

NEW INTEGRATED APPROACH FOR COMPRESSED AIR OPTIMISATION

Techniques to assess and integrate energy saving strategies on mine compressed air systems

3 NEW INTEGRATED APPROACH FOR REDUCING COMPRESSED AIR USAGE

3.1 Introduction

Different energy saving initiatives were investigated and discussed in the previous chapters. It was found that the results of similar techniques implemented at one mine differed from the results obtained at another mine. A further observation was that the results of compressed air energy saving projects are often misinterpreted.

This misinterpretation is the result of misunderstanding mine compressed air systems. It is difficult to simulate the responses of mine compressed air systems due to various factors such as the unpredictable usage patterns of each individual pneumatic tool or system, and the frequent changes to the system layout.

A simplified compressed air system analysis tool is required to understand the impact of energy saving projects on mine compressed air systems. Mine compressed air systems can be simplified by comparing it to a pressure vessel with a variable compressed air demand and supply. The effect of energy saving initiatives on the simplified system can then be scaled to determine the estimated savings that will be achieved on the actual mine compressed air systems.

System information is required to analyse the energy efficiency opportunities on mine compressed air systems. It is often difficult to find the correct information to investigate the operation of these mine compressed air systems. Techniques to gather essential system information will be discussed to ensure time-effective investigations. Energy saving projects are often done on an ad-hoc basis. A strategy to integrate the different techniques is required to ensure the most effective implementation sequence. A simplified process to populate the simplified model with the correct data will be provided.

3.2 Simplification of mine compressed air systems

The quantification of expected electricity cost savings is important to determine the financial feasibility of energy saving initiatives. This requires techniques to assess the interrelationship between pressures, flows, and so forth. Existing calculation and simulation techniques can be used to quantify the relationship between different parameters in a compressed air system [60], [61], [62].

It is difficult to use most of these techniques for mine compressed air systems due to a shortage of sufficient information. Mine compressed air systems are also very complex. It would be a very time-consuming task to evaluate energy saving initiatives by using complex simulation and calculation techniques. Detailed project investigations will be required to gather all of the information. Project investigations do not always lead to actual energy saving initiatives. All investments made to analyse the system will be lost if investigations do not lead to the implementation of energy saving projects.

This makes it impractical to use complex formulas and simulation models to identify energy saving projects on deep-level mines. Attempts to estimate savings (based on the flow requirements of equipment) revealed that these estimation methods are not accurate and can result in vastly overstated energy saving estimations [33]. The major drawback of flow-based calculations is that it is impossible to identify the demand patterns of all consumers (including leaks) in a mine compressed air system.

Commercially available simulation packages such as KYPipe can be used as an alternative simulation tool [63]. The major drawback of most simulation models for use on mine compressed air systems is that these simulation models require input data not readily available for most mine compressed air systems.

This is mostly due to the lack of proper instrumentation to measure system parameters required as input data by the simulation models. System parameters such as pipe roughness, pipe distances, pipe elevation and flow rates must then be estimated.

Incorrect assumptions result in poor accuracies of estimated savings. Comparisons between actual data and simulated data from simulations on mine compressed air systems can result in variations of as much as 27% [63].

A simplified calculation method is required to enable quick estimation of energy saving impacts on compressed air systems. Mine compressed air systems can be simplified by evaluating equations that represent the relationships between the air delivery and the air demand. Equation 3 was used in Chapter 1 and Chapter 2 to evaluate the factors that influence the compressed air demand. Equation 3 is shown again for reference purposes:

$$\dot{m}_{air} = C_{discharge} \left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \frac{p_{line}}{RT_{line}} A \sqrt{kR * 1000 \left(\frac{2}{k+1} \right) T_{line}}$$

Equation 3 can be rewritten as follows:

Equation 6:

$$\dot{m}_{air} = \frac{\left(\left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \sqrt{kR * 1000 \left(\frac{2}{k+1} \right) T_{line}} \right)}{RT_{line}} \times A \times C_{discharge} \times p_{line}$$

Where:

- \dot{m}_{air} = Compressed air mass flow rate (kg/s)
- k = Specific heat ratio
- R = Gas constant (0.287 kJ/kg.K)
- T_{line} = Line temperature (Kelvin)
- A = Minimum cross-sectional area (m²)
- $C_{discharge}$ = Discharge coefficient
- p_{line} = Line pressure (kPa)

The specific heat ratio (k) and the gas constant (R) for air will remain fixed for a mine compressed air system and will be considered to be constant values. It is assumed that the change in line temperature will also be negligible. The effect on the mass flow rate for a change in line pressure or the physical properties and number of leaks can be evaluated by simplifying Equation 6 as follows:

Equation 7:

$$\dot{m}_{air} = F_{flow_pressure_leak} \times A \times C_{discharge} \times P_{line}$$

Where:

\dot{m}_{air}	= Compressed air mass flow rate (kg/s)
$F_{flow_pressure_leak}$	= Mass flow to line pressure and leak ratio (kg/kPa·s·m ²)
A	= Minimum cross-sectional area (m ²)
$C_{discharge}$	= Discharge coefficient
P_{line}	= Line pressure (kPa)

The saving approximation method for air distribution control, developed in Chapter 2, showed that there is a direct relationship between a change in system pressure and compressor power consumption. Results showed that an absolute pressure reduction of X% would result in an approximated compressor power reduction of X% if the compressor discharge pressure remains unchanged. The reduction in mass flow only applies to the part of the system where the pressure is reduced.

The power consumption of a compressor can be evaluated by considering Equation 4. This equation is the combination of Equation 1, Equation 2 and Equation 3 and was evaluated in previous sections. This equation can be simplified by assuming that projects that focus on the changes to the demand side of the system, or the compressor delivery pressure, will not result in changes to inlet temperature, compressor efficiency, motor efficiency and intercooling. Equation 4 can then be rewritten as follows:

Equation 8:

$$P_{electrical} = F_{Power_pressure} \times p_{line} \times \left[\left(\frac{p_2}{p_1} \right)^{(n-1)/n} - 1 \right]$$

Where:

$P_{electrical}$ = Electrical power (kW)

$F_{Power_pressure}$ = Power to flow ratio (kW/kPa)

A = Minimum cross-sectional area (m²)

$C_{discharge}$ = Discharge coefficient

p_{line} = Line pressure (kPa)

p_2 = Compressor discharge pressure (absolute pressure) (kPa)

p_1 = Compressor inlet pressure (kPa)

n = Polytropic compression exponent

Equation 8 shows that a change in line pressure at a fixed inlet temperature, compressor efficiency, motor efficiency and intercooling would result in a change to compressor power consumption. Analyses of actual results in Chapter 2 showed that a factor ranging from 1.6 to 1.8 can be used to estimate the compressor power savings due to a reduction in compressor discharge pressure.

This implies that an absolute pressure reduction of 10% should result in a theoretical saving of between 16% and 18%. The saving approximation method for a change in system pressure is only applicable if the pressures remain between 300 kPa and 700 kPa. Equation 8 will not be suitable for projects that involve changes to the efficiency of compressors or motors, changes to the intercoolers, or a reduction in inlet temperature.

Equation 8 can be used to calculate the effect on compressor power consumption for projects that focus on changes to the demand side of the compressed air system as well as projects where the system pressure is reduced. A summary of the saving approximation methods that were verified in Chapter 2 is provided in Table 3.

Table 3 – Summary of saving approximation methods

Energy saving technique	Saving approximation method
Reduce compressor delivery pressure	<p>An X% reduction in absolute system pressure will result in a 1.6X% to 1.8X% reduction in compressor power consumption.</p> <p>This is only valid if the compressors can reduce output capacity by 1.6X% to 1.8X%.</p>
Reduce system pressure in selected sections of the system	<p>An X% reduction in absolute pressure will result in an $(X \times Y)\%$ reduction in compressor power consumption; where Y is the percentage contribution to the total system demand by the part of the system that will be controlled to the new pressure.</p> <p>This is only valid if:</p> <ol style="list-style-type: none"> 1. Compressors can reduce compressed air delivery by $(X \times Y)\%$ by means of capacity control systems such as inlet guide vane control, compressor shut down; 2. System pressure will remain unchanged; 3. The controlled portion of the system does not have other uncontrolled connections to the system.
Reduce compressed air flow demand	<p>An X% reduction in flow will result in an $(X \times Y)\%$ reduction in compressor power consumption; where Y is the percentage flow contribution to the total system flow through the part of the system where flow will be reduced.</p> <p>This is only valid if:</p> <ol style="list-style-type: none"> 1. Compressors can reduce compressed air delivery by $(X \times Y)\%$ by means of capacity control systems such as inlet guide vane control or compressor shut down; 2. System pressure will remain unchanged; 3. The controlled portion of the system does not have other uncontrolled connections to the system.

Simplification of mine compressed air systems can be accomplished by grouping all air consumers at a mine as either productive or non-productive leaks. An example of a productive leak following this approach is a piece of equipment that was designed to consume compressed air to provide valuable work, such as a pneumatic rock drill. A leak as a result of damage to a compressed air pipe is an example of a non-productive leak.

A mine compressed air system can then be viewed as a single pressure vessel with a demand equal to the total demand from productive and non-productive leaks. A graphical representation of this simplified view is shown in Figure 26.

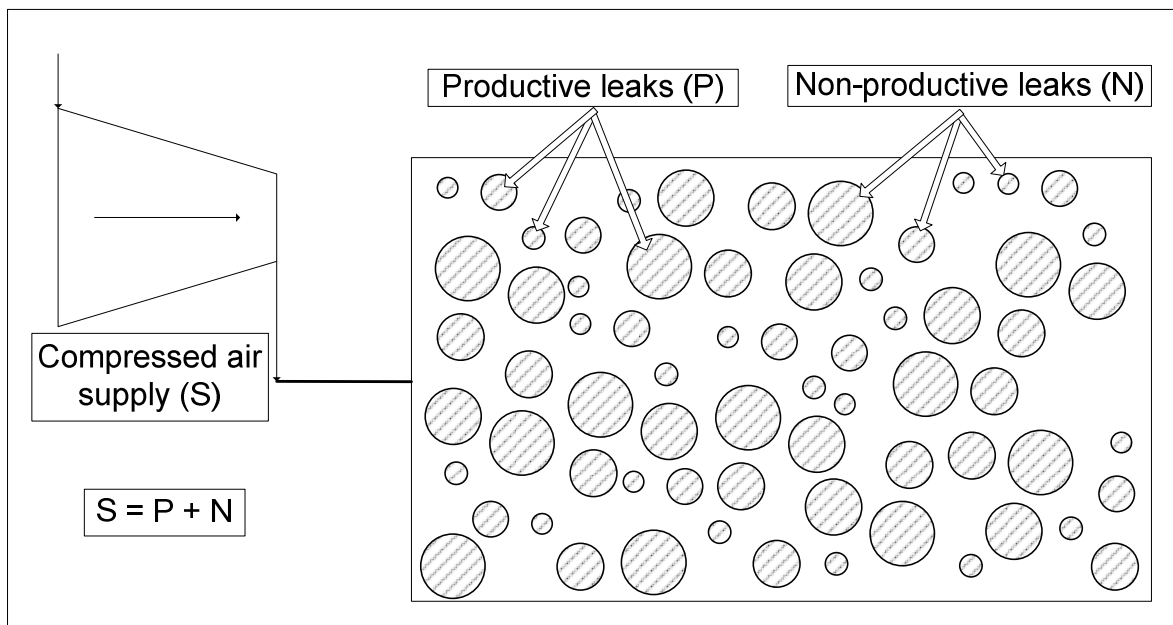


Figure 26 – Simplified view of a compressed air system

The efficiency of the system can be improved by optimising the supply- or the demand side of the system. The simplified model consists of a compressed air supply and a pressure vessel that comprises productive and non-productive leaks. This simplified view, combined with the saving approximation methods, will now be used to investigate the system's response due to different energy saving initiatives.

3.3 System response due to energy saving initiatives

The real energy savings of compressed air projects are not always correctly quantified. This occurs because the system response is often misinterpreted. The simplified model will be used to investigate the impact of different energy saving initiatives.

Leak repair is one of the first options considered when it is required to reduce compressor power consumption. Management of leaks on mine compressed air systems are difficult due to the size and the complexity of the systems. However, effective leak management on deep-level mines could be significant enough to justify employing dedicated leak-detection and repair personnel [14]. The real impact of leak repair on typical mine compressed air systems will be analysed as a first approach to energy savings. Assume that some of the leaks of the simplified compressed air system are fixed without implementing any other changes to the system.

Increased system pressure as a result of improper compressed air supply control during lower demand periods was evident at Mine 2. A constant compressed air supply rate with a reduction in demand, due to leak repair, will therefore also result in a system pressure build-up. It is known from Equation 7 that an increase in pressure would result in increased mass flow through the remaining leaks. The reduced demand due to the fixing of some leaks could thus be negated by an increased flow rate through the remaining leaks.

