Expanding compressed air demand side management through selective level control

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ABSTRACT

Title:	Expanding compressed air demand side management through selective level control
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Compressed air is a resource which is used across the deep-level mining industry for a variety of purposes throughout the 24-hour mining cycle. It has been noted that compressed air is a particularly inefficient source of mechanical power, not only in the mining industry but in global industries as well, with efficiencies as low as 10%.

The low efficiencies seen across all industries stem from the same root causes, namely: Leakages as a result of poor maintenance protocols and misappropriation of compressed air. In an attempt to address the low efficiencies in deep-level mining compressed air systems, previous studies investigated several demand side management initiatives.

Existing control valve demand side management initiatives had five main shortfalls which limited their success and sustainability: either the energy impact of the initiative was too low or the capital costs, required maintenance, project lead time and resource intensities were too high. Therefore, a hybrid control philosophy, in which a surface control valve is installed in conjunction with selected level control valves, was proposed with the aim of maximising the energy impact and minimising the capital costs, required maintenance, project lead time and resource intensities.

In this dissertation, the main study objective was the development of an analysis methodology which could be used to select the level control valves which maximised the benefit of a hybrid control approach in a deep-level mining operation. The analysis methodology enabled the identification of the hybrid control philosophy which maximised the energy impact and minimised the capital costs, required maintenance, project lead time and resource intensities.

The analysis methodology was applied to a deep-level platinum mine in the North West province of South Africa and the optimal hybrid control philosophy was identified. Upon implementation, the hybrid control philosophy achieved an annual energy impact of 10.88 GWh whilst also minimising the capital cost, required maintenance, project lead time and resource intensity. Thus, achieving the study objective.

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NOMENCLATURE

Symbol	Description	Units
F	Nominal flow rate	Nm^3/h
p	Pressure	Pa
P	Power	W
E	Energy	Wh
V	Volume	m^3
R	Gas constant	L atm/ mol K
T	Temperature	K
n	Moles	-
Greek		
β	Flow fraction	-
ω	Power density	W/m^3

LIST OF ABBREVIATIONS

PGMs	Platinum group metals
DSM	Demand side management
SSM	Supply side management
LCC	Life cycle costing
IPMVP	International performance measurement and verification protocol
CV	Control valve
PID	Proportional integral derivative
PLC	Programmable logic controller
DN	Diameter nominal

LIST OF TERMINOLOGY

Term	Description
Air amplifier	A device which uses low volumes of pressurised compressed air to generate large volumes of compressed air at a low pressure, often used for ventilation purposes.
Crosscut	The working area within a mining operation where mining personnel gain access to the ore bodies being mined. All of the utilities which are used by the miming personnel are supplied via the crosscut into the stoping areas.
Compressor surge	This is a phenomenon which occurs when the pressure downstream of the compressor is higher than the pressure which can be supplied by the compressor. This in-turn reverses the direction of rotation of the compressors impellor and damages the compressor.

CHAPTER 1 - INTRODUCTION AND LITERATURE

1.1 Preamble

The purpose of Chapter 1 is to obtain the following information:

1. Provide background on industrial compressed air systems, the use of compressed air in the South African mining industry and why compressed air is the chosen method of energy transfer.
2. Identify the equipment and processes which make use of compressed air in the 24-hour mining cycle.
3. Highlight the extent of the misappropriation and mismanagement of compressed air by end-users.
4. Understand the mechanisms of compressed air generation in deep-level mining and their impact on demand side management initiatives.

Once the background has been laid out, a detailed literature study will analyse the existing methods of compressed air demand side management. Thereafter, the advantages, disadvantages and shortfalls of the existing methods will be highlighted, leading to the need for the study and the study objective.

1.2 Compressed air use in the global industry

Compressed air is an energy carrier which is utilised in a multitude of industrial processes across the globe [1]. Industrial compressed air systems convert electricity into compressed air which is then transported and later converted into mechanical energy through equipment such as: compressed air driven tools, pneumatic cylinders and valves, pneumatic pumps, stirring, blowing, moulding and sorting [2].

Alternative energy sources can be used for majority of the processes listed above but compressed air remains advantageous for the following reasons:

- Compressed air is an extremely safe form of energy transfer and energy storage [1].
- Compressed air driven equipment is simple to construct, reliable, robust and lightweight relative to electrically driven competitors [3].

Even though compressed air systems are highly advantageous in certain aspects, compressed air systems pose one major disadvantage - low efficiency. The inefficiency of compressed air systems is attributed to two main factors:

1. Excessive baseload consumptions due to leakages and mismanagement.
2. Malpractice and misuse.

The impact of the two factors listed above results in end use efficiencies as low as 10%-15% [2].

One of the largest contributors to poor energy efficiency of compressed air systems is the baseload consumption of compressed air in industrial plants. It has been stated in several studies that compressed air leaks, due to poor maintenance, can account for 20%-50% of the total compressed air usage [4-6].

Attending to compressed air leaks should be prioritised on plant maintenance importance as leaks perform no usable work, add to utility costs, negatively affect production and are easy to identify and repair. Surprisingly, industrial plants are not predisposed to reduce unnecessary compressed air consumption (leaks) and only focus on minimising wastage when pressure losses begin to negatively affect production [7].

The second factor contributing to the low efficiency of compressed air systems is compressed air malpractice, also referred to as misappropriation of compressed air. A study conducted by Nehler showed that compressed air malpractice is prevalent throughout industry [8]. Nehler stated that compressed air is often considered to be a free resource and the behavioural attitude of operational staff is one of the main barriers to achieving energy efficiency in compressed air systems [8]. Common behavioural malpractices include: using compressed air to sweep the floor, leaving compressed air equipment running when not required and poor maintenance [9].

Due to the low efficiencies, caused by misuse and mismanagement of compressed air systems, compressed air generation often accounts for 30% of a plant's total electricity consumption and can reach 70% in extreme cases [10]. This correlates with the life cycle cost (LCC) of an industrial compressed air system as the largest cost proportion is attributed to electricity consumption at 78%, whilst the initial investment and maintenance costs account for only 22% of the LCC [1, 3, 4].

The excessive power consumption of compressed air systems is not only evident on an industrial scale but reflects on a national scale. Compressed air systems account for approximately 10% of the total electricity consumed in the European Union and China, and 9% in the US, Malaysia and

South Africa [4], highlighting the potential for energy efficiency initiatives in compressed air systems.

Industrial compressed air systems are a prime candidate for energy efficiency initiatives due to their excessive electricity consumption, low efficiency and ease of savings potential. Data collected by McKane and Hasanbeigi from the United States, Canada, the European Union, Thailand, Vietnam and Brazil reported a 56% technical savings potential on compressed air systems, majority of which were considered low-cost measures [11]. In addition to energy savings and cost reductions, energy efficiency projects have the potential to bring about a multitude of non-energy, production related benefits, which can often outweigh the cost-savings [3].

Literature highlights the extent of potential energy efficiency improvements in industrial applications. Typical installed compressor capacities in industrial applications range from 0.075 MW to 1 MW with the largest being 7.5 MW [4, 7, 10, 12-15]. The South African mining industry is also a prevalent user of compressed air systems, with typical installed compressor capacities ranging from 16 MW to 22 MW [16-19] and can reach up to 85 MW in extreme cases [20].

The issues of misappropriation and mismanagement have also been noted as the largest contributors to poor compressed air efficiencies in the South African mining industry. However, the compressed air networks found in the South African mining industry are up to ten times larger than industrial systems. In addition, the environment which the mining industries' compressed air systems are exposed to is much harsher, leading to efficiencies as low as 2% [21].

Therefore, if a 56% savings potential exists on significantly smaller compressed air industrial networks, an even greater energy efficiency potential must exist in the South African mining industry. One study claims that up 75% of a deep-level mines' compressed air consumption can be saved via supply side management and demand side management initiatives [22].

In an attempt to mitigate the effects of misappropriation and mismanagement, multiple studies have investigated supply side management and demand side management initiatives. It was noted that demand side initiatives have the potential to reduce compressed air wastage by up to 70% with the remaining 30% attributed to supply side management [23]. Therefore, the primary focus of this study is the optimisation of existing demand side management initiatives to be more efficient, less cost intensive and increase the sustainability of such initiatives in deep-level mining compressed air systems.

1.3 Mining compressed air networks

South Africa is well known for its extensive mineral reserves. Currently South Africa holds 91% of the global Platinum Group Metals (PGMs) ore reserves and 5% of the global gold ore reserves [24]. PGMs and gold ore reserves are actively being mined via large scale operations which have significant contributions to the South African mining sector. In the 2020 financial year, PGMs were the largest contributor to the mining sector at 29% and gold was the third largest at 14% [25].

The mining of PGMs and gold reserves has predominantly shifted from surface operations (open pit mining) to a method known as deep-level mining. As surface ore reserves become depleted, deep-level mining is used to access the remaining ore reserves which are at depths too great to be accessed by conventional open pit mining methods, as depicted in Figure 1.

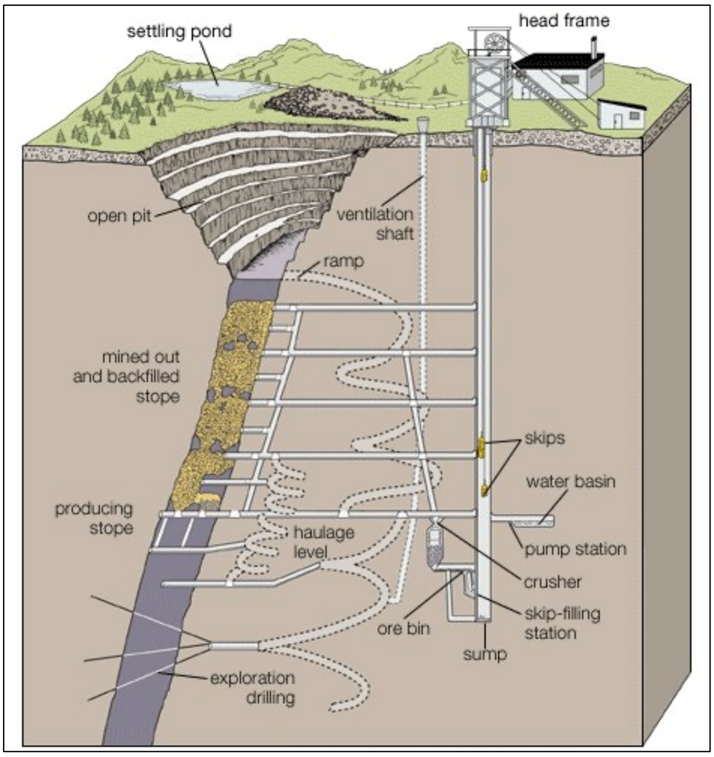


Figure 1 - An illustration adapted from [26] depicting how mining operations progress to deep-level mining due to ore reserves reaching depths no longer accessible via open pit mining methods.

Deep-level mining makes use of an extensive underground network of tunnels to gain access to the remaining ore reserves, in which compressed air is predominantly used as a form of mechanical energy.

An overview of compressed air networks in deep-level mining will be provided in Section 1.3.1 and will be followed by Section 1.3.2 and Section 1.3.3 which will investigate why compressed air is the resource of choice and discuss the alternative options that exist within industry.

1.3.1 Compressed air network overview in deep-level mining

The purpose of this section is to provide a brief overview of compressed air networks in a deep-level mining environment. Compressed air networks are generally divided into two sections commonly known as the supply side and the demand side [8].

The supply side specifically refers to the compressors which generate the compressed air, whilst the demand side refers to the end-users who make use of the compressed air. The piping network in between transports the compressed air from the supply to the demand where it is then used for various processes.

Figure 2 gives a brief overview of a simplified compressed air network and visualises the split between the supply side and demand side. A more detailed description of the supply side and demand side is given in Section 1.6 and Section 1.7.

