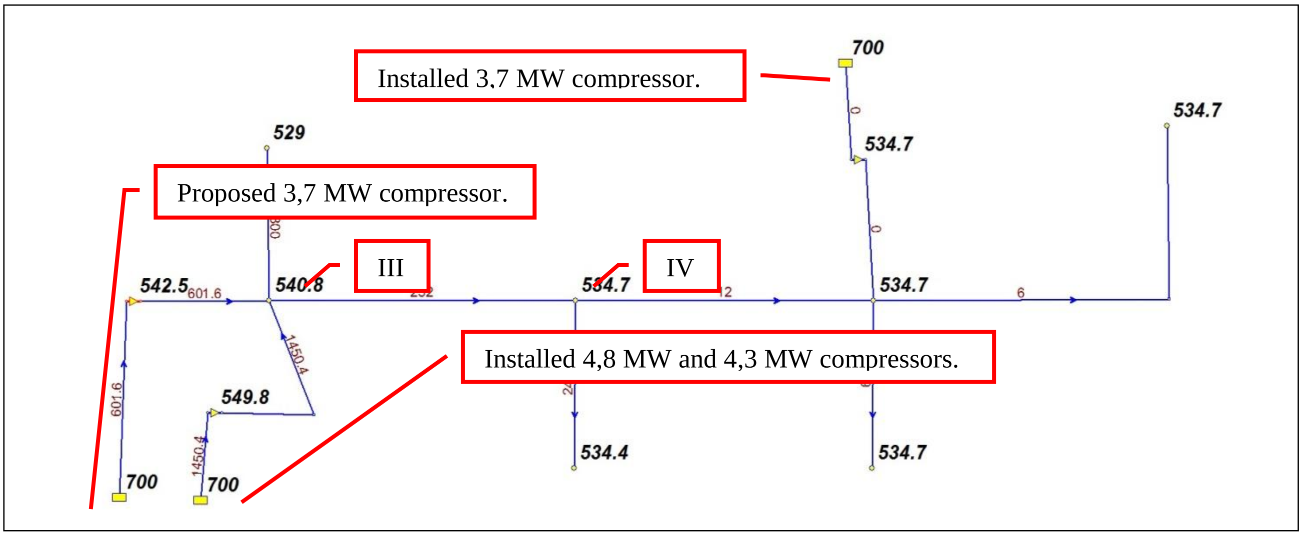

Figure 34: Simulation two – Relocated compressor configuration

For simulation two, it was assumed that the installed 3,7 MW compressor at shaft three does not deliver compressed air to the compressed air network. The proposed new 3,7 MW compressor, however, delivers 601,6 m^3/min (13,03 kg/s) compressed air to the compressed air network. The two existing compressors at shaft five deliver a combined flow of 1 450,4 m^3/min (31,4 kg/s) compressed air to the existing network.

The major pressure losses in the compressed air network, as illustrated in Figure 34, are between the pipe intersections at shaft five (indicated with the red roman III) and the intersection at shaft four (indicated with the red roman IV).

By using Equation 1, the theoretical power that is needed to compress air to 542,5 kPa at a flow rate of 252 m^3/min (5,5 kg/s) is 1 131 kW (III). The theoretical power that is needed to compress air to 534 kPa at a flow rate of 252 m^3/min (5,5 kg/s) is 1 118 kW (IV). The theoretical electrical energy loss due to pipe friction is thus calculated as 12,6 kW (III minus IV).

4.5.5 Simulation conclusion

From the simulations above, it is calculated that the potential theoretical energy saving that is realisable if the relocated compressor were to be installed in the indicated position is 189 kW. The potential saving is the difference between the theoretical energy losses that have been calculated in the two simulations (202 kW – 12,6 kW). It has been estimated that the proposed compressor relocation would cost in excess of R15 million. From a DSM perspective alone, a compressor relocation would not be justified, since the theoretical energy saving is calculated for the peak compressed air usage period only. This saving will thus only be realisable from 07:00 to 12:00 daily, when the compressed air demand is highest.

However, if the increased productivity is taken into account, due to inter alia reduced drilling time, the project becomes economically feasible, as was determined by mine personnel [54]. It is expected that the production at shaft five will increase in future, hence the relevant personnel at the mine decided to relocate the compressor to shaft five, based on the simulated pressure increase from 479,1 kPa to 540,8 kPa.

4.6 Conclusions

In this section, the value of simulations in planning DSM projects has been demonstrated. This value is illustrated by the following:

- Reduction in project implementation cost:
  Simulations were not employed in the original DSM projects that have been discussed in case studies one and two. This resulted in project delays, which resulted in energy savings not being achieved, penalties being paid and faulty/incorrect equipment being procured. Simulations were subsequently used to propose design corrections which, upon implementation, resulted in targets being met or exceeded.

  In case study four and in the simulation verification and validation case study (case study five), large capital expenditure for proposed DSM projects was prevented by identifying pressure losses through the use of simulations. Case study three exemplifies the value of simulations to reduce implementation cost, both in financial and labour terms.