A further problem encountered when system pressure increases due to low demand is the operation of equipment designed to protect the compressed air system against high system pressures. One of the control measures involved pressure relief valves (also called blow-off valves) that would open when the system pressure increased above specified values.

A photo of a compressor rated at 112 800 m³/h is shown in Figure 27. The compressor is powered by a 15 MW electrical motor. The blow-off valve of this compressor is highlighted on the photo. The exact pipe diameter of the blow-off pipe assembly is not known, but is estimated to be 200 mm. Theoretical calculations indicate that an open ended pipe with an inside diameter of 200 mm would result in compressor power consumption of 11.5 MW (refer to Appendix A for the calculations).

So, a fully open blow-off valve could result in power consumption of as much as 77% of the motor's installed capacity. The operation of the blow-off valve would therefore result in the creation of another "leak" at the supply point. Therefore no energy would be saved through a leak management programme if it is not possible to reduce the compressed air supply. The effect of the reduced number of leaks due to the leak repair on a simplified system without compressor capacity control is shown in Figure 28.



Figure 27 – Photo showing the blow-off valve of a mine compressor¹⁴

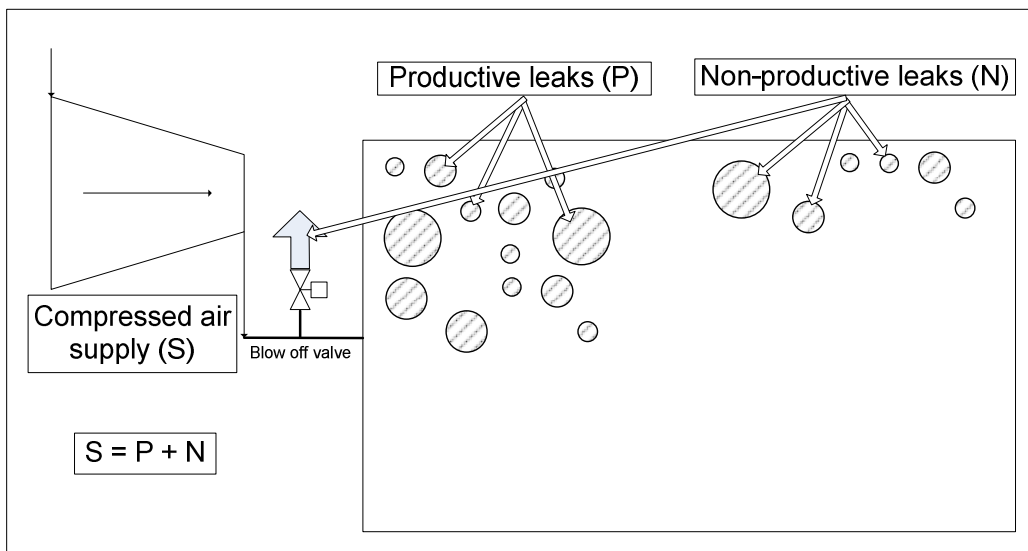


Figure 28 – Small leaks replaced by major leak due to blow-off valve

¹⁴ Photo taken at a South African mine

The results investigated in Chapter 2 showed that improvements on the supply side of compressed air systems led to reduced energy consumption on mine compressed air systems. It was observed that the use of more efficient compressors resulted in savings of as much as 47% without significant changes to the compressed air consumption patterns or the system pressure at Mine 1.

Another example of efficiency improvements that focused only on supply side optimisation was evident at Mine 2. The initial set-up of the control system at Mine 2 resulted in the inefficient operation of the compressors. Proper system configuration increased the saving by 35%. The system pressure during the production period, after the improved configuration, was on average 10% higher than the baseline pressure.

Most mining operations require higher pressures during the production shifts than during the non-production shifts. The post-implementation pressures at Mine 2 gave a better representation of the expected pressure requirements during both the production and the non-production shifts. The post-implementation pressures during the non-productive shifts were on average 9% lower than the pressures during the production shifts.

The drilling shift, also called the production shift, is known to have the highest compressed air demand. The increased demand is mostly due to productive leaks such as pneumatic rock drills. The initial set-up of the compressor control system at Mine 2 was unable to match the supply with the demand during the non-production period. An energy saving project implemented at Mine 2 proved that it is required to reduce the compressed air supply when the demand is reduced in order to realise the energy savings.

The varying pressure demand due to the shift cycles at mines makes it possible to lower the system pressure during certain times of the day. However, processing plants typically require a constant pressure supply of approximately 500 kPa over a 24-hour period. Processing plants consume between 1% and 16% of total mine compressed air demands [64]. These processing plants are often dependent on a compressed air supply from the compressed air ring. This dependency creates a requirement to have a constant ring pressure at all times even though processing plants consume only a fraction of the total compressed air demand.

Results discussed in Chapter 2 proved that it is possible to reduce compressed air consumption by controlling the distribution of compressed air. Analysis of the results verified that there is a one-to-one relationship between pressure reduction and compressor power reduction. The saving approximation method for air distribution control suggests that a reduction in absolute air pressure results in a reduction in compressor power consumption for the portion of the system that is controlled. A graphical representation of surface distribution control implemented on the simplified system is shown in Figure 29.

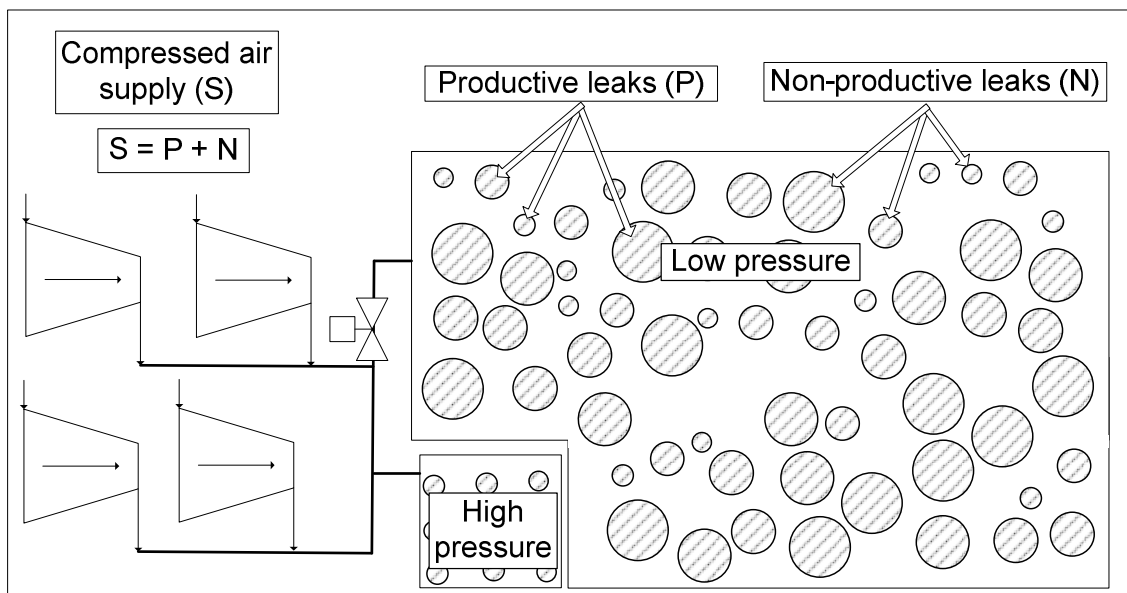


Figure 29 – Surface distribution control for the simplified system

Projects that involve surface control valves were investigated in detail and the results were discussed in Chapter 2. Control valves were installed at some mines to reduce the compressed air demand during non-peak production periods. The reduced demand due to the installation of control valves would also create an increase in system pressure if the supply was not properly adjusted.

A reduction in compressed air supply is therefore required to realise the benefits of the control valves. This was confirmed during the analysis of the results obtained from a project that involved the installation of control valves at Mine 5. The analysis proved that it was necessary to change the discharge pressure set points of the compressors along with the surface control schedules [53].

It is possible that the combination of installed compressors would not be able to adapt to the reduced demand. The installation of smaller compressors could then be considered. The simplified view, adapted to show a system with a dedicated plant compressor, is shown in Figure 30.

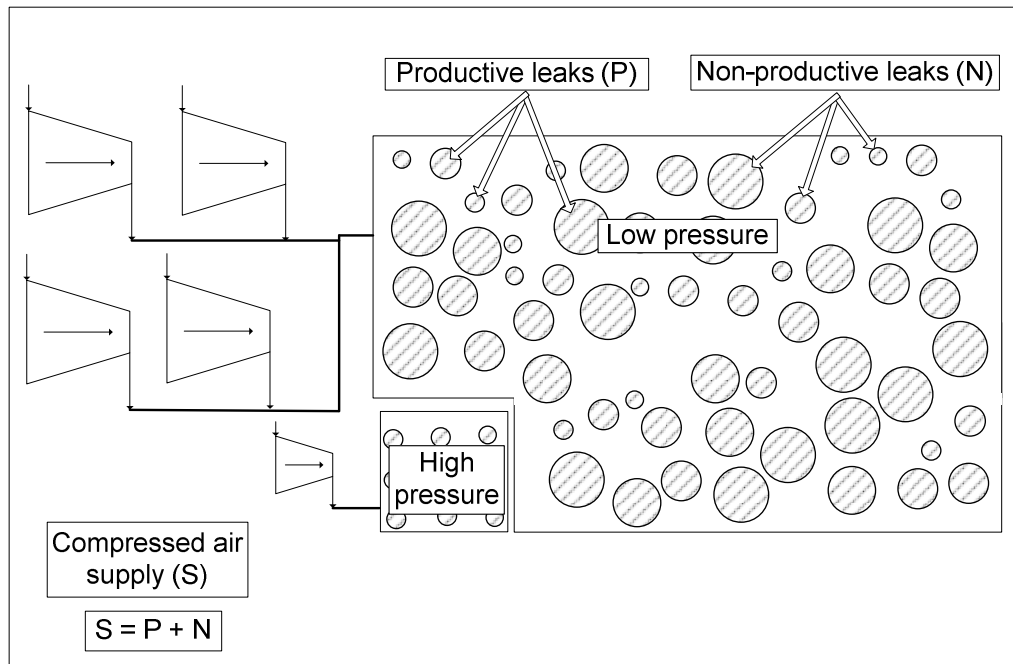


Figure 30 – Simplified mine compressed air system with a dedicated plant compressor

One of the advantages of a dedicated plant compressor is that the entire ring pressure can be reduced during non-drilling periods. Analysis of the results obtained from projects that involved surface system pressure reduction proved that the percentage of electrical savings achieved was between 1.6 and 1.8 times the percentage of the pressure reduction.

Projects that involved the installation of level control valves were discussed in Chapter 2. The pressure reduction on controlled levels resulted in an increase in upstream pressure and therefore increased the mass flow to the uncontrolled levels. Data analysis showed that the compressed air demand on the controlled levels was reduced by the same percentage as the pressure reduction percentage. The overall effect on total compressor power reduction was dependent on the controlled levels' contribution to total flow demand.

Underground valves are suited for applications where a single surface control valve cannot be used because the pressure requirements differ between the various underground levels. Different demands can therefore be met by using multiple control valves. A simplified view of a compressed air system with multiple control valves is shown in Figure 31. The reduced demand on the controlled levels is likely to cause an increase in upstream pressure. Control valves on high-pressure levels could, however, still be required to ensure that the pressures on these levels remain within the correct pressures range in the event of increased system pressures.

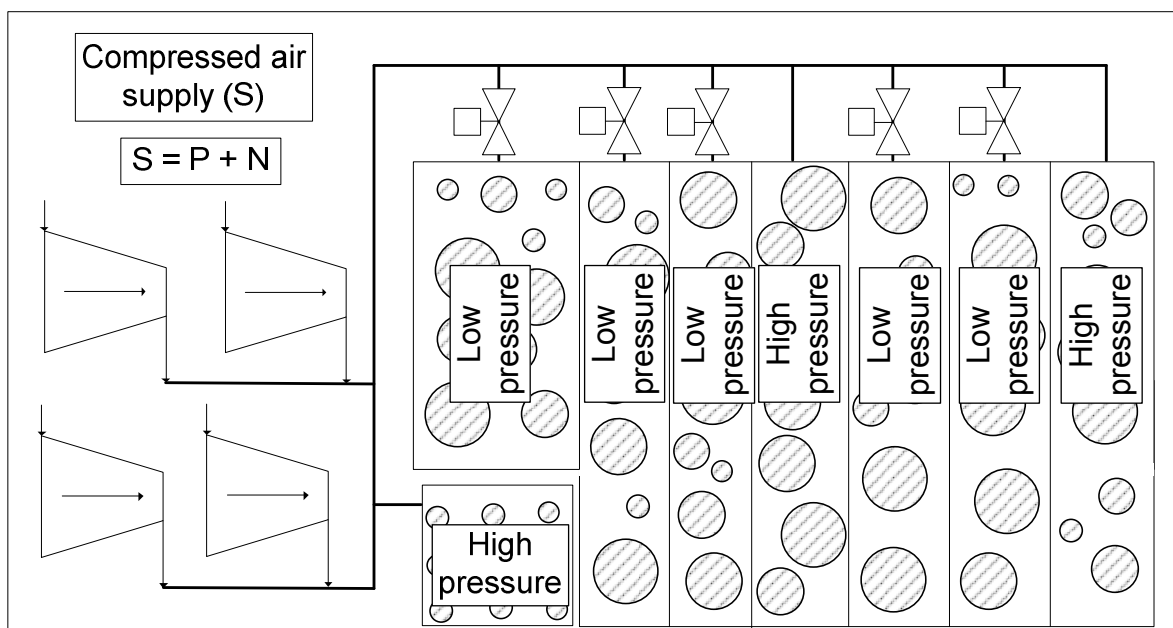


Figure 31 – Level control on the simplified system

The simplified view of a compressed air system with level control highlights the possibility of replacing high-pressure pneumatic equipment with either low-pressure pneumatic equipment or electrically powered equipment. Peak compressed air demand at all of the gold and platinum mines investigated occurs during the drilling shift.