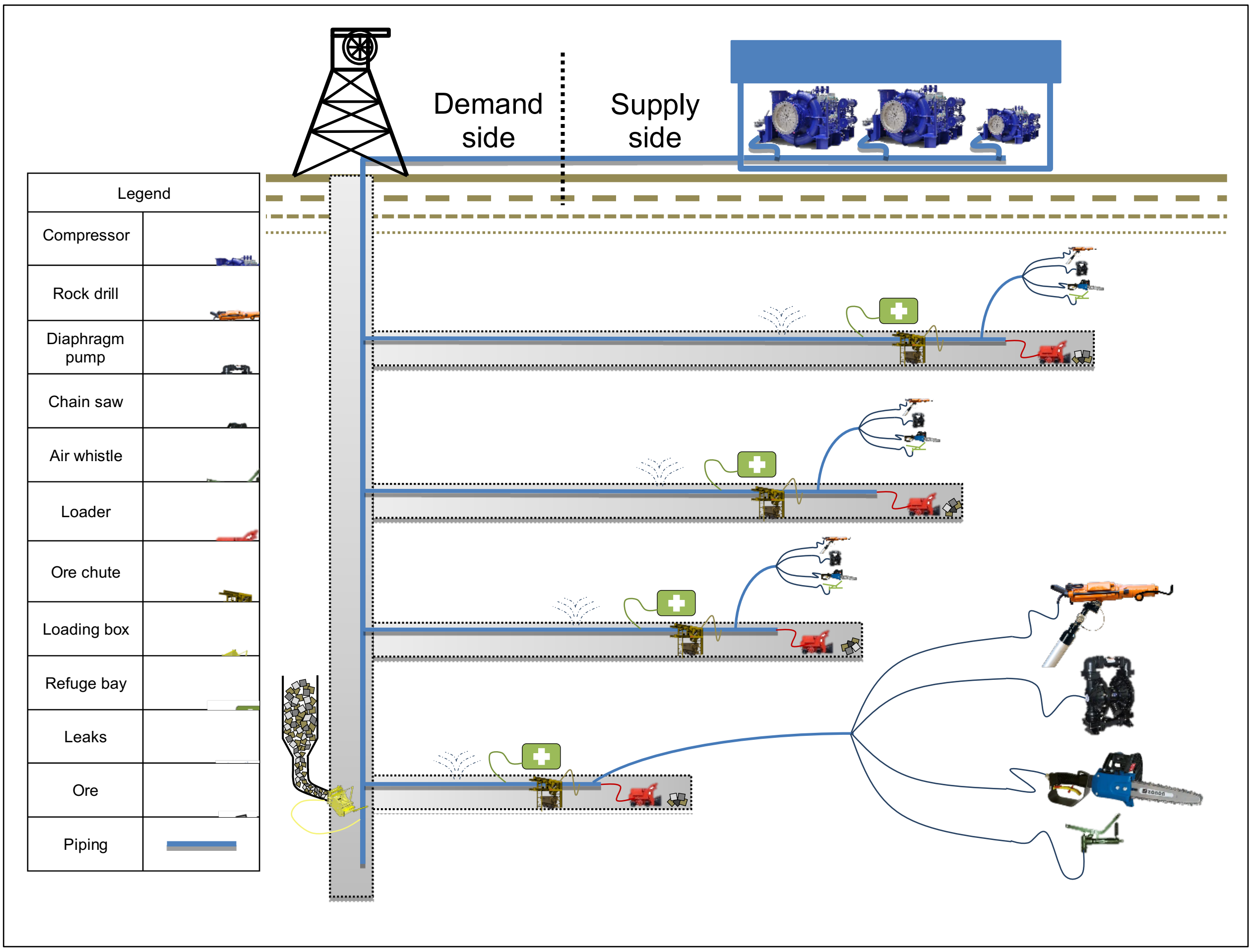


Figure 2 - An overview of a deep-level mining compressed air network, the supply side, the demand side and the associated end-users of compressed air. Adapted from [27-33].

1.3.2 The choice of compressed air

Compressed air is the main form of mechanical power used in majority of South Africa's deep-level mining operations. As stated in Section 1.2 compressed air is an inefficient resource with efficiencies as low as 10%-15% [2] and is highly susceptible to misuse and misappropriation. This begs the question – why do deep-level mining operations continue to make use of compressed air and not an alternative from of mechanical power?

Compressed air has been in use in the mining industry since the industrial revolution in the early 19th century [3] and until the late 2000's, the price of electricity was extremely cheap and electricity expenditure was not a major concern for most mining corporations. Therefore, the low efficiency of compressed air systems was overlooked in pursuit of the following advantageous properties: 1) Safety (safe form of energy transfer and energy storage), 2) scalability of the existing network, 3) reliability, 4) robustness, 5) lightweight tools, and 6) ease of use [34].

Electrically driven equipment was considered as an alternative to compressed air driven equipment during the mechanisation of the mining industry but was disregarded due to two crippling disadvantages - weight and safety. The weight of handheld electrical equipment was much higher than their compressed air competitors, leading to fatigue of the handheld tool operators and ultimately a loss in production.

In addition to the issue of weight, the issue of safety played a larger role. From a safety perspective, two main risks existed: electrocution and explosions. The risk of combining electricity, water and an ill-educated labour force, leading to electrocution, as well as combining electricity and flammable gasses, leading to explosions, was far too severe to be overlooked in pursuit of better operational efficiencies.

These factors rendered electrically driven equipment unsuitable for the South African mining industry at the time and led to the choice of compressed air systems which are still in use today.

1.3.3 Alternatives to compressed air

Although the use of electrically driven equipment was disregarded in the past, great advances made by modern day technology have brought such technologies back into the equation. The issue of weight has been resolved via a combination of lightweight materials and shifting a large portion of the load onto what is known as a power pack. In addition to this, electrical equipment makes use of seals which mitigate the risks of water and flammable gasses [21].

Furthermore, great advances have been made to detect flammable gasses underground and the labour force is more educated than before, thus allowing the mining industry to re-evaluate alternatives to compressed air systems. There are several notable companies which are prevalent in the mining industries for their alternatives to compressed air. The companies and their technologies are highlighted in Table 1.

Table 1 - Overview of alternatives to compressed air

Company	Alternative mechanical power method
Epiroc	Electro-hydraulic
HPE	Hydro-electric
HPS	Hydro-electric
Novatech	Hydro-electric

Adoption of the new technologies has been slow with only a few sites across the country no longer using compressed air as their primary source of mechanical power [21]. Many mining industries are hesitant to convert to new technologies for the following reasons, listed in order of importance:

1. Existing compressed air networks are extensive and will take time to replace
2. Large capital costs to convert the entire system
3. Inadequate infrastructure to handle additional water and electrical demands
4. The new technologies pose several risks:
    a. Lack of a proven track record
    b. Susceptibility to misuse and mismanagement
    c. Companies supplying the technology cannot meet demand for parts and spares
    d. Introducing new technology to unions and mine workers

There are several hurdles to overcome before the mining industry moves away from compressed air. Use of the new technologies can be implemented in areas where compressed air is a constraint, leading to a hybrid system of compressed air and new technologies [21]. However, mining corporations have spent vast amounts of capital on their existing compressed air systems and are likely to continue extending the compressed air network and improving their energy efficiency rather than converting.

Therefore, compressed air will remain a mainstay of mechanical power in the mining industry for years to come and energy efficiency projects will become critical to mining operations as the compressed air networks continue to grow [35].

1.4 Compressed air end-users

To understand the purpose of supply side management and demand side management initiatives, one must first understand the processes which make use of compressed air in deep-level mining operations.

Deep-level mining operations typically follow a 24-hour cycle, separated into three distinct shifts. Within these shifts, different compressed air end-users are present at different times [20, 36, 37]. The purpose of this section is to investigate the following:

1) A typical 24-hour mining cycle and the tasks of each shift within the cycle.
2) The compressed air equipment utilised to complete each shift's task.
3) The operational requirements of the different equipment to successfully complete the task.

Once the 24-hour mining cycle and end-users' requirements are defined, a pressure demand profile can be developed. Therefore, highlighting the need for either supply side management or demand side management initiatives, which will ensure that end-users' pressure demand requirements are met, without oversupplying the system, leading to greater operational efficiencies.

1.4.1 Typical 24-hour mining cycle

All deep-level mining operations have one goal – producing ore. In order to produce and extract ore from underground operations, a 24-hour mining cycle is followed. The 24-hour mining cycle is separated into three distinct shifts known as: the drilling shift, blasting shift and cleaning shift [38]. Each shift is set with a specific task, in which different compressed air equipment is utilised [36, 37]. The purpose of each shift is as follows.

1.4.1.1 Drilling shift

In deep-level mining operations, the drilling shift is tasked with drilling holes in the rockface. Holes are drilled for two purposes. The first is drilling ore-bearing panels, in order to later blast and extract the ore. The second is drilling development ends to create access ways to the remaining unmined ore bodies or for ventilation purposes. Once holes have been drilled, they are then charged up with explosives [37, 38].

1.4.1.2 Blasting shift

During the blasting shift, the explosives placed in the holes at the end of the drilling shift are remotely detonated [38]. Underground operations are cleared prior to blasting to ensure the safety of mining personnel. The underground operations remain cleared until the hazardous gasses caused by blasting have dissipated. Clearing of hazardous gasses can take as long as 3 hours.

1.4.1.3 Cleaning shift

After the ore has been blasted and hazardous gas levels are below the acceptable limit, the cleaning shift makes its way underground. The cleaning shift is tasked with removing the freshly blasted ore from the ore-bearing panels and development ends [39]. Thereafter, transporting the ore to underground silos via a network of underground locomotives. The ore is later hoisted to surface by means of a skip [37].

It is important to note that all three shifts are present in deep-level mining operations, but the times of each shift may vary for different operations. Additionally, a change of shift occurs when the current shift is transported to surface and the following shift is transported underground. There are usually no end-users present during this time. Understanding the shifts, requirements of each shift and the timing of each shift is critical to achieving maximum energy efficiency via compressed air initiatives.

An example of a 24-hour mining cycle is presented in Figure 3. Each of the mining shifts which make up the 24-hour mining cycle are highlighted by the blue areas and the change of each shift is highlighted in grey.

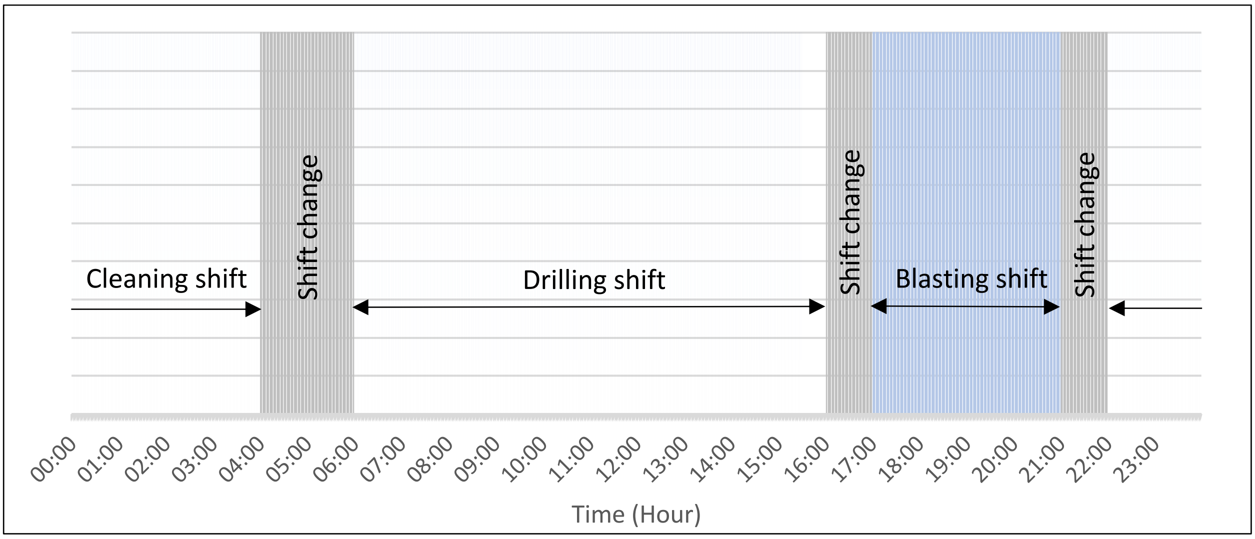


Figure 3 - Visualisation of a 24-hour deep-level mining cycle adapted from [22]

1.4.2 Overview of end-users present per shift and their operational requirements

For each shift to achieve their goals, a variety of equipment is utilised. It is critical that the highest pressure demand at the time is satisfied, ensuring all end-users' requirements are met and production is not hindered [22, 36]. To determine the maximum pressure requirements, the equipment which is critical to production with the highest pressure demand requirements are considered.

Table 2 highlights the critical underground equipment in use during the different shifts. The maximum pressure requirements of the critical equipment for each shift are highlighted in red.

Table 2 - Overview of critical underground compressed air equipment present during different shifts.

Shift	Equipment	Purpose of equipment	Pressure demand (kPa)
Drilling shift	Rock drills	Drilling holes in rock face	450 - 600 [40]
	Diaphragm pumps	Pumping water away from the rock face	150 - 550 [41]
	Air whistles	Signal moving of equipment or moving of ore by winches	150 - 200 [42]
	Refuge bays	Safety area in case of emergency. Ventilated with compressed air.	150 - 200 [42]
Blasting shift	Refuge bays	Safety area in case of emergency. Ventilated with compressed air.	150 - 200 [42]
Cleaning shift	Loaders	Loading ore from haulage development ends into hopper cars.	350 - 450 [42]
	Ore chutes	Transferring ore collected from stopes into track-bound hopper cars.	400 - 500 [20]
	Air whistles	Signal moving of equipment or moving of ore by winches	150 - 200 [42]
	Refuge bays	Safety area in case of emergency. Ventilated with compressed air.	150 - 200 [42]
Shift changes	Refuge bays	Safety area in case of emergency. Ventilated with compressed air.	150 - 200 [42]

1.4.3 Potential for energy efficiency initiatives

Using the maximum pressure demand requirements per shift, highlighted in Section 1.4.2, the maximum pressure demand requirements can be extrapolated to the 24-hour mining cycle. Rather than oversupplying the system with a constant 600 kPa, energy efficiency initiatives can be used to match the supply with the demand requirements of all end-users, leading to greater operational efficiencies [37]. The relation between pressure and operational efficiency of compressed air networks is further explained in Section 1.5.