- Reduced project implementation period:
  In case study three, a simulation was developed prior to the implementation of a DSM project, circumventing the time consuming installation of unnecessary pipes. DSM projects in case studies one and two, which did not employ simulations in the analysis and planning phase, were delayed.

- Determination of DSM project feasibility:
  In case studies one and two, simulations were used to determine the most feasible compressed air and water reticulation layout. In case studies three, four and five (simulation done in section 3.2.4), simulations were used to determine the most efficient project design and to determine project feasibility, based on techno-economic analyses.

- Improvement in DSM project design:
  In case studies one, two and three, the value of simulations to improve DSM project design has been demonstrated through improved mine compressed air layout, improved valve design and additional surface pipe configurations, respectively.
- Improved component design:
  In case studies one and two, simulations were used to determine the most appropriate valve configuration and valve types to be used in DSM projects.

The simulations that have been used in these case studies did not only indicate the outcome of proposed DSM interventions, but also the effect of proposed design changes on production. It is thus evident that simulation models have significant value for mine DSM projects.

5 Conclusions and recommendations

5.1 The value of simulation models

This study demonstrates the potential of simulations to plan new and to correct implemented DSM solutions by allowing the analysis of energy consumption in complex technical systems and the quantification of the savings potential of DSM interventions to inform design changes in order to attain energy savings.

In the study, the value of simulations for mine DSM projects is emphasised. In order to demonstrate the benefit of simulations in planning and implementing mine DSM projects, a number of preconditions have to be met. These include

- using simulation software which is validated, verified and applicable to the range of conditions prevailing in the mine for which the simulation is developed;
- the availability of mine layout and design information;
- information pertaining to mine operations;
- accurate operational data for use in simulations; and
- proficiency in using the simulation software, which includes an understanding of the underlying principles that are employed as well as the limitations of the simulation software.

Should plant data and information that are needed for simulation not be available, realistic assumptions have to be made. It is desirable that the implications of assumptions should be analysed in a parametric study to quantify the influence of variations in the range of parameters that is related to assumptions. This requires the necessary skills to use the simulation software.

In this study, the value of simulations is demonstrated with reference to mine compressed air and dewatering systems. Simulations are shown to add value to mine DSM projects in the planning and implementation of these projects to attain energy savings by allowing a reduction in project implementation cost, a reduction in the time that is needed for DSM project implementation (and hence increased up-time for better production), and determining project feasibility as well as DSM project, component and control design improvements.

Table 9 summarises the significance of simulations as demonstrated in this study:

Table 9: Summary of the potential value of simulation models that have been demonstrated throughout this study

Value demonstrated in **Value demonstrated by using simulations**	**Correction to existing DSM Project**		**New DSM Project**		
	Case study one Compressed air network	Case study two High-pressure water reticulation	Case study three Compressed air delivery	Case study four Relocation of large mine compressor	Simulation, validation and verification case study
Reduction in project implementation cost	●	●	●	●	●
Reduced project implementation period	●	●	●		
Determination of DSM project feasibility	●	●	●	●	●
Improvement in DSM project design	●	●	●		
Improved component design	●	●			

5.2 Future work and recommendations

Recommendations for future work are the following:

- Recommendations pertaining to software:
    i. It is recommended that more modules and/or combinations of software packages should be included in simulations for a wider range of applications. This would lead to DSM projects having a wider reach in plants, resulting in higher energy savings.
    ii. The development of a holistic approach with regard to energy savings is recommended. This is applicable to mines and/or other industries. All processes and operations at a mine, including ore transport, plant maintenance, cooling and ventilation can be simulated and optimised in order to achieve energy or cost savings or both.
    iii. The design and development of in-house software in conjunction with in-house products such as REMS is recommended in order to allow the use of a single software package to perform both simulations and control.

  iv. It is recommended that financial models should be developed to assess projects that are based on financial feasibility by quantifying and comparing the cost-benefit ratio of technically viable solutions. This should include the total cost of ownership of proposed design changes as well as the influence of proposed solutions on production output. By using simulation models to ascertain the technical viability of projects and financial models to determine financial feasibility, a more complete and rigorous techno-economical assessment of proposed interventions can be done.

- Recommendations for simulation applications:
  i. It is recommended that simulations should be applied to a wider range of sub-systems to identify the potential for more energy savings.
  ii. In order to circumvent unintended consequences that are related to DSM projects which are intended to save energy (and hence reduce the energy-related impact on the environment), it is recommended that the total impact of proposed design changes on the environment should be taken into account in DSM projects.
  iii. The use of a formal mine configuration management system should be encouraged as good management practice to support current and future design changes, analyses and plant maintenance.
  iv. It is proposed that the implications of assumptions (in the case of incomplete layout and other relevant data) should be analysed in a parametric study to quantify the influence of variations in the range of parameters that are related to these assumptions.

The impact of simulations in DSM projects has been demonstrated in this study by simulation, analyses and comparison of innovative design proposals to achieve significant energy savings.

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