Pressure requirements during the drilling shifts are normally determined by the pneumatic rock drills. The pressure requirements of other pneumatic equipment - such as loaders and the cylinders that operate loading box doors and chutes - are normally equal to, or less, than the requirements of the rock drills. The operating times of these loaders, loading boxes and so forth are, however, not always limited to the drilling shift alone.

It is inefficient to pressurise an entire mine compressed air system just to have sufficient pressure for equipment such as loading box cylinders that have low duty cycles and consume only a fraction of the total compressed air supply. Projects that involve the conversion of pneumatic cylinders on ore-loading equipment to hydraulically powered alternatives enable lower pressure requirements of only 120 kPa during non-drilling times [45].

Pneumatic equipment replacement that focuses on the replacement of equipment with high-pressure requirements with low duty cycles allows the reduction of system pressure during non-drilling periods. The replacement of high-pressure, high-flow pneumatic equipment that operate during fixed periods per day - such as pneumatic rock drills - with alternative power sources such as electricity or hydraulics proved to be too expensive considering the technologies currently available.

The replacement of high-pressure, low duty cycle pneumatic equipment could remove the need for level control valves. However, investigations revealed that the shift cycles at some mines differ between levels. So, surface pressure reduction would be limited to times when the pressure requirements on all levels are similar. This would limit the control period and therefore reduce the savings.

Maximum reduction in compressor power consumption by means of the mentioned techniques requires the integration of the different techniques. The first requirement for this approach is the daily stopping and starting of “top-up” compressors. The second requirement is automated demand control with surface and underground control valves.

The effect of demand control savings can be maximised by removing high-pressure equipment that operate during non-drilling periods from the main compressed air ring. Options to remove these systems from the ring include the installation of dedicated compressors as well as hydraulic conversions. A simplified view of a compressed air system with integrated control and management is shown in Figure 32.

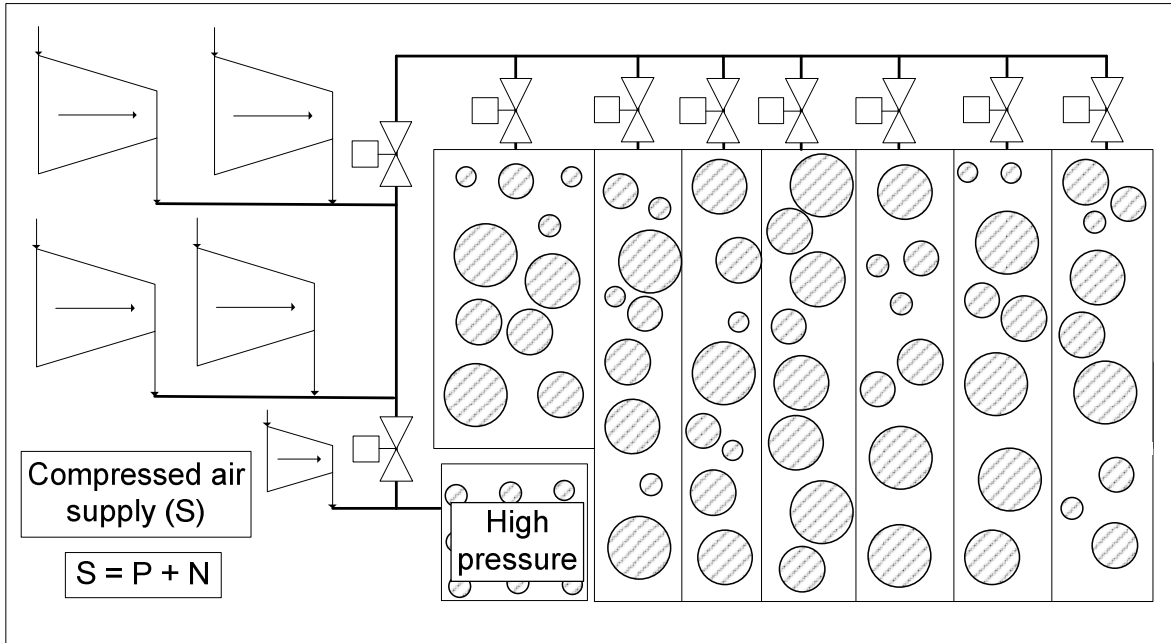


Figure 32 – Simplified view of a mine compressed air system with integrated control and management

3.4 Gathering of system information

Correct information is required to determine the scope of energy saving projects on mine compressed air systems. A big problem during investigations was the unavailability of information relevant to the reduction of compressor power consumption. The availability of information that is not relevant could result in “overanalysis” of the system. This section provides techniques to identify which data and information are required to analyse the scope of energy saving projects on mine compressed air systems.

The first requirement is to understand the surface compressed air layout. It is not practical to try to understand the layout of the compressed air systems because it changes too frequently. A surface layout of the compressed air system that indicates the location and the capacity of the compressors is required. Major compressed air users must be indicated on the layout. Critical constraints applicable to the surface system must be gathered. This includes details such as the minimum surface pressure requirements for the different production periods.

Detailed information about all compressors is required. Information required is summarised as follows:

- **Location** – The estimated distance between compressor locations and end-users.
- **Typical compressor supply capacity** – The nameplates of most compressors state the designed flow capacity. Actual flows can be confirmed with measurements from flow meters if available.
- **Compressor capacity range** – Inlet valve control on compressors enables capacity control. The control range of the compressor will depend on the design and set-up of the machine. It is required to know the safe operating range of each compressor in the system. Most centrifugal compressors used on deep-level mines have control systems installed to prevent surge. Some mines also have monitoring systems such as Supervisory Control and Data Acquisition (SCADA) systems installed. Data logged by these monitoring systems can be used in the system analysis.

Flow data for individual compressors is, however, not always available. The flow ranges determined for similar compressors installed at other mines could be used to estimate the flow ranges for the compressors without flow data.

Temporary flow meters can also be installed to determine the capacity range of the compressor. The installation of most compressed airflow meters does, however, require drilling of holes and welding of sockets onto the pipes. The pipes must therefore be depressurised before commencement of the installation. This requires system downtime and is not always a feasible solution.

- **Typical power consumption per compressor** – The actual power consumption of compressors must be determined to evaluate energy saving possibilities. The monitoring systems installed at some mines could possibly log compressor power consumption. However, such logging systems are not always operational or not installed at all. The operation of critical compressors at deep-levels mines is often monitored by compressor attendants.

The attendants are required to periodically write vital compressor information such as pressures, temperatures, vibrations and compressor power consumption onto paper log sheets. The log sheets can be used to determine the typical power consumption profiles of the compressors.

These log sheets are not always accurate, though, due to writing errors or because attendants fail to regularly log all data. The actual power consumption of the compressors is not always logged by the operators. Other logged parameters can then be used to determine the running status of the compressors.

The electrical power consumption of compressors will vary according to demand. Most compressors operate between fixed upper- and lower power values. Compressor running statuses would thus not provide an accurate representation of compressor power consumption.

Portable power loggers can be installed in the absence of reliable log sheets or electronically logged data. A big drawback of temporary loggers is time delays experienced during the investigation because the loggers must be installed for extended periods to ensure that an accurate representative baseline is logged.

- **Level of automation** – The level of compressor automation differs from mine to mine. Compressors without any automatic control were found at some mines. Operators at these mines are required to manually change inlet valve positions, operate the blow-off valve, control all auxiliary equipment and stop and start the compressor according to demand.

This is in contrast with other mines that have full automatic control. Some of these automatic control systems have the capability to stop and start without any operator intervention. A fully automatic control system will control the blow-off valve, inlet valve position, control auxiliary equipment and stop and start the compressor according to demand.

It is important to know the individual compressors' control capabilities. Some compressors could require inexpensive upgrades to allow fully automatic control, where others would require an expensive upgrade.

- **Stopping and starting constraints** – It was found that some mine personnel do not allow daily stopping and starting of compressors. One of their biggest concerns is the risk of extra maintenance requirements due to increased wear. A further concern is the risk of a compressor that fails to start again when additional supply is required.

The mine personnel would therefore prefer that most compressors are operated with open blow-off valves while demand is low.

A system comprising multiple compressors and shafts requires a reliable control communication system to ensure optimal operation. Proper compressed air control can only be implemented if critical information such as system pressures at various points and running statuses of all compressors are known. Pressure requirements for mining operations depend on the type of pneumatic equipment used during the different shift cycles. A list that provides an indication of the typical pressure requirements of different users during different periods is required.

One of the major challenges in mine compressed air systems is to understand the requirements for compressed air at each level. Detailed layouts that show all compressed air users on all the levels are hardly ever available. The dynamic operation of mines also results in frequent changes to the compressed air system. Changes to the systems will most likely occur from the time of the investigations to the time when the projects are approved.

A simplified view showing the typical layout of underground levels could identify underground valve installation. The pressure requirements for the different shift cycles must be determined. The typical location and pressure requirements of pneumatic equipment combined with their operating schedules could be used to identify focus areas. The requirements and estimated locations for the refuge bays must be determined if underground control valves are considered

Typical system pressure profiles are required to simulate the response of the system. SCADA data or manual log sheets can be used to determine the baseline pressure profile. Portable temporary loggers can be installed if other data is not available. If available, flow measurements can be used to identify unaccounted air consumption typically attributed to leaks.

3.5 Integration of different techniques

Results from existing energy saving projects on deep-level mines proved that it is often beneficial to integrate different energy saving strategies. Previous attempts to integrate some commonly used energy saving techniques implemented on mine compressed air systems can be summarised as follows [33]:

1. Reduce the demand for compressed air by replacing or converting pneumatic equipment with alternative power supplies.
2. Reduce the pressure requirements of equipment.
3. Limit pneumatic equipment usage by changing their operating periods to enable a varying pressure profile with reduced pressure set points during certain periods.
4. Manage consumption due to air leaks by performing regular inspections and maintenance on the compressed air system.
5. Ensure that pipe sizes are suited for the flow requirements.
6. Separate high pressure systems from low-pressure systems.
7. Implement compressor capacity control systems.
8. Reduce compressor inlet air temperature.
9. Install intercoolers and aftercoolers on the compressors.
10. Replace existing motors with more efficient motors.
11. Install VSDs for capacity control.

Results from two case studies where the integration techniques were implemented realised a combined daily average saving of 8 MW [33]. It was therefore proved that significant savings are possible with the integration of the energy saving techniques.

A major requirement not addressed by Snyman [33] is the need to have a preferred implementation sequence. As an example, a reduction in compressed air demand as suggested by Points 1, 2, 3 and 4 would not result in energy savings if the supply for compressed air was not reduced. This would merely result in an increase in system pressure, resulting in increased flow through leaks in the system.

The integration of these strategies must therefore be done in the correct sequence to maximise the savings and minimise the implementation costs. The combination of the implementation costs and the predicted energy cost savings of projects determine the payback periods of projects.

A strategic approach must thus be followed to determine the saving strategy that would provide the most suitable solution. A compressed air saving strategy was developed for deep-level gold mines in South Africa. Different energy saving strategies, including the replacement of compressed air equipment with alternatives, were investigated [64].

The implementation sequence for the different strategies was compared to the predicted total mining group power consumption. The contribution of the compressors to the total power consumption of the mining group is shown in Figure 33. The particular mining group has two separate mining complexes. The two complexes are referred to as complex A and B respectively. Compressor power consumption at these two complexes contributed 14% to the total energy consumption of the mining group [64].