Figure 4 shows an example of the pressure demand requirements of underground end-users over a 24-hour mining cycle versus constantly supplying 600 kPa. The pressure demand of the underground end-users is presented by the black line and the constant 600 kPa supply is highlighted by the dotted red line. The area between the constant supply pressure and the end-users pressure requirements highlights the potential for increased energy efficiency.

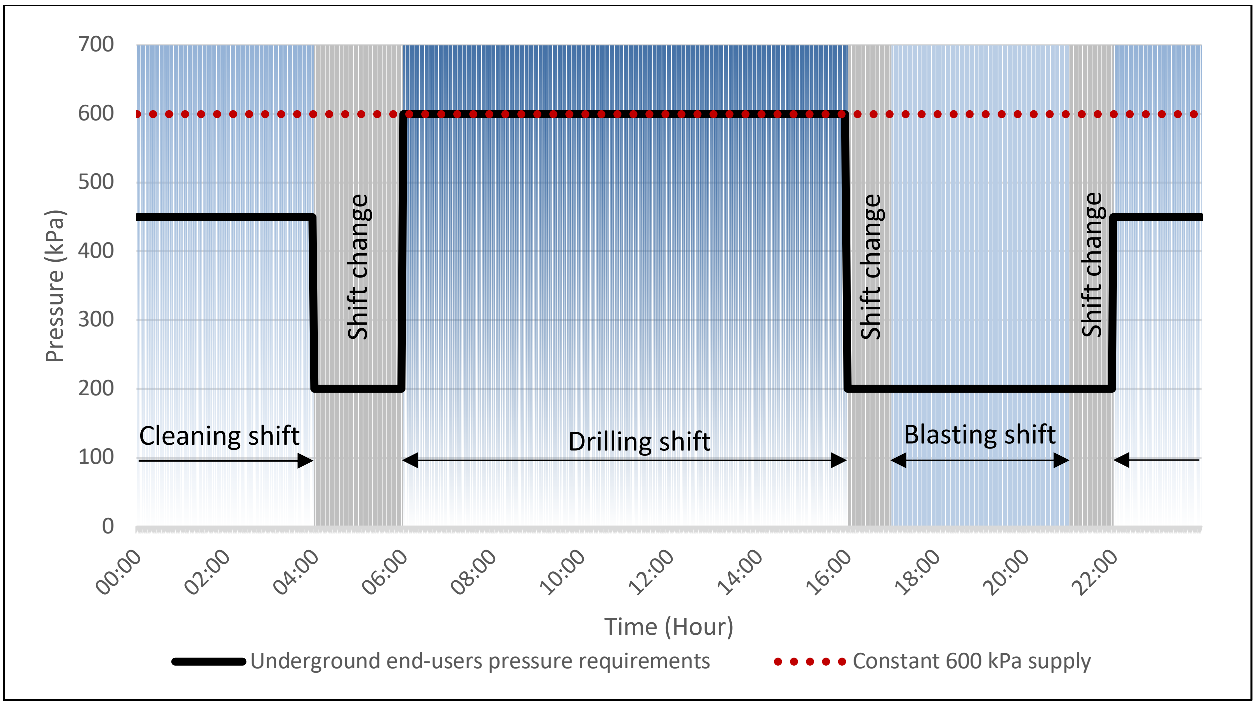


Figure 4 - Pressure demand requirements overlayed on a 24-hour mining cycle, highlighting the potential for increased energy efficiency.

Achieving the energy efficiency potential highlighted in Figure 4 can be achieved via supply side management initiatives, demand side management initiatives or a combination of both. Determining which method will yield the best results will require an in-depth analysis of each specific site’s compressed air network.

1.5 Misappropriation and mismanagement of compressed air

In Section 1.2, compressed air use in the global industry was investigated and discussed. Several studies revealed that potential for energy efficiency initiatives existed in first world, small scale industrial plants. One of the main issues faced in the industrial sector is the misappropriation and mismanagement of compressed air as it is considered a free resource [8].

The South African mining industry makes use of much larger compressed air systems with extensive underground piping networks [37]. Due to the scale and inaccessibility of mining compressed air networks, the effects of misappropriation and mismanagement are more prevalent than in small scale industrial plants [35, 37, 43].

Several studies have shown that up to 75% of the total compressed air consumption can be attributed to misappropriation and mismanagement, labelled as unauthorised end-users [22, 35]. Unauthorised end-users increase the constant baseload flow required to meet end-users' operational requirements [35, 44, 45], thereby hindering the ability to achieve high operational efficiencies, whilst also negatively affecting production [35, 46].

The following sections investigate the extent of misappropriation and mismanagement of compressed air in the mining industry and their effect on operational efficiency. Thereafter, the need for energy efficiency initiatives to combat the poor operational efficiencies will be highlighted.

1.5.1 Misappropriation of compressed air

Misappropriation of compressed air is defined as the utilisation of compressed air for tasks outside the defined scope of operation. Compressed air is often misused by end-users due to a lack of awareness of the cost of compressed air as well as a culture which considers the misappropriation of compressed air to be acceptable [4, 22].

In industrial plant applications it was found that compressed air was used for unauthorised tasks such as sweeping the floor, ventilating humid areas, and cleaning of work benches [3]. The same issues exist within the South African mining industry. The most common forms of compressed air misappropriation in the South African mining industry are listed in order of significance below:

1. Ventilating with compressed air [35-37, 45, 47, 48]
    a. Direct ventilation using a hose or piercing the piping with a nail.
    b. Ventilation by means of an air amplifier.
2. Leaving inactive equipment running / not isolating inactive areas [36, 48]

The issues listed above negatively affect the energy efficiency of compressed air systems as they are not viewed as useful work and result in unnecessary compressed air consumption. Additionally, these issues are difficult to address as they require a psychological change in the workforce, which is resource and time consuming [4].

1.5.2 Mismanagement of compressed air networks

Mismanagement of compressed air is the second factor which contributes to the large baseload consumptions of compressed air systems in the mining industry. Mismanagement can be viewed as a lack of maintenance and repairs on existing compressed air systems [22]. This leads to unnecessary compressed air consumption, which again performs no useful work.

The two main issues faced in compressed air management are: repairing leakages within the system and blanking-off inactive areas.

Leakages are common within compressed air mining networks due to the harsh underground conditions. Leaks are caused by several factors such as rusted piping, worn out gaskets, collisions with underground equipment, rock falls, poor welding as well as low quality valves and fittings [22, 35, 37, 49].

The second issue is the monitoring and maintenance of compressed air piping in inactive areas. Inactive areas are isolated for safety reasons and are inaccessible to mining personnel [22]. Therefore, that section of piping cannot be effectively monitored and maintained, nor is it being used [22]. Inactive areas are often responsible for a large portion of the baseload leakage and should be blanked off to avoid any unnecessary compressed air consumption [46, 47, 49, 50].

Compressed air mismanagement is common for two reasons. The first is a lack of awareness / poor maintenance culture as mentioned in Section 1.2. The second is that compressed air networks can be extremely difficult to maintain due to the scale and inaccessibility of the compressed air network. The issues of misappropriation and mismanagement, listed above, are often ignored by maintenance personnel until the wastage begins to negatively affect production [3].

1.5.3 Impact of misappropriation and mismanagement

The impact of misappropriation and mismanagement is highlighted in Figure 5. This data was collected during a test which was conducted during the cleaning shift, in which no authorised end-users are present within the crosscuts. During the test, the crosscut valves on a single level were isolated to determine the total amount of compressed air being utilised by the crosscuts. The test revealed that 85% of the compressed air consumption of the level during the cleaning shift was attributed to un-authorised compressed air usage within the cross-cuts, as shown in Figure 5. The total baseload consumption of the level was approximately 2000 Nm³/h with 1800 Nm³/h being consumed by the cross-cuts.

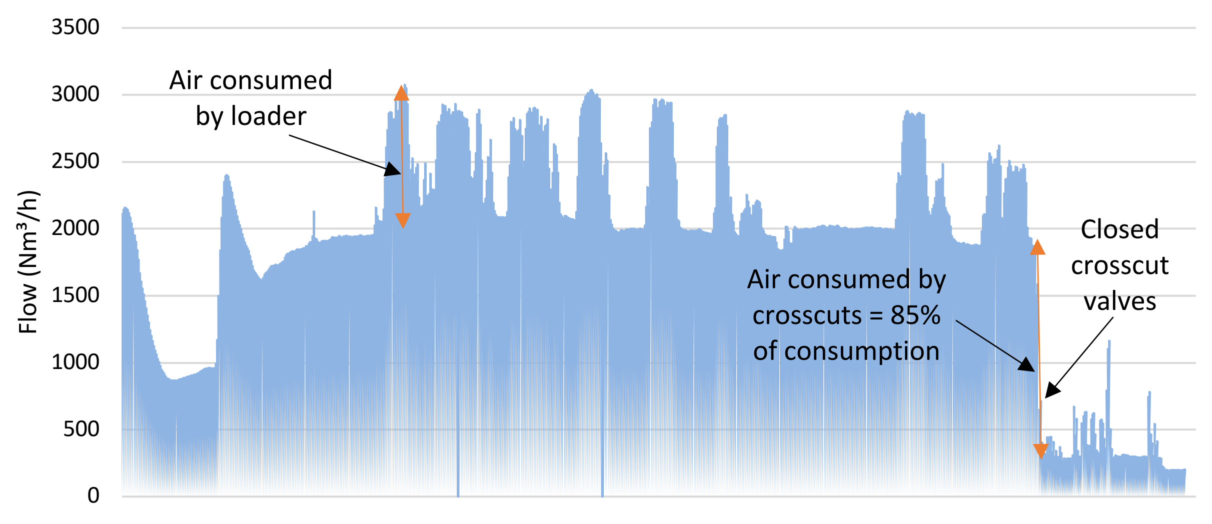


Figure 5 - A test conducted to determine the total amount of air consumed by unauthorised end-users within the crosscuts on a level in a platinum mine.

Additionally, the authorised end-users (loader) are also noted in Figure 5. The compressed air consumed by the loader is shown to be periodic. This is due to the loader being a regulated consumer of compressed air, which consumes no air when it is inactive.

1.5.4 Effect of unauthorised end-users on the system efficiency

The compressed air consumption of unauthorised end-users has a large impact on the overall efficiency of compressed air systems, accounting for up to 75% of the total compressed air consumption [22]. Unauthorised end-users perform no useful work and therefore their consumption drastically reduces the compressed air systems' efficiency. The key differences between authorised and unauthorised consumers are highlighted in Table 3:

Table 3 - Comparison of authorised end-users versus unauthorised end-users.

Type of user	**Regulated consumption**	**Constant consumer in 24-hour cycle**	**Open-ended**
Authorised	Yes	No	No
Un-authorised	No	Yes	Yes

Authorised end-users are regulated, used periodically and are not open-ended. Therefore, they do not contribute to the baseload consumption of compressed air systems. Whilst unauthorised end-users are constant, unregulated, open-ended consumers which account for majority of the baseload consumption throughout the entire 24-hour mining cycle.

Due to the unauthorised consumers being open-ended and unregulated, their consumption is directly proportional to the pressure supplied to them as well as their orifice size [20]. This effect is illustrated in Figure 6 which highlights the linear relationship between supply pressure and mass flow rate, as well as the exponential relationship between orifice diameter and mass flow rate.

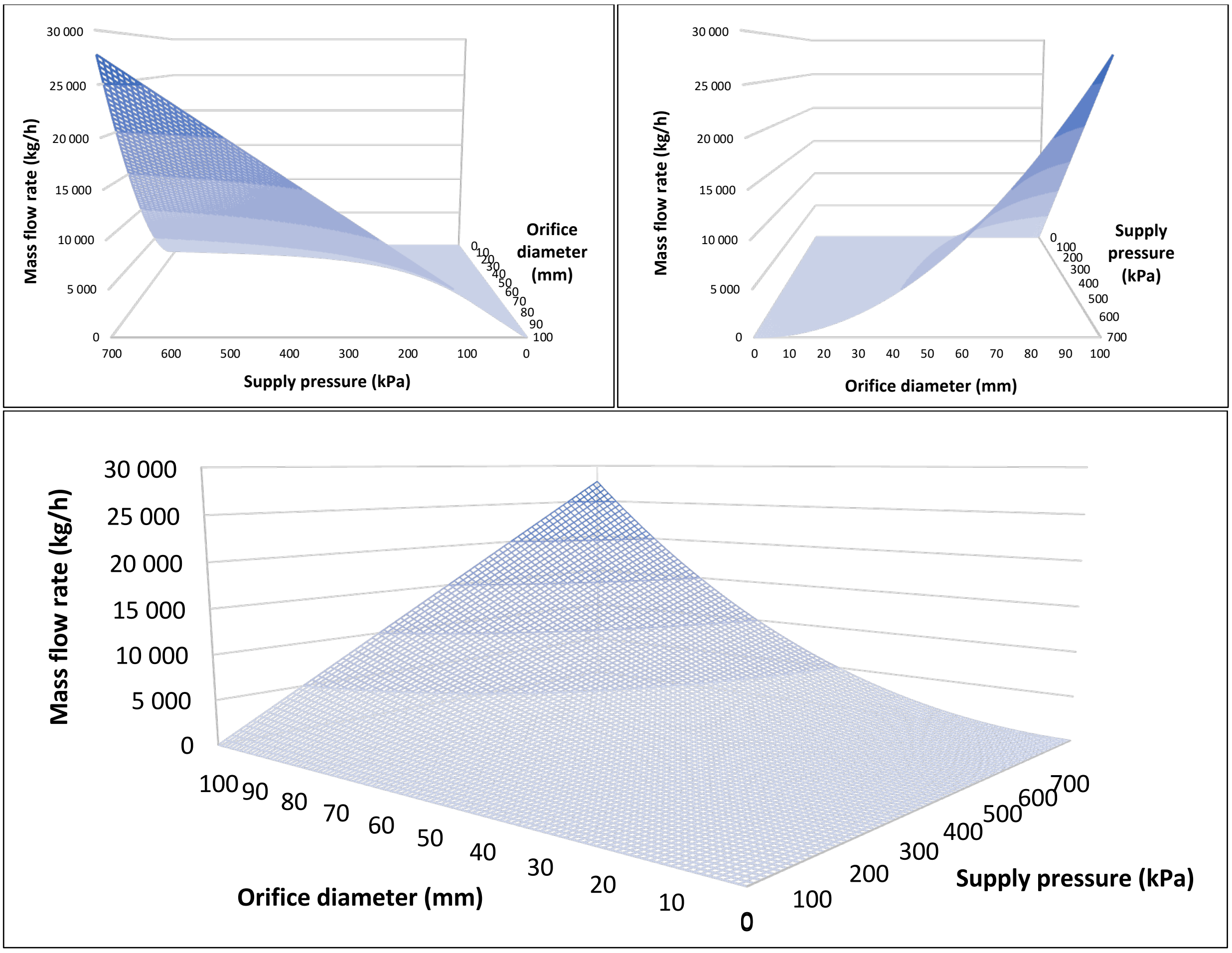


Figure 6 - Visualisation of the effect of pressure and orifice size on the mass flow rate.

It is clear from Figure 6 that the pressure supplied to unauthorised end-users must be minimised to reduce their compressed air consumption. This is of particular importance for unauthorised end-users which make use of large orifice diameters and consume exponentially more air than end-users with small orifice diameters.

Viewing Figure 4 in conjunction with Figure 6 highlights the importance of matching the supply pressure with the authorised end-users' pressure requirements in order to minimise the adverse effects of unauthorised ends-users.

In a study conducted by Zietsman, the extent of the compressed air consumption of unauthorised end-users is highlighted [22]. Zietsman compared the simulated theoretical consumption of authorised end-users to the actual consumption of a typical deep-level mining shaft as shown in Figure 7 [22].

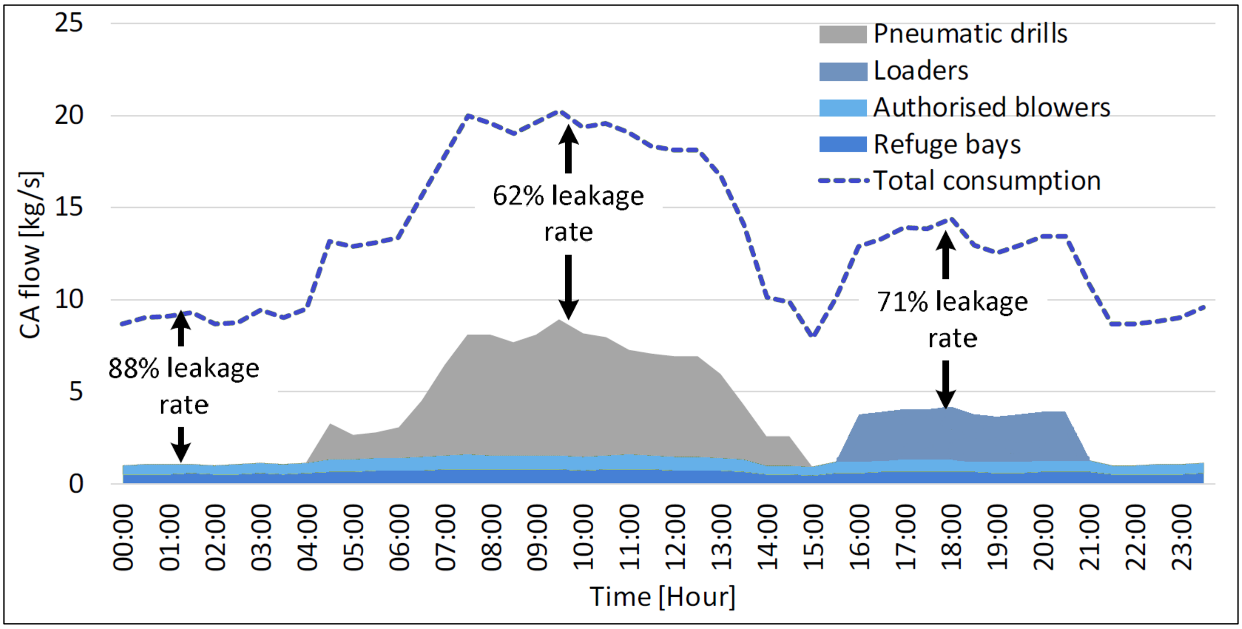


Figure 7 - Comparison of the simulated consumption of authorised end-user's versus the actual consumption. Highlighting the consumption of unauthorised end-users [22].

The average difference between the consumption of authorised end-users and the total shaft consumption is approximately 75%, all of which can be attributed to unauthorised end-users, thus resulting in extremely low system efficiencies.

Therefore, unauthorised end-users must be supplied as little pressure as possible, or they must be eliminated in order to reduce their compressed air consumption and in turn reduce their negative impact on the compressed air network efficiency and production.

1.5.5 Need for energy efficiency initiatives

It is evident that misappropriation and mismanagement of compressed air networks is the primary cause of poor system efficiencies. The continued expansion of deep-level mining compressed air networks will only exacerbate this issue [22].

Addressing the behavioural issues surrounding misappropriation and mismanagement of compressed air systems is difficult due to two factors:

1. A long-running culture within the work force which believes this wastage is acceptable.
2. The size, accessibility, and scalability of the existing compressed air networks in deep-level mines.

Therefore, many studies have turned to engineering solutions which minimise the impact of unauthorised compressed air end-users by limiting the pressure which is supplied to them, thereby reducing the load on compressors, resulting in a reduced energy consumption [22].

The breakdown of existing engineering solutions is as follows:

1. Supply side management
    a. Optimisation of compressor control to meet end-user requirements via starting and stopping of compressors as well as guide vane control.
2. Demand side management
    a. Surface control valves.
    b. Level control valves.
    c. Crosscut isolation.
    d. Leak management and maintenance.

The engineering solutions listed above remain necessary throughout the life cycle of a compressed air network because the effects of unauthorised end-users can be mitigated through management initiatives, but they will never be entirely eliminated, especially in the extensive compressed air networks found in deep-level mines.

For the purposes of this study, supply side management will not be investigated in detail, as the focus of this study is on improving existing demand side management strategies. It is important to note that in order to achieve the energy efficiency potential brought about by demand side management initiatives, supply side management must be implemented.

1.6 Compressed air supply

The purpose of the following section is to give a general overview of compressed air supply systems in the South African mining industry and the limitations thereof. Although, the focus of this study is not supply side management, an understanding of the supply is required to achieve the energy efficiency potential brought about by demand side management initiatives.

1.6.1 Overview of compressed air supply methodology

Compressed air supply systems in the South African mining industry make use of several compressor types, with installed capacities ranging from 16 MW to 22 MW [16-19]. Deep-level mines require high volumes of compressed air with pressure demands ranging from 200 kPa to 600 kPa within the 24-hour mining cycle [22], as highlighted in Section 1.4.2.

In deep-level mining operations, compressors are located in a compressor house on surface near the headgear and make use of an extensive steel piping network to transport compressed air to the end-users [42]. Multistage centrifugal compressors are most suitable for mining operations and are usually equipped with inlet guide vane control and blow-off valves, to achieve a wider supply pressure control range [34, 51].

To satisfy the varying demand requirements, compressors of various sizes / capacities are connected in parallel with one another and supply air into a common manifold [49], as shown previously in Figure 2. These compressors, of various sizes, are then toggled on and off in an attempt to match the supply with the demand requirements [34].

Often, the compressed air demand can reach a midpoint, where running one compressor is insufficient to meet the demand requirements but running two compressors will result in oversupply.

Inlet guide vane control is used in such situations to reduce the outlet pressure of the compressors by limiting the inlet airflow. This enables the compressed air supply system to match the demand requirements more effectively, resulting in lower energy consumption and preventing compressors from going into surge protection (blow-off) [51].

The second line of defence against compressor surge is the use of a blow-off valve. This is a valve which expels excess air, produced by the compressor, into the atmosphere, thereby lowering the outlet pressure of the compressor and preventing surge [51]. Compressor blow-off must be avoided as far as possible as it results in unnecessary compressed air wastage, leading to reduced operational efficiencies [17].

In addition to the use of guide vane control and blow-off valves, mining operations with multiple shafts often connect their compressed air supplies to one another, thus enabling the mining operations to better match their supply with their demand. This is commonly known as a ring-fed network. More information on compressed air supply networks is given in Section 1.6.2.

It is important to note that each mining operation is unique and may differ in the following aspects: type of compressed air supply (standalone or ring-fed), number of compressors, size of compressors, type of compressors and availability of guide vane control. All these factors will directly affect the ability to achieve better operational efficiencies by matching the supply with the demand. Understanding the mining operation in question and the tools available for supply side management are critical in achieving the energy efficiency opportunities provided by demand side management (DSM) initiatives [22, 47, 52].

1.6.2 Existing supply networks

Compressed air supply networks are divided into two categories, namely: standalone networks and ring-fed networks [49]. The choice of network is dependent on the mining operation and the extent of their ore deposits. Mining operations with small, localised ore reserves make use of a single shaft and therefore a standalone compressed air network. Whilst areas with large, widespread ore reserves make use of multiple shafts and a ring-fed compressed air network.

Both supply layout methods pose several advantages and disadvantages. Careful analysis and understanding of the existing supply layout are required to select DSM initiatives which will achieve maximum energy efficiency.

1.6.2.1 Standalone compressed air supply

A standalone compressed air supply network is comprised of a single compressor house, which feeds a single shaft's end-users [49]. Within the compressor house there are several compressors of different sizes to accommodate the varying demand of the shaft. The baseload consumption of end-users is supplied by one large compressor while the remaining compressors act as reserve capacity and are utilised when the compressed air demand increases.

These compressors tie into a common manifold and discharge compressed air into a single pipeline. This pipeline then distributes the compressed air to the relevant surface and underground end-users as shown in Figure 8 [49].

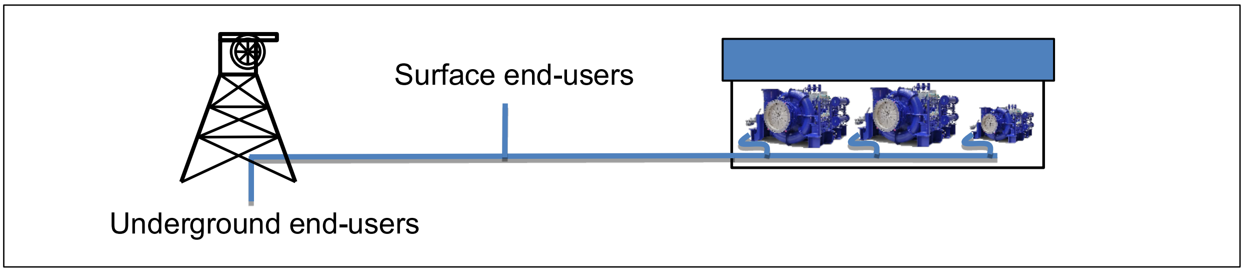


Figure 8 - Overview of a standalone compressed air network [30].

Standalone networks are generally much smaller than ring-fed systems, resulting in a reduced network capacitance, thus making them highly susceptible to rapid pressure fluctuations. Guide vane control in standalone systems is critical to minimise the effect of rapid pressure fluctuations when trying to satisfy midpoint demands, therefore ensuring protection of compressors against compressor surge whilst minimising compressor blow-off.

When implementing DSM projects on a standalone network, the supply network will reach a midpoint where guide vane control will be necessary to achieve the maximum energy efficiency.

1.6.2.2 Ring-fed compressed air supply

A ring-fed compressed air network is comprised of multiple compressor houses which feed multiple shafts and end-users simultaneously [49]. The infrastructure remains the same as standalone networks, with compressors of different sizes tying into a common manifold, except for one key difference. The shafts are connected to one another, usually on surface, via a network of steel piping.

Many ring-fed networks begin as standalone systems and convert to ring-fed networks as mining operations expand. Isolation valves are present between the shafts, enabling the shaft to operate as a standalone system if the need arises. An example of a ring-fed network is given in Figure 9.