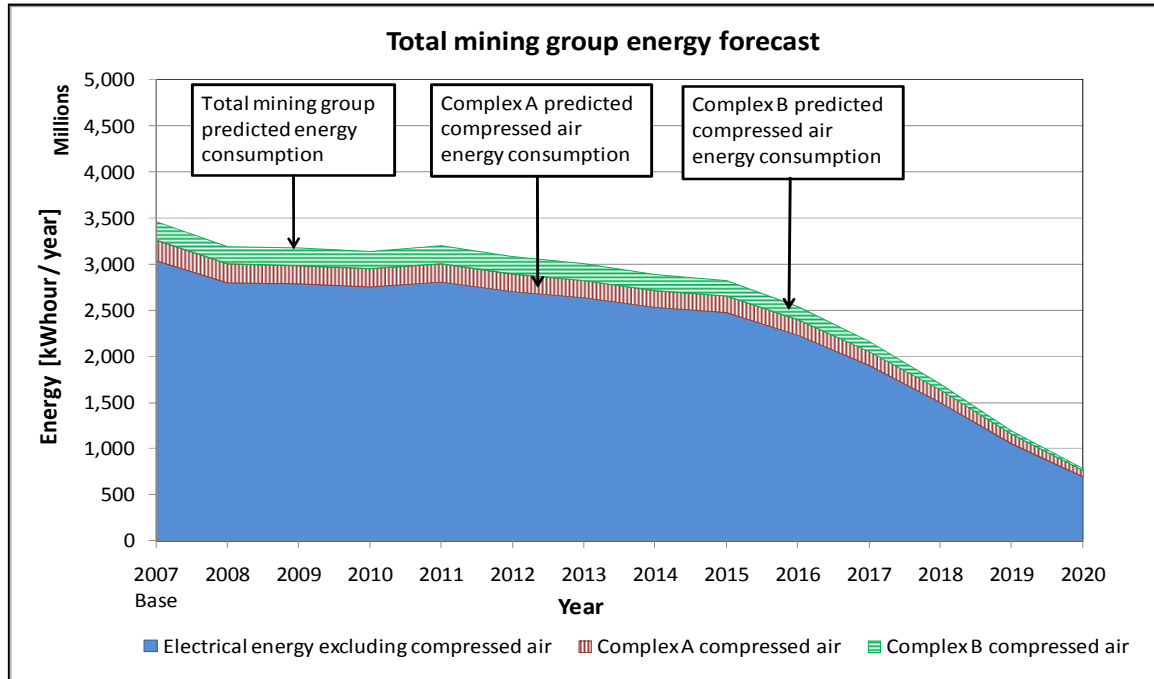


Figure 33 – Mining group energy forecast [64]

This study was based on a system where all the compressors were fully automated. It was therefore assumed that compressed air supply would automatically change according to the demand for compressed air. Most mines considered during this study did not have automated compressors. Savings as a result of improved compressor operation will be considered as the first approach for energy saving projects.

The savings opportunity for compressor selection and control depends on the existing system set-up. Savings of as much as 50% were achieved by means of efficient compressor control [22]. It was also seen that many of the energy saving projects that focused on other techniques (such as valve control) required changes to compressor control philosophies. It is evident that efficient compressor selection and control are important for any energy saving project. The first focus of energy saving projects must then be to ensure that the correct combinations of compressors for different shift cycles are selected.

The system pressure of compressed air systems is normally determined by the equipment with the highest pressure requirement. It was, however, found at mine compressed air systems that system pressures are often higher than what was really required to compensate for other system inefficiencies such as pressure losses.

These pressure losses can occur due to long pipe lengths, leaks, undersized pipes, rough inside surfaces and so forth. Analysis of mine compressor control systems showed that most control systems cannot properly adapt compressed air supply during low demand periods. This resulted in pressures that were much higher than what is really required.

The strategic plan developed by Kleingeld assumed a saving of 20% for underground valve control for systems without any existing valve control. A further assumption is that the saving would be between 10% and 15% where some control valves were already installed prior to the commencement of a new project. This type of control was referred to as network control. The projected cash flow for underground control valves according to the strategic plan is shown in Figure 34 [64].

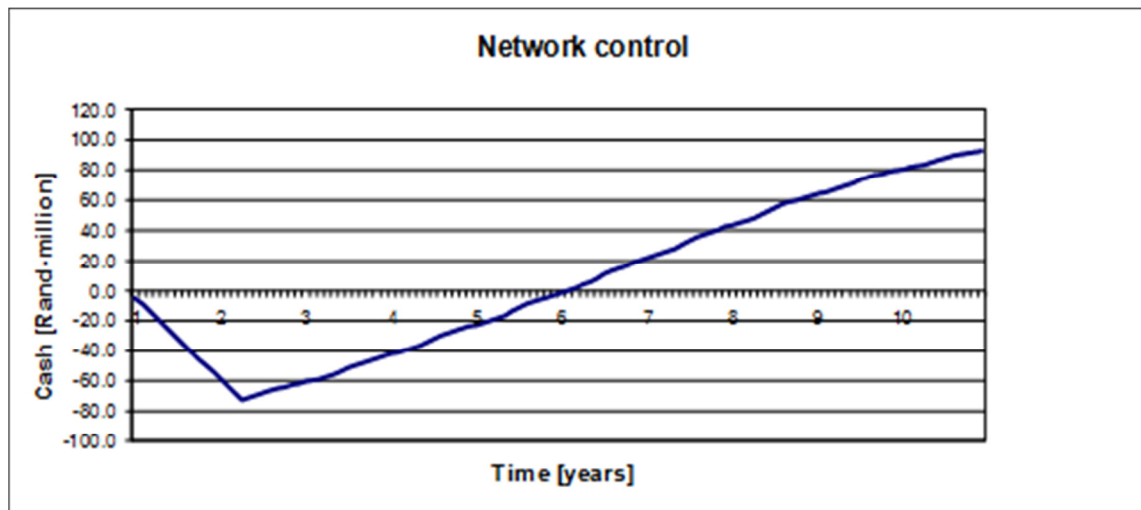


Figure 34 – Projected cash flow for network control [64]

Results analysed in Chapter 2 proved that pressure reduction through valve control could be used to reduce compressor power consumption. Valve control is well suited when the different surface compressed air users have varying pressure requirements. A good example is precious metal processing plants that depend on compressed air supply from the compressed air ring. The entire compressed air ring must be pressurised according to plant pressure requirements during periods when much lower pressures are required at the shafts.

The flow consumption of processing plants is typically much lower than that of typical production shafts. Pressure requirements for most of these plants range between 450-500 kPa. The plants require a minimum compressed air pressure throughout the entire day. This minimum requirement is often higher than other consumers' requirements at the shafts while the shafts have varying pressure requirements throughout the day.

Control valves could be used to reduce the pressure of the shaft compressed air systems during periods with lower pressure requirements. This would result in decreased losses through leaks as well as improved system efficiency due to a decrease in pipe friction losses.

Savings in flow demand could therefore be realised while the pressure requirements of the high-pressure users such as the processing plants are maintained. The decrease in consumption must be followed by a decrease in compressor delivery to reduce electricity consumption.

Underground operations on most mines follow a fixed-shift cycle. It is, however, not possible to hoist all workers between surface and underground working levels at the same time. Operation of mining equipment such as rock drills will not commence at the same time on all levels. So, control valves installed on underground levels could result in increased savings by controlling according to the shift cycle of each level. The additional savings due to the improved control would not always be enough to offset the increased costs of the underground valves compared to a single surface control valve.

High-pressure equipment such as pneumatic loading boxes and transfer chutes do not always follow the normal shift cycles. This increases the shaft pressure requirements outside peak drilling periods. The savings due to a surface control valve would therefore be limited by the requirements of the loading boxes. Correct placement of underground valves could then be used instead of a single surface valve to increase the savings. For instance, the control valve could be installed just after the compressed air connection for the loading box. This would enable a reduction in level pressures during blasting periods. A big drawback of underground valves is that accessibility to the valves makes maintenance tasks difficult that result in valve failures that impede sustainable savings.

The harsh operating environment of the underground control valves necessitates a rigorous maintenance plan to ensure the correct operation of these valves. The installation of multiple underground valves instead of surface valves could result in improved savings compared to a single surface control valve. This does, however, require that all underground valves are fully functional at all times and that no leaks exist in the main distribution columns.

The installation of a surface control valve in conjunction with underground valves will most likely result in the most sustainable savings. The merits of underground control valves must be determined for each individual project. The installation of these control valves would, however, not result in reduced electricity consumption if compressed air supply is not also reduced.

The plan developed by Kleingeld considered the use of section isolation valves that close automatically during non-production times. This was done to eliminate leaks closer to the working areas during periods when compressed air is not required. This type of control was referred to as advanced network control [64].

The plan assumed that an additional saving of 3.3% would be realised if these isolation valves were installed along with level control valves. The estimated project cash flow for the advanced network control is shown in Figure 35. The estimated project payback for advanced network control was more than the estimated life-of-mine plan at the time of the study. Thus it is not a suitable energy saving approach.

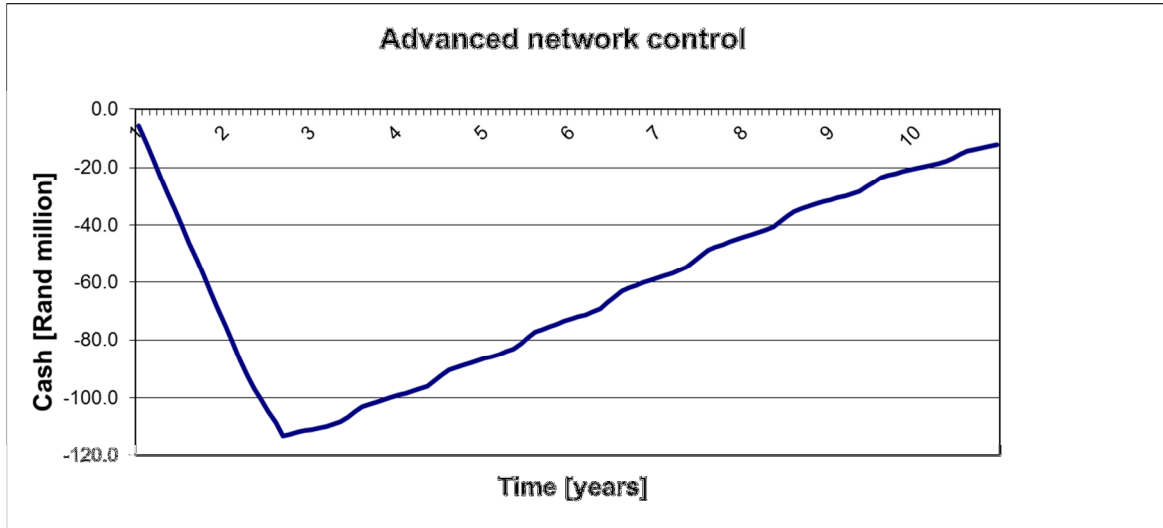


Figure 35 – Projected cash flow for advanced network control [64]

The pressure set points of the control valves determine the savings achieved. These set points are determined by the equipment with the highest pressure requirement. The replacement of these higher pressure equipment that use alternative power supplies will result in lower pressure set points. The replacement of the pneumatic equipment will thus increase the savings.

The high-level plan developed by Kleingeld mentions that most loaders require 450 kPa for proper operation. However, there are some loaders that only require 350 kPa to operate efficiently. The loaders at the mines considered by Kleingeld operate throughout the day. It was assumed that the replacement of 450 kPa loaders with 350 kPa loaders would result in an average daily saving of 30% during working days [64].

The projected cash flow for the replacement of high-pressure loaders with low-pressure loaders estimates a payback period of approximately eight years [64]. The inefficiencies of compressed air systems resulted in the development of alternative technologies. The alternative technologies include electric rock drills, high-pressure water power rock drills, hydraulic loaders, hydraulic loading boxes and so forth. Care should be taken when considering these alternative technologies since the increased maintenance costs on these systems could make it less attractive than compressed air.

Loading boxes is an example of equipment that requires supply pressures of between 450 kPa and 500 kPa when in operation. Most loading boxes have much lower duty cycles than other pneumatic mining equipment such as rock drills and loaders. It will therefore consume much less compressed air. The entire mine compressed air system must, however, be pressurised to ensure sufficient operation of the boxes. The use of alternative technologies such as hydraulic systems will allow a reduction in system pressure during non-drilling periods if control valves are also installed.

The replacement of all pneumatic cylinders on loading boxes could reduce the need for underground control valves. A single surface control valve would then be sufficient. The replacement of the pneumatic loading equipment with hydraulic loading equipment is expensive. It is generally much more expensive to convert one loading box than to install one level control valve. Some ore-loading systems will, however, not require hydraulic conversions on every level. Conversion of critical loading systems, such as the shaft bottom-loading system, could be sufficient to reduce pressure requirements.

Compressed air requirements on surface include processing plants, ore-loading systems and workshop equipment. Surface control valves can be used to reduce losses through leaks in the shaft compressed air systems. This approach ensures sufficient pressure for the surface pneumatic system.

Complete system pressure reduction is possible by removing surface high-pressure equipment from the main ring. Dedicated compressors can then be installed to supply compressed air to the processing plants and workshops. Hydraulic conversions can be used for equipment such as loading boxes. This will maximise the savings of reduced surface pressures because the delivery set points of the compressors could be reduced.