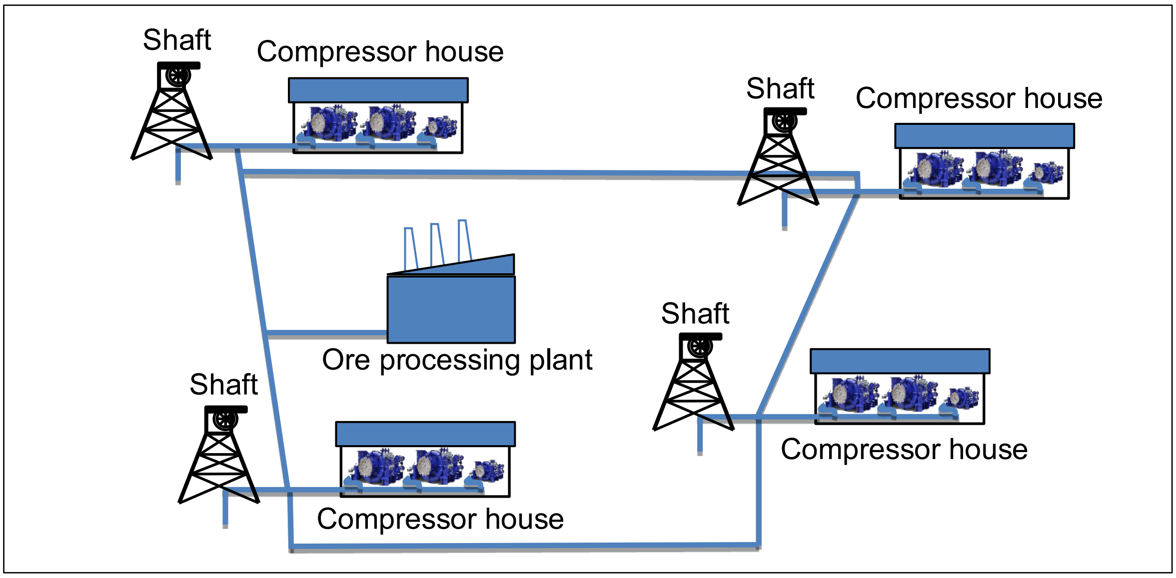


Figure 9 - Overview of a ring-fed compressed air network [30].

Ring-fed compressed air systems also run baseload compressors and have reserve capacity to accommodate an increase in the demand. The use of guide vane control is still present in order to maximise the energy efficiency of the system but is not as critical as in standalone systems.

The issues of midpoint demand on ring-fed networks are easier to mitigate for two reasons:

1) A larger selection of compressors is available to meet midpoint demands [37].
2) A larger compressed air network capacitance, creating a buffer against rapid pressure fluctuations.

For these reasons ring-fed networks bode well for DSM projects on mining operations where guide vane control is limited. A disadvantage of ring-fed systems is that DSM projects must be implemented on all major consumers to achieve the full benefit. Otherwise, the reduction in compressed air consumption at one shaft is lost to the demand of the other shafts.

Understanding the difference in the two supply methodologies and the potential for DSM initiatives is required to maximise the energy efficiency made possible by DSM initiatives [22]. Two keynotes to take away from Section 1.6 are:

1) Inlet guide vane control is critical to maximising the energy efficiency achieved by DSM initiatives in standalone compressed air systems [53].
2) Implementation of DSM initiatives on ring-fed networks must encompass all the major consumers present on the compressed air ring, ensuring that a reduction achieved on one shaft, due to a DSM initiative, is not lost to the demand of another shaft.

1.6.3 Limitations of existing supply methods

The compressed air networks described in Section 1.6 produce the compressed air utilised by end-users. It is important to note that this supply can be considered “limited” as adding additional capacity to the network is an expensive, resource intensive and time-consuming process.

End-users often misuse and mismanage compressed air, resulting in compressed air demands spiralling out of control and exceeding the available supply. Therefore, implementation and maintenance of DSM initiatives is of high importance in all compressed air networks, ensuring that the demand does not exceed the available supply.

1.7 Compressed air demand side management

The purpose of the following section is to perform a detailed investigation into existing DSM strategies within the mining industry. The strategies identified for investigation are surface control valves, level control valves, crosscut isolation as well as leak management and maintenance [22, 36, 42, 49]. The goal of the strategies listed above is to manage and mitigate the pressure supplied to unauthorised end-users or eliminate unauthorised end-users entirely, leading to a reduction in compressed air wastage and increase operational efficiencies.

As mentioned previously, this study is focused on the optimisation of DSM initiatives. However, it is important to understand the order in which such initiatives are implemented, as well as when the supply side must be revisited to match the demand. Figure 10 illustrates the order of implementation generally followed and when the supply side is to be revisited during the optimisation of compressed air efficiency in deep-level mining operations.

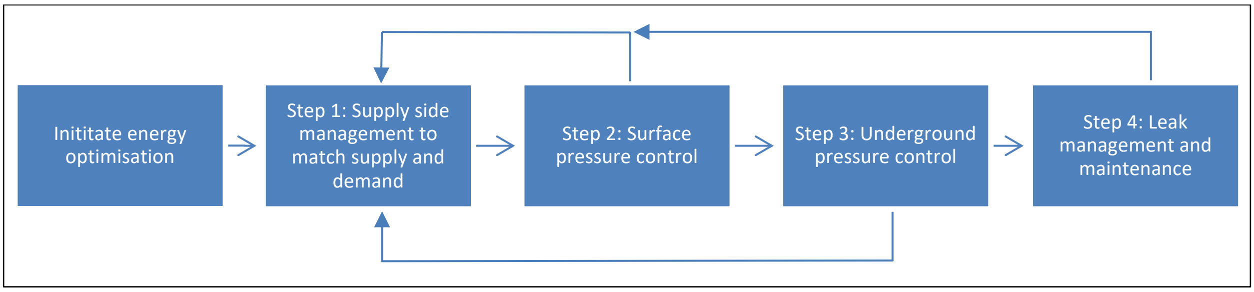


Figure 10 - Diagram illustrating an integrated approach to compressed air optimisation (adapted from [16, 22, 36]).

Steps two to four are seen as DSM initiatives. Once the logistics of steps two to four have been investigated and understood, a summary of each strategy will be compiled to determine the advantages, disadvantages, and effectiveness of each solution. Thereafter, a detailed overview of several studies will be completed in order to determine shortfalls within the existing research community, leading to the need for the study.

1.7.1 Demand side pressure control initiatives

The first step in optimising compressed air networks is to match the supply of compressed air to meet the end-user requirements using only compressor-control as highlighted previously in Figure 10. However, optimisation of the supply side is limited to the end-user with the highest pressure requirement on the existing network [42]. Therefore, end-users with lower pressure requirements are often oversupplied, leading to unnecessary compressed air consumption.

To further optimise the compressed air network, control valves or isolation valves are installed at the breakaway points where lower pressure demands are required [20, 49, 54]. Installation of a control valve enables a finer level of pressure control which cannot be achieved using compressor-control alone.

Figure 11 gives a simple example of how a control valve can be beneficial in a compressed air network where underground end-users have different pressure requirements relative to the surface end-users. In Figure 11, a control valve has been installed such that it is downstream of the surface end-users and upstream of the underground end-users, thereby controlling the pressure supplied to the underground end-users.

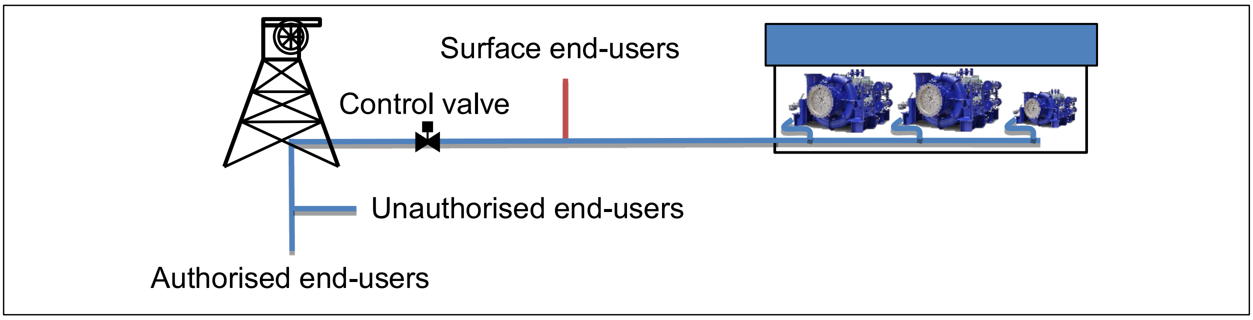


Figure 11 – An illustration of a typical compressed air network which can benefit from the installation of a control valve.

In this example the surface end-users require a constant 600 kPa whilst the underground end-users have varying requirements throughout the 24-hour mining cycle [37]. If only compressor control is used, the underground end-users will be supplied with a constant 600 kPa, leading to excessive compressed air wastage.

However, installation of the surface control valve, as shown in Figure 11, enables the ability to match the pressure downstream of the surface control valve to the underground end-users' pressure requirements, thereby reducing the overall demand of the compressed air network, leading to increased system efficiencies [49, 53]. The difference in pressure profiles between the surface end-users and the underground end-users is highlighted in Figure 12. The surface end-users pressure requirements are represented by the dotted red line and the underground end-users pressure requirements are represented by the black line.

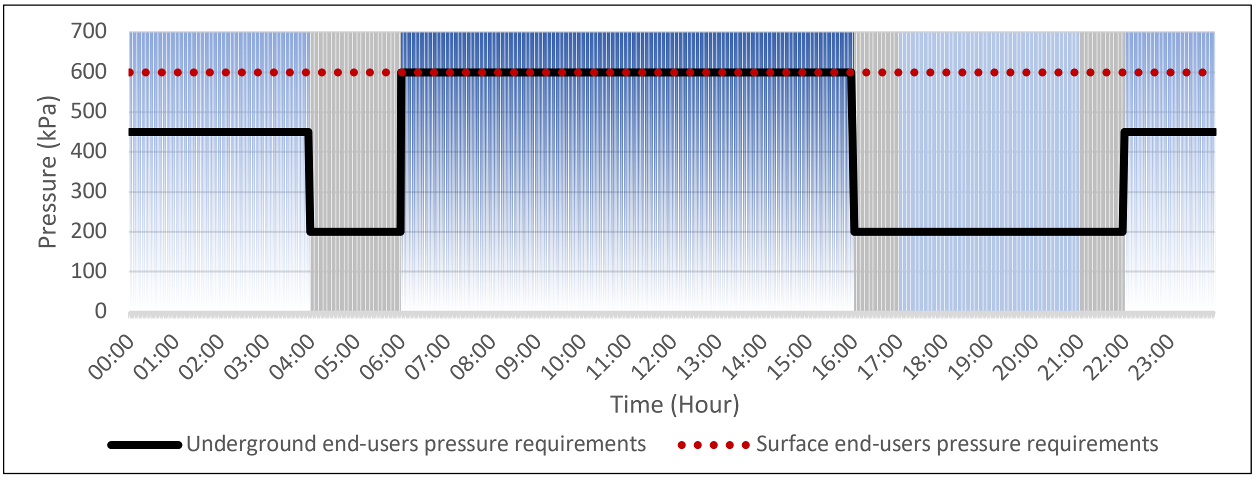


Figure 12 – A comparison of the pressure demand requirements of all underground end-users vs surface end-users, highlighting the difference in their pressure requirements over a 24-hour period.

Therefore, if a difference in the pressure profile of various compressed air end-users exists, a control valve can be used to further optimise the demand of the entire compressed air network [20, 36, 49, 54]. This principle applies to all forms of demand side pressure control initiatives such as surface control, level control and crosscut isolation.

The various DSM pressure control initiatives can be identified as different tiers of control, all operating on the same basic principle of the difference in pressure schedule. Surface control represents the highest tier of control and crosscut isolation represents the lowest tier of control. Figure 13 gives an infrastructural overview of the tiers of control which presently exist in the deep-level mining industry, namely: surface control, level control and stope isolation.

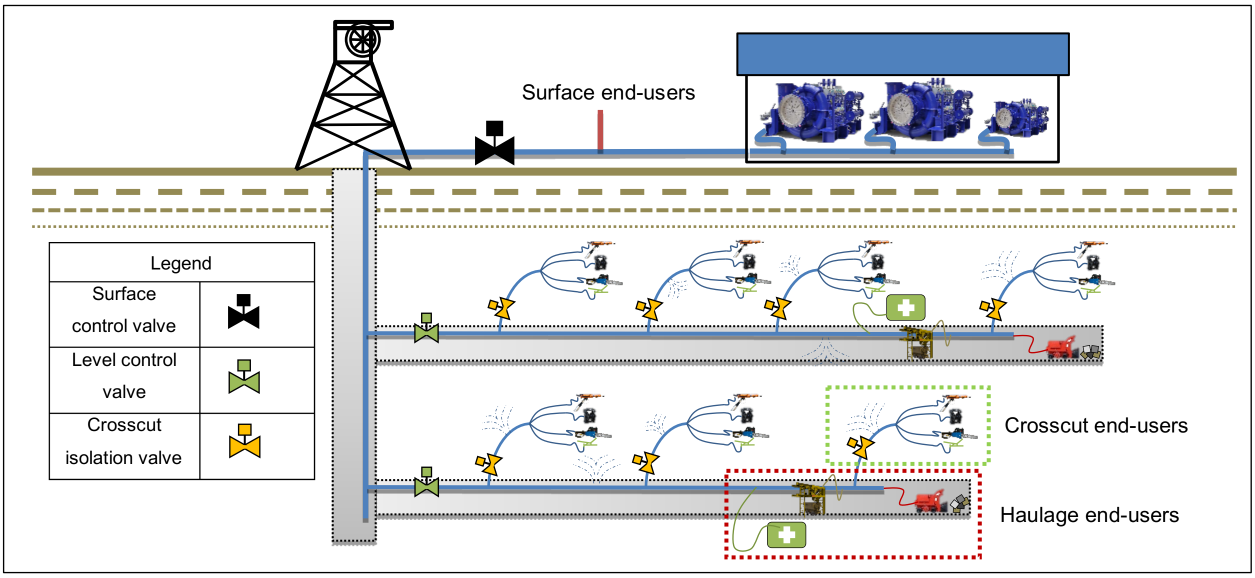


Figure 13 - Illustration of the different tiers of control which can be implemented on a deep-level mine.