The minimum pressure requirements of all mines differ. The strategic plan developed by Kleingeld suggested a minimum pressure requirement of 150 kPa for mine compressed air systems. This minimum pressure is required to ensure a positive pressure in underground refuge bays. No known alternatives exist to replace compressed air as a means of continuous ventilation of refuge bays. But, most other pneumatic mining equipment can be replaced by non-pneumatic alternatives [64].

The strategic plan does, however, suggest that it would not be feasible to replace all the pneumatic systems used in the processing plants. Compressed air would thus always be required for the plants and the refuge bays. The projected cash flow for a shaft pressure reduction of 150 kPa is shown in Figure 36. It is apparent from the graph that it would not be feasible to re-equip a compressed air operated mine with alternative solutions from available technologies [64].

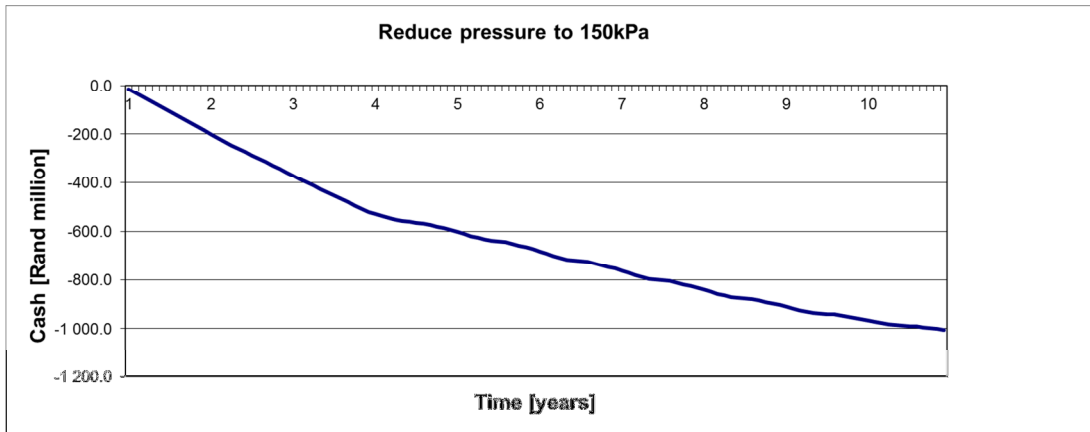


Figure 36 – Projected cash flow for reducing ring pressure to 150 kPa [64]

The strategic plan developed by Kleingeld assumes that sufficient new research and development could replace the need for compressed air for refuge bay requirements. This would enable a mine to operate without any compressed air. The predicted cash flow for the complete removal of compressed air at mines is shown in Figure 37 [64].

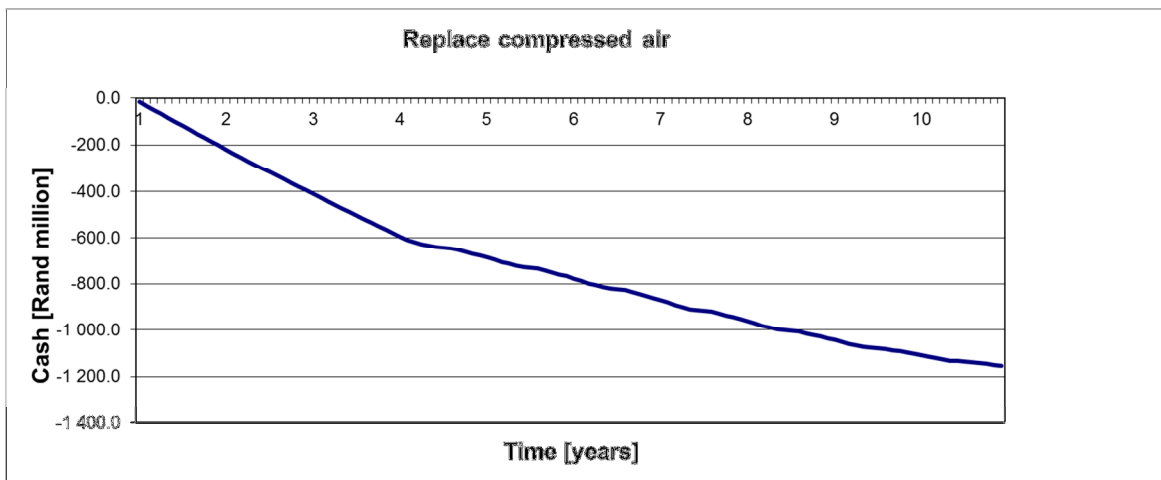


Figure 37 – Projected cash flow for replacing compressed air [64]

A comparison between the different approaches of the plan developed by Kleingeld is shown in Figure 38. The strategic plan suggests that good system control provides the best value for money with a payback period of six years. It also important to realise that some projects aimed at reducing compressor power consumption are not financially feasible.

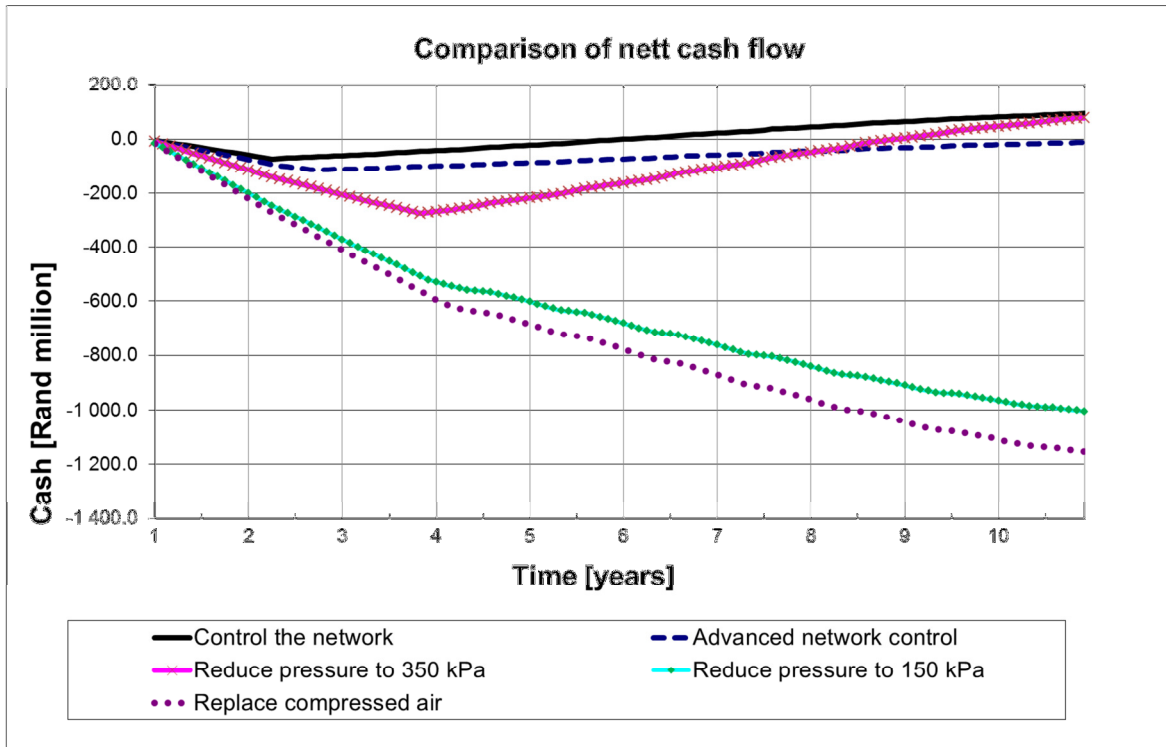


Figure 38 – Nett cash flow for the different initiatives [64]

The implementation sequence for the integrated approach can be summarised in the three easy steps shown in Figure 39. The estimation methods derived and verified in chapter 2 were used as basis to develop a simulation model to predict energy savings for the measures summarised in Figure 39. The simulation model requires input data presented according to the simplified model. A compressed air system must be simplified according to the supply and demand sides before the simulation model is populated.

More details regarding the simulation model cannot be provided because the intellectual property of the model is held by the sponsors of this study. The application of the simulation model will be discussed by using an example of a typical mine set-up.

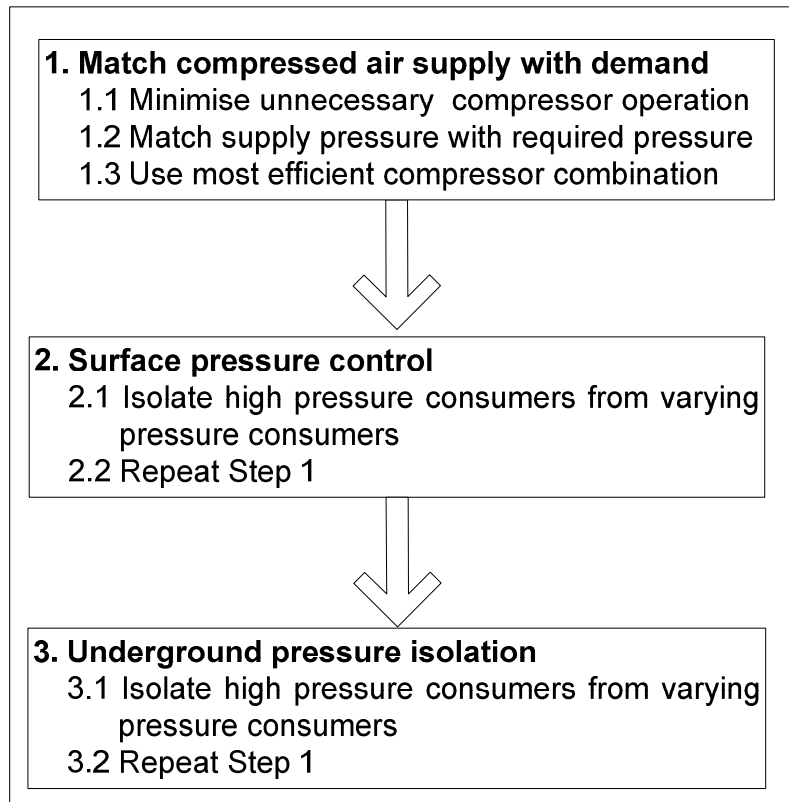


Figure 39 – Flow diagram for integrated approach

3.6 Populating the model with the required data

The procedure to populate the model with system parameters and historic data will be discussed by using a simplified imaginary deep-level mine. This simplified mine will be referred to as Mine X. A simplified layout of a mine compressed air system can be used to indicate the supply and demand points of the system. The surface compressed air layout of Mine X is shown in Figure 40.

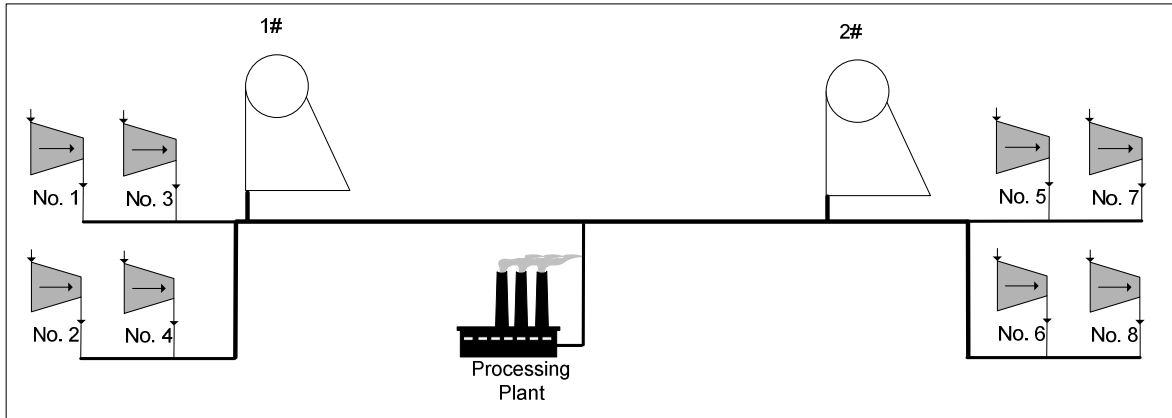


Figure 40 – Simplified surface compressed air layout for Mine X

A view of the simplified model for the same compressed air system is shown in Figure 41. A list of all major consumers and compressors is required to determine whether the efficiency of the system can be improved. A list of the major consumers at Mine X with their operating times is summarised in Table 4.

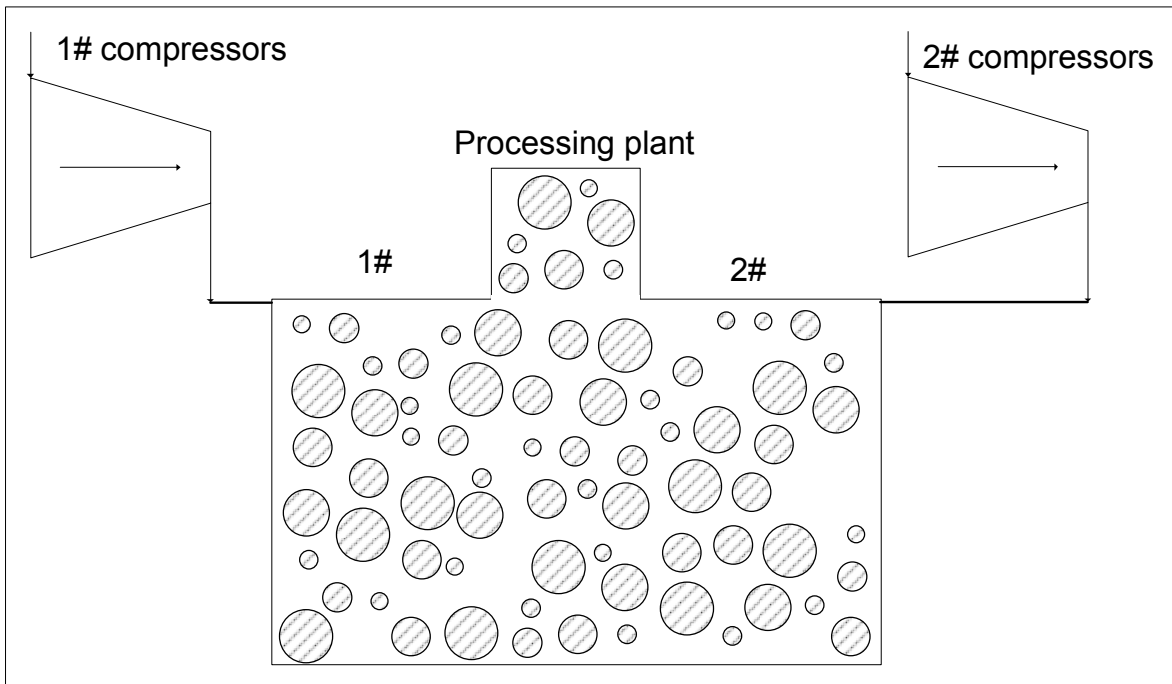


Figure 41 – Simplified model for Mine X

Table 4 – Major consumers at Mine X

Consumer	Pressure requirements	Typical operating hours
Processing plant	500 kPa	Continuous
Shaft surface ore-loading systems	450 kPa	Continuous
Shaft bottom ore-loading systems	450 kPa	Continuous
Loading boxes on each underground level	450 kPa	Operated on an ad-hoc basis for short periods. Must be always available for operation.
Refuge bays	250 kPa	Continuous
Loaders	450 kPa	22:00 to 14:00
Rock drills	500 kPa	07:00 to 14:00
Saws and winches	450 kPa	22:00 to 14:00 (low duty cycles)
Explosive loaders	450 kPa	13:00 to 16:00

Table 5 – List of compressors at Mine X

Compressor Name	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Location	1#	1#	1#	1#	2#	2#	2#	2#
Installed capacity (kW)	2 500	5 000	5 000	5 000	10 000	5 000	5 000	5 000
Maximum power consumption during normal operation (kW)	2 400	4 800	4 800	4 800	9 000	4 800	4 800	4 800
Minimum power consumption during normal operation (kW)	1 500	3 000	3 000	4 500	6 000	3 000	3 000	4 500
Designed flow capacity (m ³ /h)	25 000	50 000	50 000	50 000	100 000	50 000	50 000	50 000
Maximum flow rate during normal operation (m ³ /h)	22 500	45 000	45 000	45 000	90 000	45 000	45 000	45 000
Minimum flow rate during normal operation (m ³ /h)	15 000	30 000	30 000	40 000	60 000	30 000	30 000	40 000
Automatic inlet valve control (Yes/No)	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Automatic blow-off valve control (Yes/No)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Automatic stop-and-start capability (Yes/No)	Yes	Yes	No	No	No	Yes	Yes	No
Baseload / top-up compressor	Top-up	Top-up	Baseload	Baseload	Baseload	Top-up	Top-up	Baseload
Mine authorisation to stop and start (Yes/No)	Yes	Yes	No	No	No	Yes	Yes	No

The compressor power consumption and pressure baseline profiles from Mine X are shown in Figure 42. The first step of the integrated approach entails the correct scheduling of compressors to limit an oversupply of compressed air. An oversupply of compressed air results in higher than required system pressures and excessive operation of blow-off valves. Analysis of the baseline pressure profile can be used to determine if the supply meets the demand at Mine X.

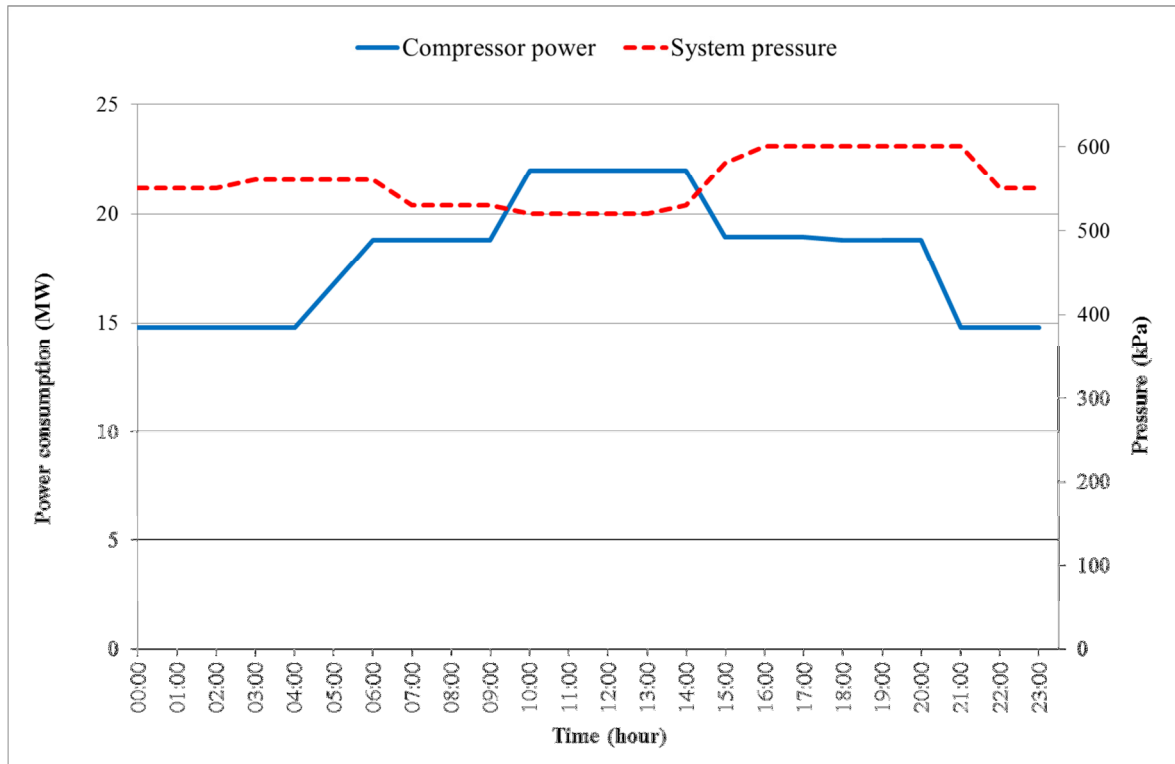


Figure 42 – Compressor power consumption and system pressure baselines for Mine X

It is observed in Figure 42 that the actual system pressure is at its lowest during the peak production shift. The highest pressure requirement from major consumers such as the rock drills is 500 kPa. This requirement is less than the actual minimum pressure of 520 kPa achieved during peak production shifts. It can be assumed that a 20 kPa safety buffer in the system pressure is enough to account for the pressure losses in the system. It is further observed in Figure 42 that the baseline system pressure reaches much higher pressures, as high as 600 kPa, outside the peak production periods.

These high pressures indicate an oversupply of compressed air outside peak production periods. So, there is scope to reduce compressor power consumption outside the peak production period. It is expected that a control strategy that would ensure a constant system pressure of 520 kPa throughout the day would result in energy savings. A comparison between the baseline pressure profile and the proposed pressure profile is shown in Figure 43.

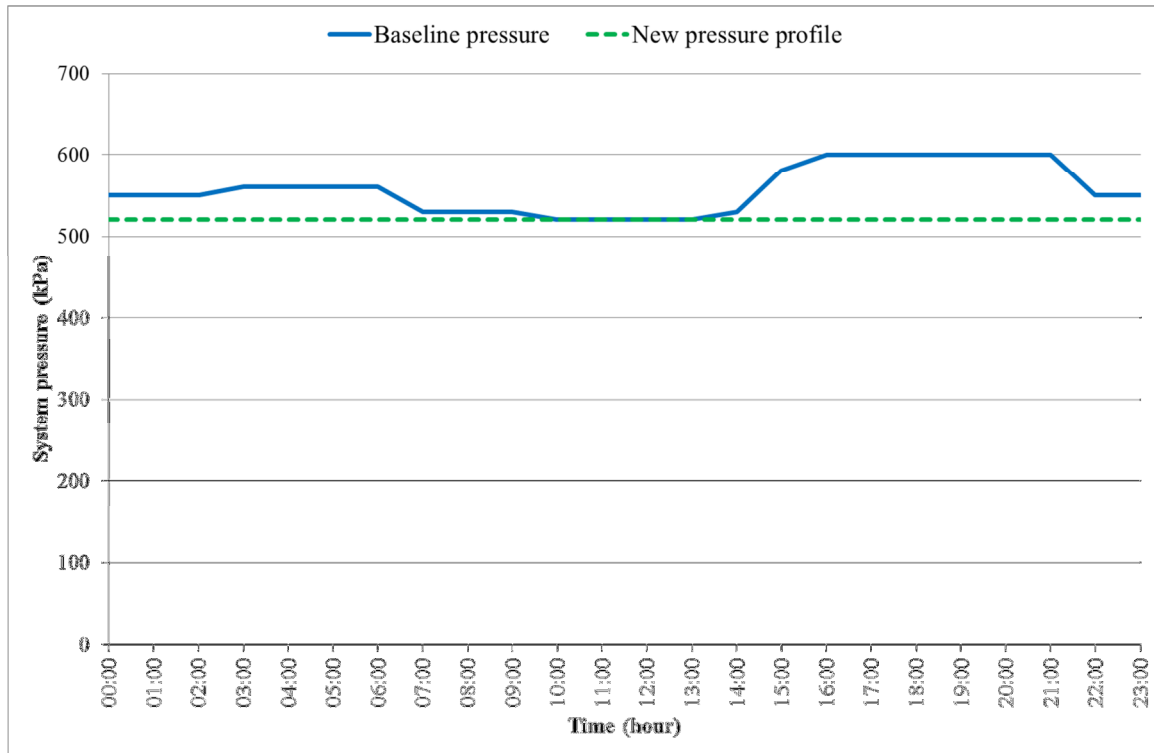


Figure 43 – Comparison between baseline pressure and required pressure for Mine X

Results achieved for previously implemented projects were analysed in Chapter 2. These results showed that the ratio between compressor power savings and pressure reduction vary between 1.5 and 2, although values between 1.6 and 1.8 are more common. Potential power savings can therefore be conservatively calculated by multiplying the pressure reduction percentage with a value of 1.5.

The saving approximation method for a change in system pressure was used to estimate the savings from improved compressor control. A comparison between the baseline compressor power consumption and the expected compressor power consumption with improved compressor control is shown in Figure 44. It is estimated that a daily average saving of 1.6 MW will be achieved if proper compressor control scheduling is implemented at Mine X.