It is critical that each tier of control, highlighted in Figure 13, supplies enough pressure to satisfy all authorised end-users downstream of the relevant control valve. Section 1.7.1.1, Section 1.7.1.2 and Section 1.7.1.3 further expand on the different pressure schedules and pressure requirements for the various tiers of control as well as which end-users must be satisfied by each tier of control.

1.7.1.1 Surface control valves

Surface control is viewed as the first tier of demand side pressure management. This is the broadest range of control as it must account for all underground end-users in the shaft, excluding the loading box which usually has a dedicated line that ties-off before the surface valve, as shown previously in Figure 2 [49, 53].

Following the 24-hour shaft schedule, the surface control valve will supply the required pressure when the first end-users arrive at their working area and will only begin to restrict the pressure once the last end-users leave their working area, for each shift cycle [20]. The different level schedules which must be accommodated by the surface valve are highlighted for the drilling shift in Figure 14. It is clear in Figure 14 that the surface control valve supplies 600 kPa when the first level starts working and can only begin to throttle the pressure after the last level stops working.

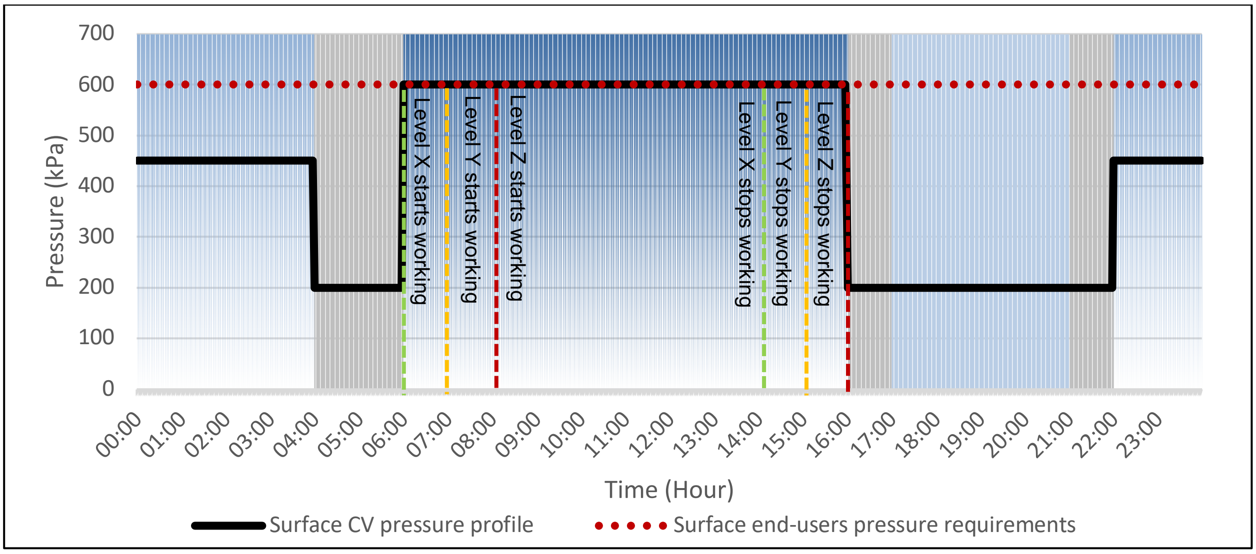


Figure 14 - Example of the pressure control profile of a surface control valve which must satisfy the demand requirements of all underground end-users.

Therefore, the surface control valve's pressure profile must encompass all end-users across all levels of the Shaft, per shift, according to the shaft's schedule [20, 37]. These end-users can be viewed in Figure 13.

Surface control valves have proven to be beneficial in both stand-alone networks and ring-fed networks due to the difference in pressure schedules between underground end-users and surface end-users as highlighted in Figure 14. Figure 14 serves as an example of the benefit which can be realised by a surface control valve in a standalone compressed air network. An example of the benefit of surface control valves on a ring-fed network is given in Annexure A.

1.7.1.2 Level control valves

Level control valves are viewed as the second tier of demand side pressure management. Level control valves can achieve a higher resolution of control than a surface control valve alone, as each level can be controlled according to the corresponding levels' shift schedule [36, 53]. The difference in each level's schedule creates the opportunity to further optimise the control as highlighted by the level control profiles relative to the surface control profile in Figure 15 [20].

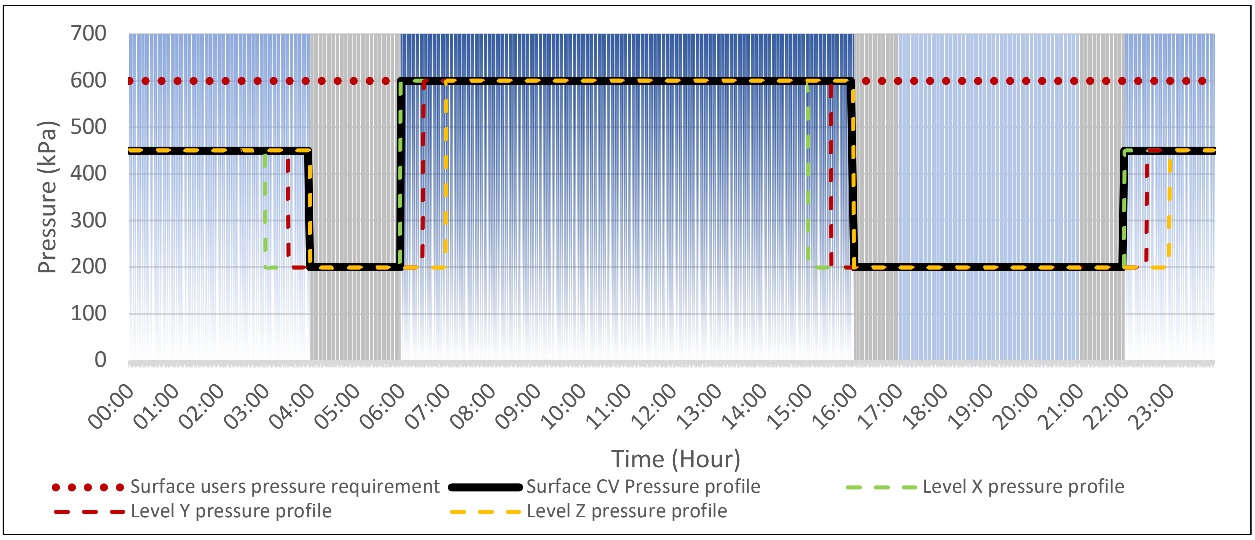


Figure 15 - An example of how level control valves can be beneficial if there is a difference in each level's schedule.

The pressure profile of level control valves must account for all end-users within the haulage (loaders, ore chutes and refuge bays) as well as in the working areas / crosscuts (rock drills, diaphragm pumps, chainsaws and air whistles), as shown previously in Figure 13. Equipment which is used prior to the level valve will not be affected by level control.

Therefore, the level control valve must supply the required pressure when the first crew of the respective level arrives at their working area and can only begin to throttle the pressure when the last crew of the respective level leaves their working area [49].

It is important to note that the implementation of level control valves does not require the implementation of a surface control valve. It is common to install only level valves, usually in a standalone compressed air network, in order to achieve a finer level of control.

However, when level control valves are installed downstream of a surface control valve, it is of critical importance that the surface control valve's pressure profile encompasses the pressure profiles of the level control valves as shown in Figure 15. This ensures that all the levels receive the pressure they require and are not hindered by the surface control valve throttling below a level's pressure requirement.

1.7.1.3 Crosscut isolation valves

The final tier of demand side pressure management is crosscut isolation. Crosscut isolation is the finest level of control, which is as close to the end-user as possible. Crosscut isolation is superior to level control due to the difference in each crosscuts' operational schedule. The further refinement and isolation benefit of crosscut isolation, when compared to surface and level control valves, is shown in Figure 16 for a single level.

It is clear in Figure 16 that each crosscut operates on a slightly different schedule and when compared to the level control valve profile are further refined during the drilling shift. Furthermore, the crosscut isolation valves can be completely isolated outside of the drilling shift.

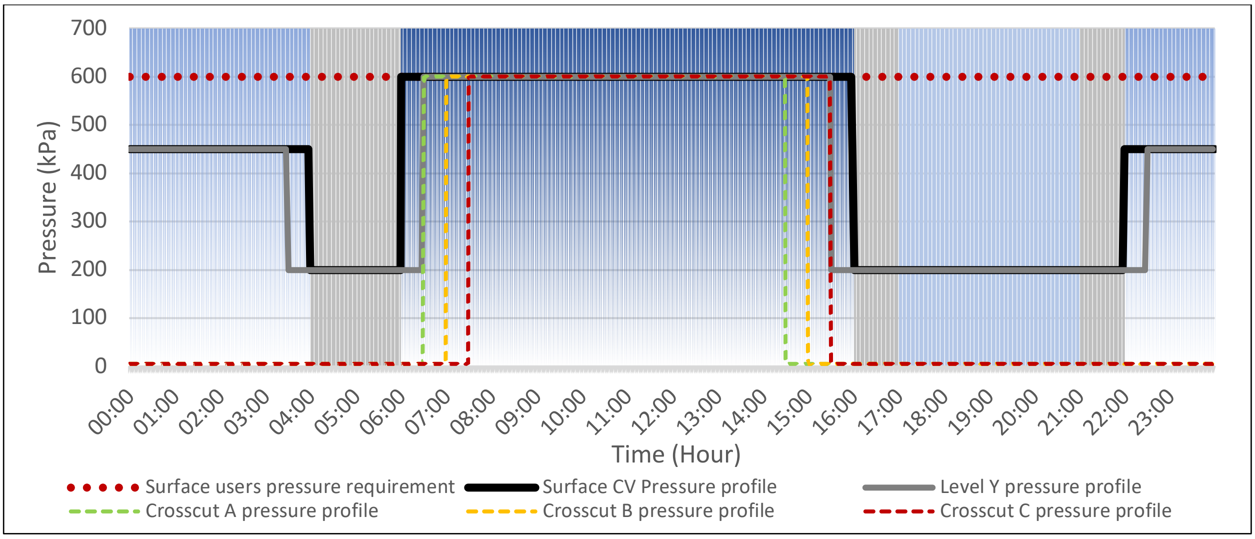


Figure 16 - An example of the benefits that can be achieved via crosscut isolation when compared to surface and level control.

The pressure profile of each crosscut isolation valve must account for all end-users within the working area / crosscut downstream of the crosscut isolation valve, as highlighted previously in Figure 13 [55]. The main end-users which must be accommodated by crosscut isolation are: pneumatic rock drills, diaphragm pumps, chainsaws and air-whistles.

Due to the logistics of the 24-hour mining cycle, pneumatic equipment in the crosscuts is generally only active during the drilling shift, therefore allowing the crosscuts to be isolated during all other periods in the 24-hour mining cycle [20, 22, 54]. The only end-user which requires pressure outside of the drilling shift are the air-whistles, which are used as safety signalling devices when the winches are in operation. In order to isolate the air during this period, the air-whistles must be replaced with electrical signalling devices.

It is also important to note that crosscut isolation does not require the preceding tiers of control to be implemented. However, if surface control or level control is installed upstream of crosscut isolation valves' it is critical that the surface and level control valves' pressure profiles accommodate the control profile of the crosscut isolation valves.

1.7.1.4 Control valve summary

It is clear from Section 1.7.1.1, Section 1.7.1.2 and Section 1.7.1.3 that demand side pressure control initiatives (control valves) can be used to manage the pressure supplied to unauthorised end-users more effectively than compressor control alone, thereby reducing the overall wastage of the compressed air network, resulting in improved compressed air network efficiencies.

Due to the logistics of deep-level mining operations, each working area operates on a slightly different schedule, which is influenced by the travelling time from surface to the working area [49]. It is this difference in schedules which allows each subsequent tier of control to achieve a finer level of control than the one preceding it [36].

This is highlighted in Figure 17 which shows an example of the difference in possible pressure profiles for the different tiers of control. The dotted red line highlights the surface end-users pressure requirements and also represents the pressure that would be received by underground end-users if no control valves are in place. The black line represents the surface control valves pressure profile which must satisfy all the underground end-users across all levels. The dashed green line presents a single levels pressure profile and highlights the scheduling benefit which can be achieved when compared to the surface control valves pressure profile. Lastly, the dashed yellow line represents a single crosscuts pressure profile and also highlights the scheduling benefit relative to a level control valve as well as a surface control valve.