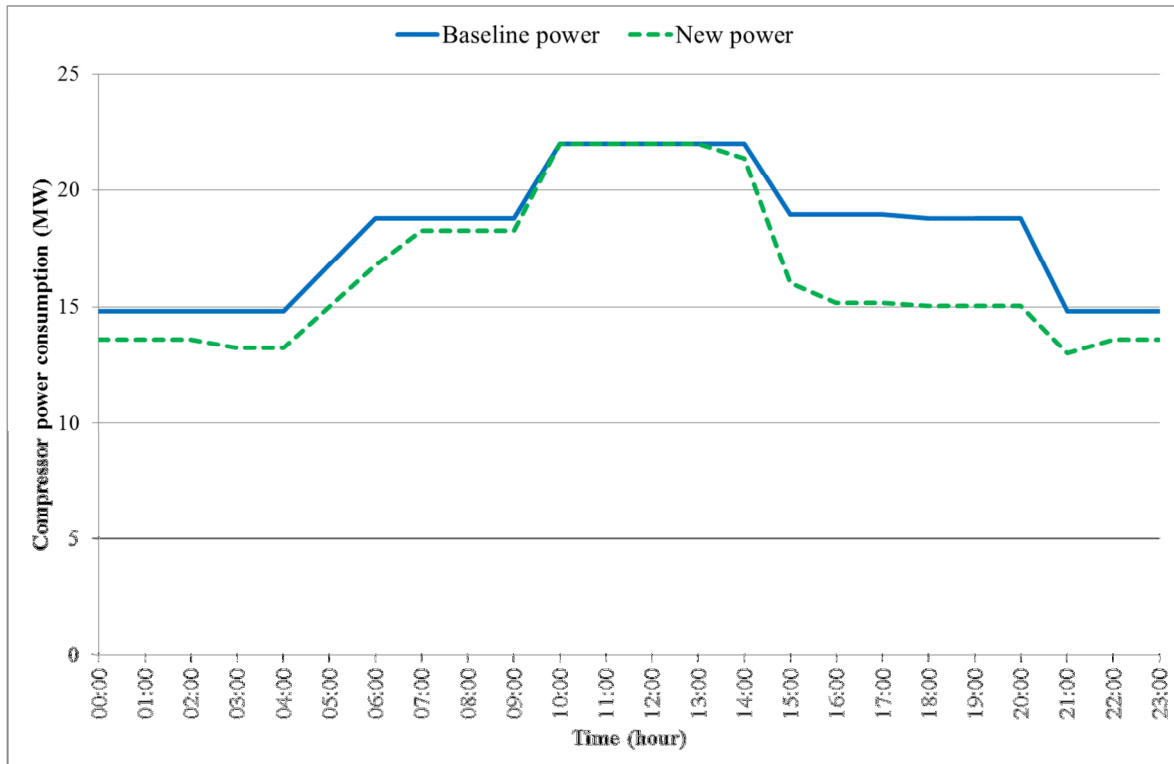


Figure 44 – Expected savings for proper compressor control and scheduling at Mine X

The new integrated approach developed earlier suggests isolating consumers with constant high-pressure requirements (especially on surface) from other consumers with varying pressure requirements. The simplified model for Mine X was adapted to isolate the surface loading boxes and the processing plant from the underground mining network. A graphical representation of Mine X with surface control valves is indicated in Figure 45.

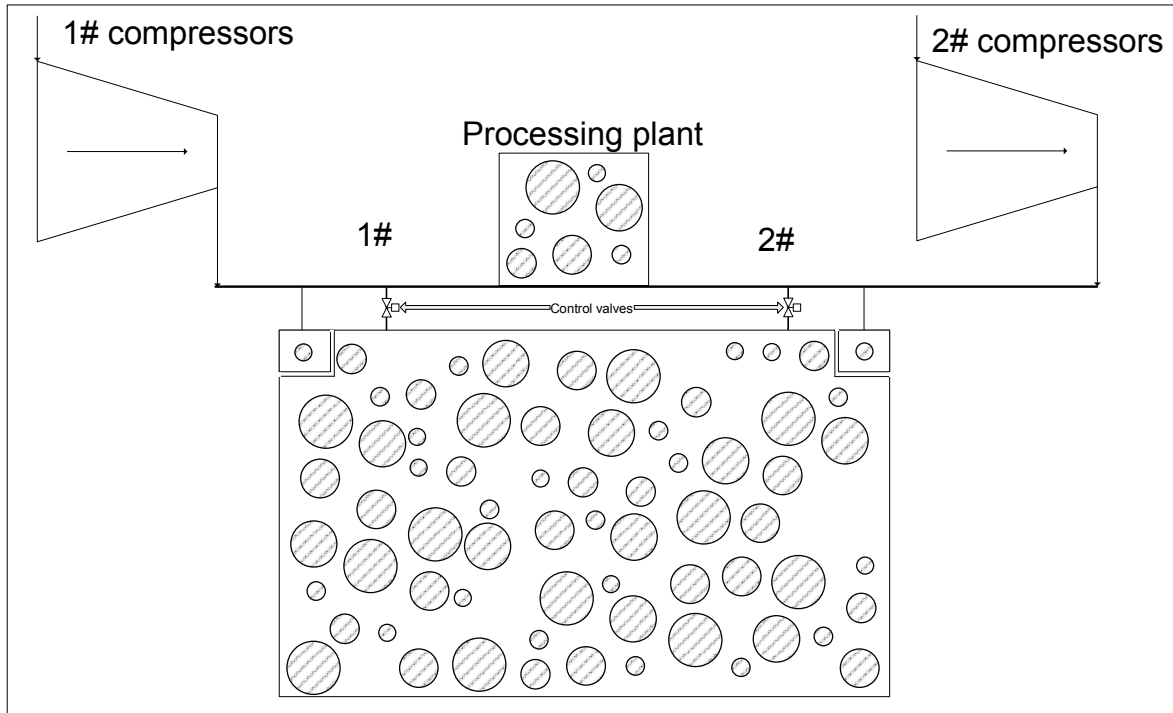


Figure 45 – Simplified view of surface valve control at Mine X

The layout in Figure 45 indicates two control valves to isolate the high-pressure system from the low-pressure system. An alternative approach would be to install a dedicated compressor at the processing plant and hydraulic power packs, or small dedicated compressors, for the loading boxes. The installation of control valves will most likely cost much less and the additional energy savings benefits would not justify additional expenditure.

A comparison between the baseline pressure and the shaft pressure is shown in Figure 46. The surface system pressure would, however, remain the same as the new pressure profile shown in Figure 43. The saving approximation method for air distribution control by means of control valves suggests that the percentage pressure reduction is almost equal to the percentage power reduction. This saving approximation method was used to calculate the savings for the installation of control valves at Mine X.

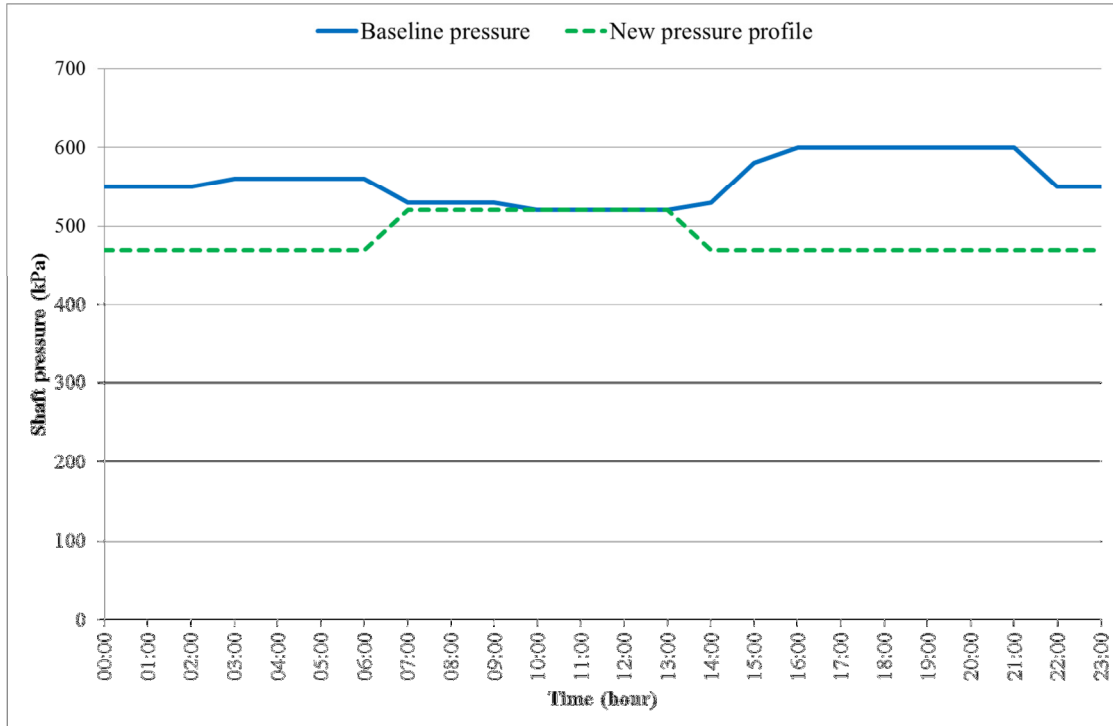


Figure 46 – Comparison between baseline pressure and shaft pressure with surface control valves

Calculations suggest an estimated saving of 0.6 MW when control valves are added to the system. The compressor power consumption profile for surface valve control is shown in Figure 47. These savings would, however, only be realised if the compressor control strategy is updated to account for the reduction in demand.

The existing compressor combination at Mine X will result in an oversupply of compressed air during certain periods of the day. This is likely to result in the operation of the blow-off valves at the compressors. Simulated results show that it would be possible to increase the saving by approximately 250 kW by improving the control band of the existing compressors. Upgrades to the compressors must therefore be considered to maximise the savings.

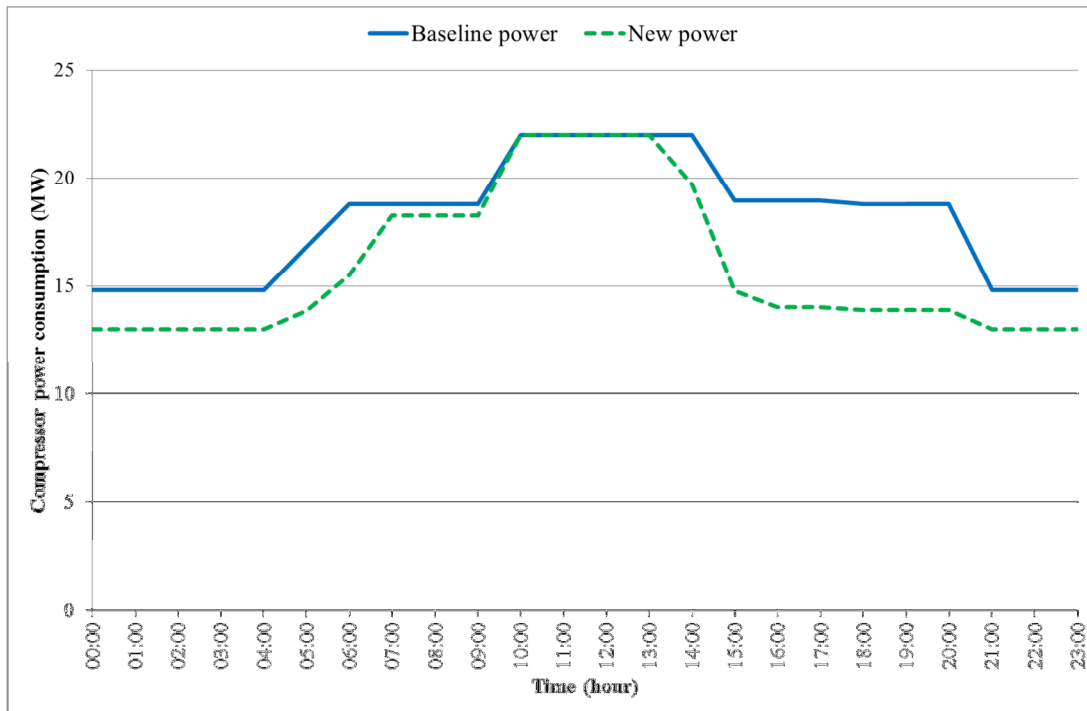


Figure 47 – Expected power consumption for surface valve control at Mine X

The next step of the integrated approach suggests the isolation of high-pressure consumers from the low-pressure consumers on the underground levels. The focus is to isolate consumers with low flow requirements at high pressures from lower pressure consumers. The loading boxes at Mine X require a pressure of 450 kPa when in operation. The operation of these loading boxes does not follow the normal shift cycle and would require a shaft pressure of 450 kPa even during blasting periods. The only other consumer during the blasting periods is the ventilation of refuge bays.

The isolation of the loading boxes will therefore result in lower level pressures during the blasting shift. The loading box situated on surface is supplied with high pressure because it was already isolated for the surface control valve scenario. The shaft bottom-loading box is operated whenever ore is hoisted from the shaft. The isolation of this loading box from the low-pressure equipment is thus required to reduce the underground pressure.

The loading boxes on the levels are sometimes operated when ore is loaded on the specified levels. The first approach would be to persuade mining personnel to change the operating shifts of these loading boxes to follow the same shift cycle as the rest of the mine.

It is, however, expected that mining personnel would not be willing to adapt to a new shift cycle. The installation of level control valves downstream of the loading box connection points can therefore be considered to allow lower system pressures during blasting and cleaning periods. These valves would also ensure that the shaft bottom-loading box can be operated without any disruption.

The simplified model was adapted to indicate the isolation between the high- and low-pressure systems by using an underground control system. The simplified model with underground valve control is shown in Figure 48. It is evident from the underground control system that the compressed air network closer to the shaft area can remain at higher pressures than the system downstream of the control valve. This enables the operation of loading systems closer to the shaft area during non-drilling times.