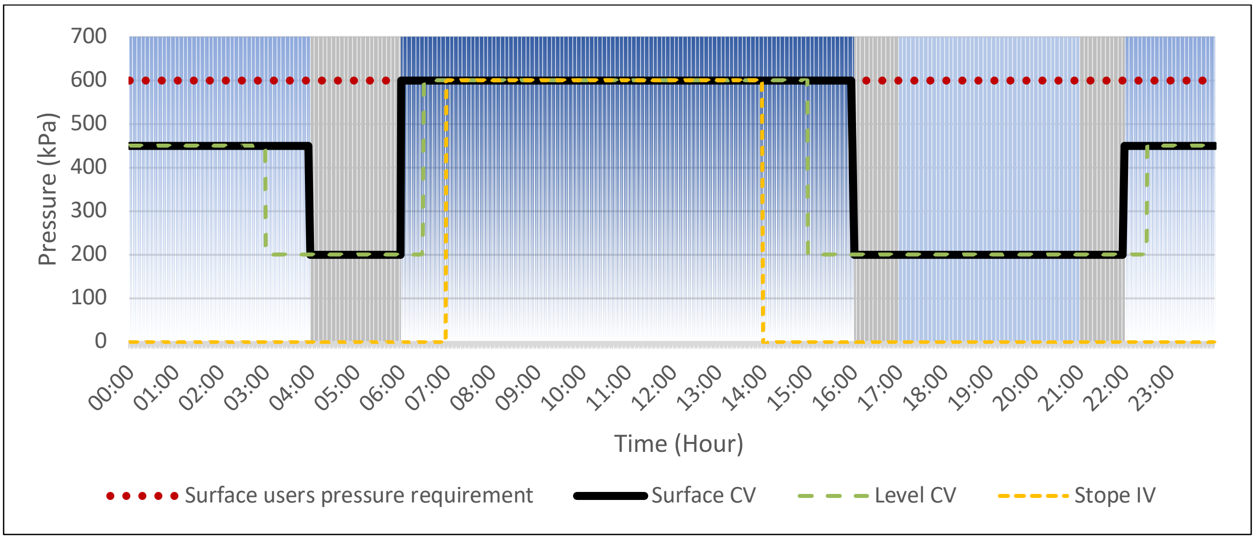


Figure 17 - A comparison of the possible pressure control profiles for the different tiers of control, highlighting the difference in each tier's profile over a 24-hour period.

When implementing a control valve, it is of utmost importance that the pressure profile of the relevant tier of control satisfies all end-users' pressure requirements downstream of the control valve [37]. The pressure requirements and shift cycles of the end-users differ from site to site. Therefore, a thorough understanding of the end-users' schedules and pressure requirements is critical to determine which tier / tiers of control are best for the specific site being investigated. The illustrations given in Section 1.7.1.1, Section 1.7.1.2 and Section 1.7.1.3 are merely examples which highlight the potential benefits of the different tiers of control.

Implementation of more than one tier of control at a specific site is not uncommon. However, the value add over and above an existing tier of control can be limited and must be investigated thoroughly to ensure a benefit can be achieved. Additionally, it is of utmost importance that the control schedule of a secondary tier of control is satisfied by the primary tier of control [20].

It is important to note that throttling the pressure via means of surface valves, level valves and crosscut isolation only treats the symptoms of the unauthorised end-users and is viewed as an artificial reduction in consumption [36, 37, 45, 47, 56], whilst leak management and maintenance is viewed as direct treatment of the issue at hand by eliminating the unauthorised compressed air end-users [57].

In a perfectly managed compressed air network, there would be no need to implement demand side pressure control initiatives as there would be no wastage to mitigate. However, as mentioned in Section 1.5.5, unauthorised compressed air consumption due to leakages will never be entirely eliminated due to the harsh environment and intrinsic size of deep-level mining compressed air networks.

Additionally, the issue of misappropriation and misuse of compressed air cannot be addressed by leak management and maintenance initiatives. Therefore, demand side pressure control initiatives remain critical in optimising compressed air networks throughout their lifecycle.

1.7.2 Leak management and maintenance

If the issue of unauthorised compressed air end-users is to be directly addressed, leak management and corrective maintenance is considered the obvious solution to address majority of the leakage related compressed air wastage [36, 52, 53, 55].

The process begins with a visual audit of the entire compressed air network to locate leakages within the system [4, 44-46, 57]. Thereafter, the audit findings are noted in a report in which the leaks are ranked by severity. Using the report of the audit findings, an action plan is drawn up to repair the identified leakages, prioritising the largest leaks first as they have the greatest impact [16, 17]. Once the repairs have been made, a follow up audit is required to confirm that the necessary repairs have been implemented. The continuous process of leak management is depicted in Figure 18:

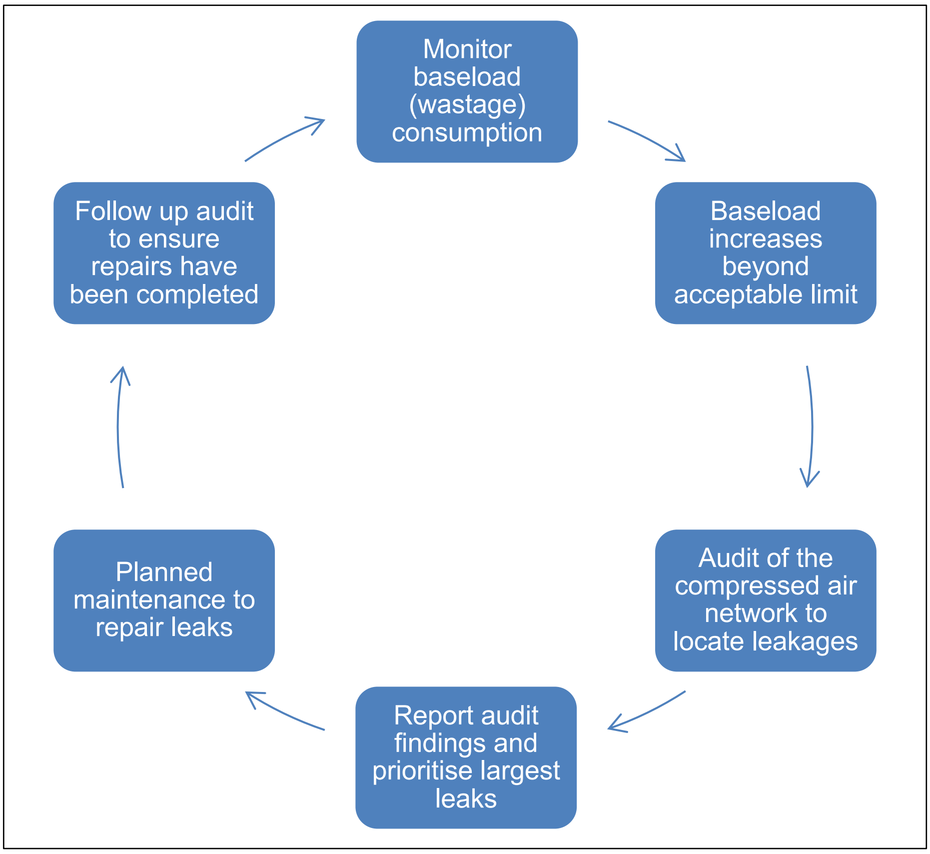


Figure 18 - Flow diagram of a typical leak management process.

Leak management, in theory, is a relatively simple process in which leaks are identified and repaired. However, due to the scale and inaccessibility of deep-level mining compressed air networks it is an extremely time consuming, resource intensive and an impractical task [46, 54, 57, 58]. This method of demand side management is considered to be the most time consuming [59]. One study highlighted this as it took four auditors a total of three months to audit the underground compressed air network of a single shaft [46].

A large proportion of the leakages are known to be found in the stoping areas / crosscuts, which are often avoided in such audits due to inaccessibility and safety reasons [20, 57]. Therefore, many of the leaks are not reported in the audit findings and are not repaired.

Repairing the identified leaks is a time-consuming process in which the compressed air network must be isolated to make the repairs. Due to the continuous schedule of mining operations, this work can only take place during downtime which is scheduled for such maintenance.

Due to the issues listed above, this method of demand side management often yields underwhelming results as the effect of the leak repairs is not as great as expected. One study showed that after leaks were repaired, less than 25% of the expected improvement was achieved [60].

Therefore, a more effective method to identify the areas with the largest leakages is required to make leak management and maintenance a more practical approach to demand side management which will yield greater results [22].

1.7.3 Summary of all solutions

In Section 1.7.1 and Section 1.7.2 the basic principles of each DSM initiative were investigated. Now that an understanding of each initiative has been developed, a detailed analysis of the various DSM initiatives can be completed to determine the advantages, disadvantages and overall energy impact of each initiative.

When pursuing compressed air optimisation in the deep-level mining industry, there are several key factors which must be satisfied for the respective DSM initiative to be both successful and sustainable. Each factor and its preferred outcome are listed as follows:

1. Capital cost – Moderate to low
2. Project lead time – Moderate to low
3. Required maintenance – Low
4. Resource intensity – Low
5. Overall energy impact – High

Capital cost refers to the total capital which must be spent to implement the project. The project lead time refers to the total time spent from initiation to commissioning of the project. The required maintenance refers to how often maintenance must be conducted as well as the extent of the maintenance. The resource intensity refers to how much time will be required from mine personnel to sustain the benefits of the DSM initiative. Lastly, the overall energy impact refers to the energy reduction which is achieved by the DSM initiative, leading to greater operational efficiencies.

Each DSM initiative is analysed in Table 4 according to the factors listed above such that they can be easily compared. The parameters of each initiative are highlighted according to how well they satisfy the requirements for a deep-level mining application, green meaning fully satisfied and red meaning not satisfied at all. Thereafter, the DSM initiatives which should be the key focus for further optimisation of compressed air networks in deep-level mines are highlighted.

Table 4 - Summary of the advantages, disadvantages, and overall energy impact of DSM initiatives [22, 49, 53, 55]

Key factors	Surface control	Level control	Crosscut isolation	Leak management
Capital cost	Low	Medium	High	Low
Project lead time	Low	Medium	High	High
Required maintenance	Low	Medium	High	High
Resource intensity	Low	Medium	High	High
Overall energy impact	Moderate	High	Extremely high	Moderate

From Table 4 it is clear that crosscut isolation and leak management are not suitable as primary projects to improve deep-level mining compressed air systems. Due to their large project lead times, high maintenance requirements and high resource intensities, they do not fall into the primary scope for compressed air optimisation in the mining industry. These initiatives are generally implemented after surface or level control is implemented, and are considered to be tertiary measures, as shown in Figure 10 at the start of Section 1.7.

Surface control meets many of the requirements listed in Table 4, with the only downfall being its moderate energy impact. This can be improved by rather implementing level control valves across all the levels. However, level control valves will require larger capital investment, a longer project lead time, increased maintenance as well as an increased resource intensity when compared to a surface valve alone.

Therefore, a hybrid control approach is proposed in which a surface control valve is implemented in conjunction with carefully selected level control valves. This approach aims to reduce: the capital cost, project lead time, maintenance requirements and resource intensity, when compared to level control alone, whilst also improving the energy impact from a moderate level to a high level by minimising the wastage on the largest level consumers, which cannot be achieved by surface control alone.

1.7.4 Critical analysis of existing compressed air DSM initiatives

Critical analysis of existing literature is required to determine if such a hybrid approach has been used in the past. The factors to be considered when consulting the literature are as follows:

1. Was surface control implemented?
2. Was level control implemented?
3. If both were implemented, was it a hybrid system which made use of selected level control valves?
4. If selected level control valves were installed downstream of an existing surface valve, was there an analysis methodology used to determine which levels would yield the highest efficiency increase?

The results of the literature study are summarised in Table 5. Studies which meet the requirements listed above are highlighted in green and studies which do not meet the requirements are highlighted in orange.

Table 5 - Summary of literature studied regarding demand side management initiatives

Ref	Surface control	Level control	Hybrid control	Analysis methodology	Shortcomings
[53]	Y	Y	N	N	Surface control or level control alone, no combined control.
[10]	N	Y	N	N	Installation of control valves on areas which have lower pressure requirements in an industrial plant.
[49]	N	Y	N	N	Results of analysis methodology discussed but methodology not shared.
[37]	Y	Y	N	N	Study is focussed on compressor selection which takes valve control into account.
[20]	Y	Y	N	Y	Analysis methodology used and described but no hybrid approach used.

Ref	Surface control	Level control	Hybrid control	Analysis methodology	Shortcomings
[46]	N	Y	N	N	General overview on how to use benchmarking to locate inefficient compressed air usage. Little to no detail regarding valve control.
[22]	Y	Y	N	N	Brief overview of DSM via throttling. The focus is on crosscut isolation and general compressed air management.
[56]	Y	Y	N	N	This study is focused on optimising compressor control and briefly mentions the benefit of control valves.
[50]	Y	N	N	N	The main focus on this study is on guide vane control, with the recommendation of surface control to further optimise the system.
[52]	Y	Y	N	Y	Analysis methodology is presented to analyse splitting the system into different pressure zones but no hybrid approach is used.
[35]	N	N	N	N	Analysis of how to improve compressed air efficiency. Implementation of a control system to mitigate wastage and misappropriation of compressed air is recommended by the author.
[55]	Y	Y	N	Y	In this study, a simulation is used as an analysis methodology to determine the benefit of control valves. However, no hybrid approach is investigated.