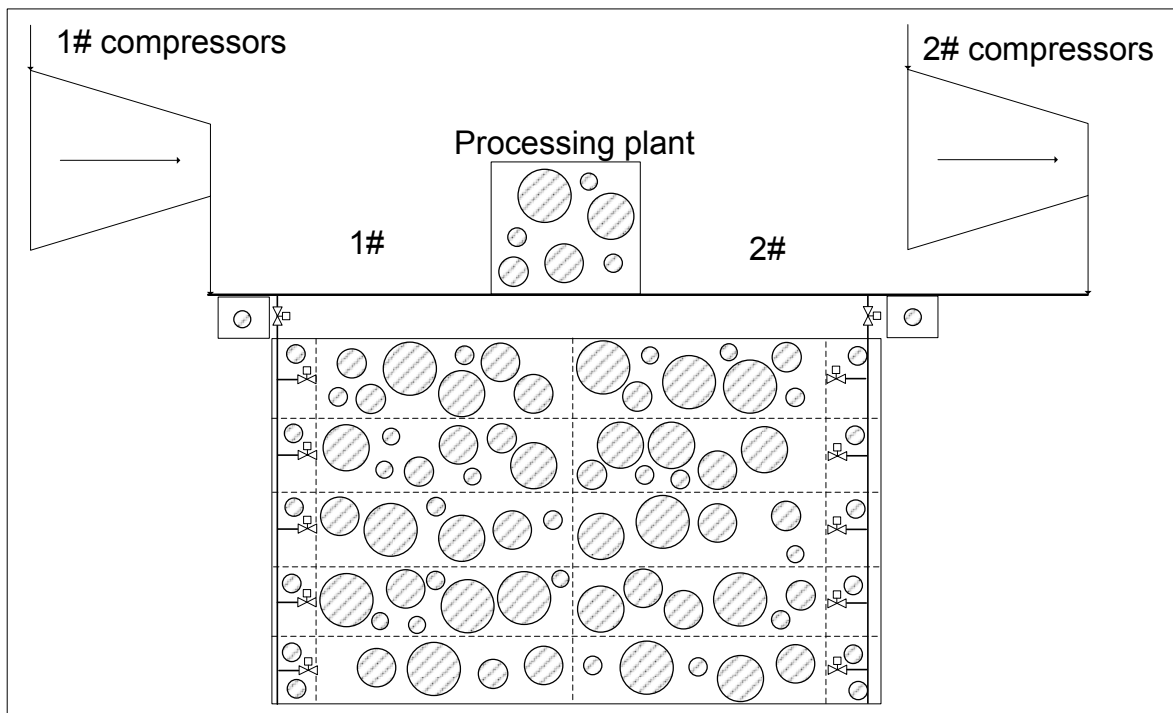


Figure 48 – Simplified model for underground valve control at Mine X

Another approach would be to retrofit loading boxes to operate with non-pneumatic systems such as hydraulic systems. A cost-benefit analysis must be used to decide between underground control systems and the retrofitting of pneumatic systems. The isolation of these constant high-pressure users from the varying pressures of the levels is expected to result in energy savings.

The comparison of the suggested underground level pressure profile with underground valve control is shown in Figure 49. The saving approximation method for air distribution control by means of control valves suggests that the percentage pressure reduction is almost equal to the percentage power reduction. This saving approximation method was used to calculate the savings for the installation of control valves at Mine X.

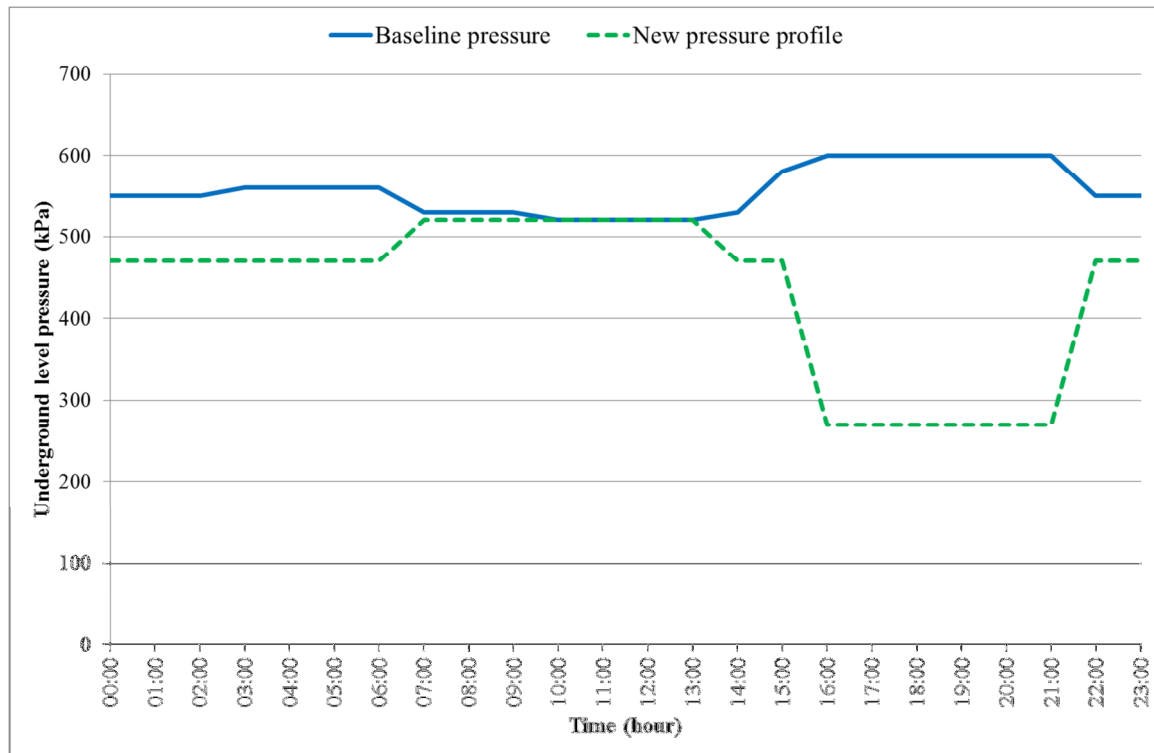


Figure 49 – Comparison between baseline pressure and underground pressure profile

The simulation model provided an estimated saving of 1.2 MW with underground valve control. An additional saving of approximately 240 kW could be achieved if the compressor control bands could be improved with additional upgrades. A comparison between the original compressor power baseline and the expected power profile is shown in Figure 50.

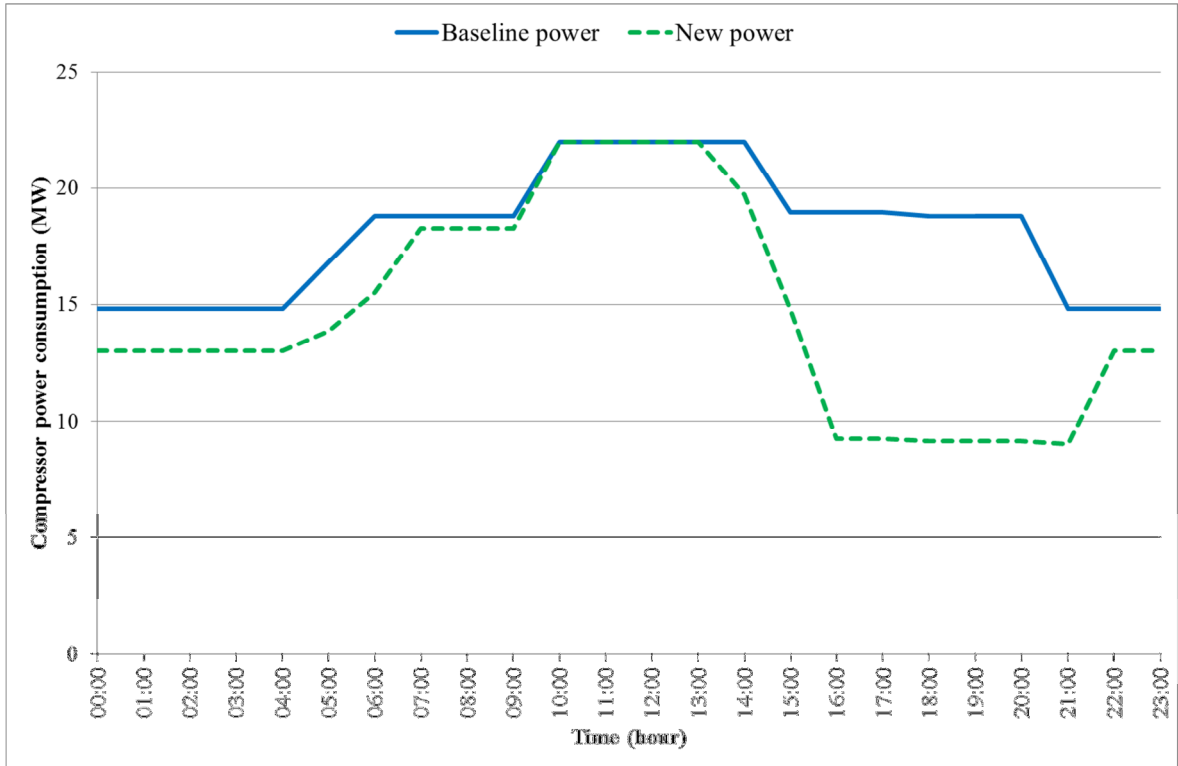


Figure 50 – Expected power consumption for underground control and loading box conversion

A comparison between the baseline and the expected power profiles for the different initiatives is shown in Figure 51. The results are summarised in Table 6. The expected savings during the Eskom evening peak periods are also shown in the table. These figures can be used when applying for project funding. Different financing options will be discussed in Chapter 4.

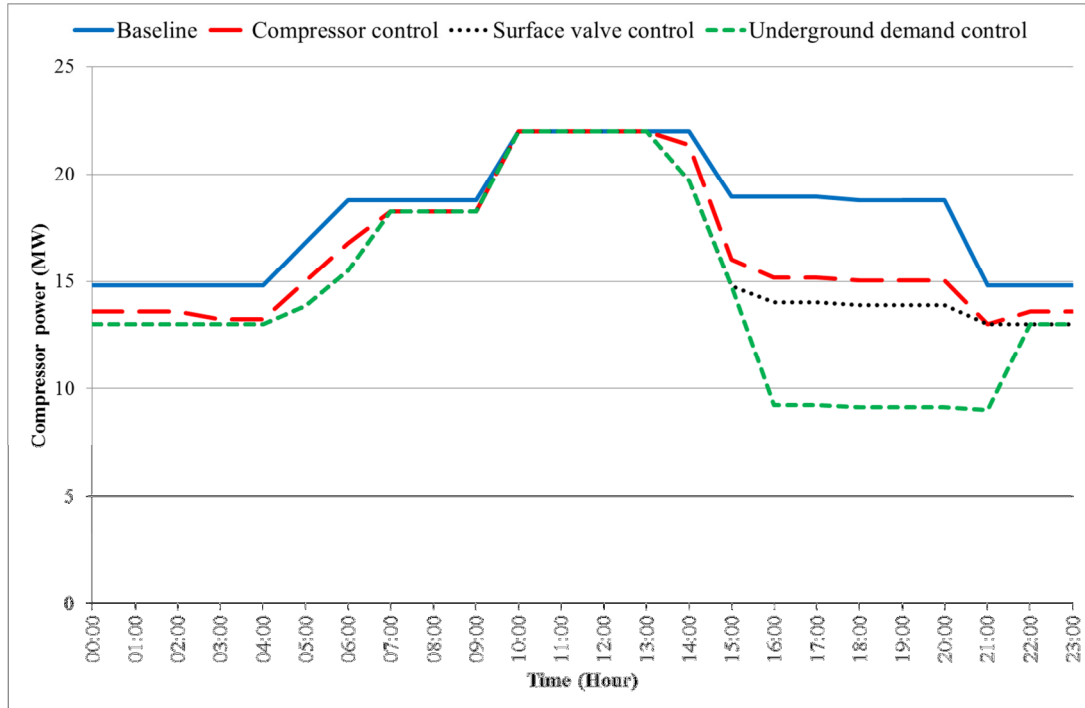


Figure 51 – Comparison between baseline and power profiles for different energy saving strategies

Table 6 – Comparison between savings achieved for the different energy saving initiatives

Initiative	Energy efficiency from previous phase (MW)	Peak clip from previous phase (MW)
Compressor control	1.6	3.8
Surface valve control	0.6	1.2
Underground control	1.2	4.7
Total saving	3.4	9.7

3.7 Conclusion

A mine compressed air system was simplified by comparing it to a pressure vessel. The pressure vessel is seen as a buffer between the supply and the demand of the compressed air system. Situations where compressed air demand exceeds the supply result in a decrease in system pressure. An oversupply of compressed air results in an increase in system pressure which leads to unnecessary losses in the system.

The response of different energy saving initiatives was tested against the model. The most evident finding was that initiatives that focus on a reduction in compressed air demand are unlikely to result in savings if compressed air supply could not be adjusted to the reduced requirements.

It is often difficult to analyse energy efficiency opportunities on mine compressed air systems. This is mostly due to the unavailability of essential data. An approach to gather essential system data showed that it is possible to evaluate compressed air systems by using limited data. The required data can also be logged with portable monitoring equipment if no data is available.

The integration of the different techniques was discussed to obtain a simplified integration sequence for the selected saving initiatives. The integration technique was reduced to three easy steps. The population of the model was discussed by means of an example. The three-step integration technique will be followed to reduce compressor power consumption of deep-level mines. The results from various case studies where the new integrated approach were applied will be discussed in the next chapter.