Ref	Surface control	Level control	Hybrid control	Analysis methodology	Shortcomings
[16]	Y	Y	Y	N	Implementation of control valves on water system in a deep-level mine which made use of a hybrid approach. Can be applied to compressed air.
[16]	Y	Y	N	N	Implementation of control valves on all levels and surface. No hybrid approach used. Results discussed but not methodology.
[44]	Y	Y	N	Y	Analysis methodology developed to determine the impact of energy efficiency initiatives. Not application specific.

It is clear in Table 5 that many studies make use of control valves which can further increase the efficiency of compressed air systems by matching the supply pressure with the end-user pressure requirements as closely as possible [10, 16, 20, 22, 37, 44, 46, 49, 52, 53, 55, 56]. These studies implemented surface control, level control across all levels or surface control in conjunction with level control across all levels of the shaft. However, no studies investigated the use of a hybrid control philosophy on compressed air networks.

The more detailed studies shared their analysis methodology [20, 52, 55]. Whilst the studies which took a broader approach to compressed air management only showed the benefits of control valves and not the analysis methodology used [10, 16, 20, 22, 37, 44, 49, 53, 56]. The most notable studies which were conducted by van der Zee, van der Linde and Cabello et al. are discussed in detail as follows:

Study 1 – van der Zee [16]

In the study conducted by van der Zee, control valves were used to optimise both water and compressed air systems. Analysis of the resulting water DSM project showed that a surface control valve, selected level control valves and crosscut isolation valves were installed on the water network. The surface control valve limited the pressure supplied to all the underground working areas. Selected level control valves were installed on the less active mining levels to limit the flow to these areas. The crosscut isolation valves were installed on the highly active mining areas as they maximised the energy benefit and ensured that the upstream end-users' pressure requirements were still satisfied. Thus, van der Zee implemented a hybrid control methodology on the water supply system of a deep-level mining operation.

The surface control valve contributed a power reduction of 550 kW whilst expanding the control valves to represent that of a hybrid philosophy generated an additional power reduction of 3 280 kW. When expanding from surface control alone to the hybrid control philosophy an additional 38 valves were installed, thus increasing the required maintenance, project lead time and resource intensity. Additionally, it was noted that the project would have been expanded further if it wasn't for the high capital cost of purchasing and installing control valves across all the levels. Even though this particular project was implemented on a water network, the use of the hybrid control philosophy could be applied to a compressed air network.

In the same study by van der Zee, the use of control valves for compressed air was also investigated, however only level control valves across all levels were implemented. Thus, no hybrid control philosophy was implemented on the compressed air network even though it was implemented on the water network. The level control valves achieved a total power reduction of 1 450 kW.

Study 2 – van der Linde [55]

In the study conducted by van der Linde, the theoretical power reduction that could be achieved by the use of surface control valves and level control valves was simulated in order to compare the two control strategies. Additionally, the capital costs, labour costs and maintenance overhead costs were analysed. The optimal strategy which satisfied the mining operation's requirements was then selected and implemented. The use of a hybrid control philosophy was not investigated by van der Linde in this study.

The simulation of the surface control valve was completed for a total of 2 surface control valves and highlighted a potential power reduction of 57.7 kW at a total implementation cost of R360 000. In addition, the simulation of level control valves across all levels was completed for a total of 33 level control valves and highlighted a potential power reduction of 160.1 kW at a total implementation cost of R5 795 000.

Thus, it was concluded that the surface control valves achieved a moderate power reduction with low capital costs, labour requirements and maintenance costs whilst the level control valves achieved a power reduction three times higher than that of the surface control valves but drastically increased the capital costs, labour requirements and maintenance costs.

Study 3 – Cabello et al. [10]

In the study conducted by Cabello et al., the use of DSM initiatives in an industrial battery manufacturing plant was investigated. The study began by determining the sections in the manufacturing plant which had the largest compressed air consumptions. The battery assembly, air filtering, grid manufacturing and quality control sections were found to be the areas with the largest compressed air consumption.

These sections were then analysed to determine if control valves could be installed to lower the pressure supplied to the sections in question, in turn reducing their compressed air consumption. The battery assembly, air filtering and grid manufacturing were identified as prime candidates for pressure control valves as their pressure requirements differed from the rest of the manufacturing plant. The installation of the control valves resulted in compressed air demand reductions of 10% in the battery assembly section, 25% for the air filtering section and 10% for the grid manufacturing section.

Although this study was not implemented in the mining industry, the installation locations of each pressure control valve were carefully selected to maximise the power reduction which could be achieved by the DSM initiative rather than installing control valves across all sections of the manufacturing plant. Thus, supporting the methodology of installing control valves in carefully selected areas rather than installing them across all areas.

1.7.5 Summary of the selected literature

Therefore, from the literature analysed in Table 5 as well as the detailed case studies, it is clear that the studies which made use of surface control alone benefitted from minimal capital costs, low maintenance requirements, low resource intensities and short project lead times but they could only achieve a moderate energy reduction on the compressed air network.

The studies which made use of level control valves, across all levels of the shaft, benefitted from a greater energy reduction impact on the compressed air network. However, they suffered from increased capital costs, moderate maintenance requirements, high resource intensities and moderate project lead times. Additionally, no studies investigated the use of a hybrid control philosophy in deep-level mining compressed air networks.

1.8 Need for the study

There are a large number of studies which have investigated the potential benefits of control valves as a DSM initiative on compressed air systems. Multiple studies made use of both surface control valves and level control valves across all levels to optimise the compressed air network energy efficiency.

A large majority of the studies analyse compressed air systems as a whole and control valves only make up a small portion of their investigations. Therefore, the analysis methodology used to determine the benefit of the control valves was not shared. Only a handful of studies investigate the benefits of control valves in detail and share the analysis methodology used to quantify the value-add of the control valves.

However, the downfall of these studies was either a moderate impact on the compressed air network efficiency via surface control alone or excessive capital costs, extended project lead times, increased maintenance requirements and high resource intensities via implementation of control valves across all levels. No studies investigated the potential of using a hybrid approach, in which a surface control valve is installed in conjunction with selected level control valves on a deep level mining operation’s compressed air system.

Therefore, the need exists to develop a methodology to determine the optimal hybrid control valve layout which will maximise the energy impact of the DSM initiative on the compressed air system, whilst also minimising the capital cost, project lead time, maintenance requirements and resource intensity.

1.9 Study objectives

The objective of this study is to develop an analysis methodology which can be used to accurately select which level control valves will maximise the benefit of a hybrid control valve approach in compressed air systems in deep-level mines. The main objectives are as follows:

1. Develop a methodology which can determine the benefits of a hybrid control valve approach with the aim of:
    a. Maximising the energy impact of the DSM initiative.
    b. Minimising capital cost, required maintenance, project lead time and resource intensity.
2. Implement and verify the hybrid control philosophy analysis methodology.

1.10 Dissertation overview

Chapter 1: Introduction and Literature

In Chapter 1, background is given on the inefficiency of compressed air networks in the global industry as well as the deep-level mining industry. The cause and effect of misappropriation and mismanagement is highlighted. The SSM and DSM initiatives used to mitigate and manage wastage are discussed. The issues of the existing DSM methods are highlighted. A need for the study and study objective are then formulated.

Chapter 2: Methodology

In Chapter 2, a methodology is developed to determine the theoretical energy impact of a hybrid control philosophy in deep-level mining compressed air systems. The methodology is written such that it can be used to analyse any shafts' compressed air network. Thereafter, the necessary infrastructure improvements to implement the hybrid control philosophy are presented and the validation and verification process is discussed.

Chapter 3: Results

In Chapter 3, a case study is analysed in which the methodology developed in Chapter 2 is implemented. After the theoretical benefit has been determined, the necessary infrastructure changes are made to implement the selected hybrid control philosophy. Thereafter, the energy impact is validated, and the theoretical model is verified.

Chapter 4: Conclusion

In Chapter 4, the findings of the research paper are discussed. Shortfalls are highlighted and future recommendations are made.

CHAPTER 2 - METHODOLOGY

2.1 Preamble

In Chapter 2, a theoretical analysis methodology is developed to determine the optimal hybrid layout for level control valves in a deep-level mining compressed air system. The analysis methodology developed is summarised in Figure 19 and is applicable to any deep-level mining compressed air network.

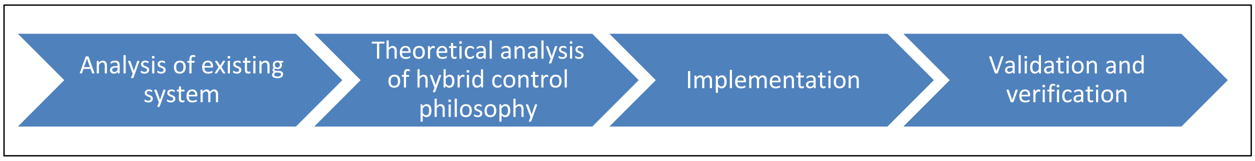


Figure 19 - Summary of the analysis methodology used in Chapter 2

The methodology begins with an investigation into the existing compressed air network reticulation, available instrumentation, existing control valves in the network and the compressed air distribution across the different levels. This information is used to develop baselines of the existing compressed air consumption which will later be used to theoretically determine the benefits of hybrid control as well as verifying the energy impact of the project upon implementation. Thereafter, the pressure requirements of the authorised end-users are determined in conjunction with the shaft schedule.

Using this information, the theoretical energy impact per level is determined and the optimal hybrid layout is chosen. The goal of the chosen layout is to maximise the energy impact of the DSM initiative whilst minimising the capital cost, required maintenance, project lead time and resource intensity.

After the optimal hybrid control philosophy has been selected, the procedure to effectively implement the hybrid control philosophy is discussed. In this discussion the control philosophy, different types of valves, actuators and instrumentation required are investigated. Thereafter, the method of implementing the theoretical pressure profiles is presented.

Upon implementation of the project, the energy impact of the hybrid control philosophy is quantified by comparing the achieved flow reductions with the baseline flow profiles. The achieved energy impact is then compared to the theoretical energy impact to verify the accuracy of the theoretical model.

2.2 Analysis of the existing compressed air network

The primary step in determining the theoretical benefit of a hybrid control philosophy is gaining a thorough understanding of the existing compressed air network. Each compressed air network is unique and must be treated as such. The existing infrastructure, compressed air distribution, current baselines, pressure demand requirements of authorised end-users and the shaft schedule are the critical components required to determine the theoretical benefit of a hybrid control philosophy. The following section describes how such an analysis is conducted, whilst also highlighting the different methods which exist for each section of the analysis.

2.2.1 Existing compressed air infrastructure

The compressed air network is responsible for transporting compressed air from the compressor house to the respective end-users on surface as well as underground. As stated in Section 1.7.1, control valves or isolation valves can be installed at the breakaway points where lower pressures are required by end-users, allowing further optimisation of the compressed air network. Therefore, an understanding of the existing compressed air network is required to determine if the existing infrastructure supports the implementation of a hybrid control philosophy.

When implementing a hybrid control philosophy, a control valve is installed on surface as well as selected underground levels. Therefore, the analysis of the existing compressed air infrastructure is split into two sections. The first will investigate the implementation of a surface control valve and the second will investigate the implementation of level control valves.

The two factors to be investigated when analysing the compressed air network for each of the two sections are:

1. The end-users which must be satisfied by the reticulation network.
2. The existing compressed air reticulation.
    a. Existing control valves.
    b. Installed instrumentation.
    c. Compressed air line sizes at optimal installation locations.

Using the information above, the possible control valve installation locations can be determined. In some instances, it may be necessary to make changes to the compressed air reticulation to allow the implementation of a control valve.

The required information, listed above, can be gathered by inspecting the compressed air reticulation engineering drawings or by means of a visual audit. The engineering drawings can provide a large amount of information with little effort required. However, the engineering drawings are not always available and are often not up to date. Therefore, it is recommended that the engineering drawings are consulted to get an initial idea of the existing reticulation network and thereafter this information should be confirmed via a visual audit of the area in question.

The layout of compressed air networks in deep-level mining operations all follow a similar design in which the compressed air is transported from the compressor house to the relevant end-users via a network of steel piping. Surface end-users and ring-fed networks connect to the main compressed air line on surface. Thereafter, the main line goes underground where each level ties-off from the mainline accordingly.

2.2.1.1 Surface control valves

The first area of investigation is the possibility of implementing a surface control valve. An example of an optimal surface control valve layout is shown in Figure 20. Figure 20 highlights the typical end-users found in a deep-level mining operation, which must be considered when installing a surface control valve. These end-users are surface end-users, a connection to a ring-fed network, an isolated loading box line and the underground end-users.

Additionally, the instrumentation required to enable the implementation of a control valve is depicted in Figure 20 by the grey dots which are encircled in either green or red. The grey dots encircled in green represent the pressure instrumentation that is required, and the grey dot encircled in red represents the flow instrument that is required. Lastly, the ideal installation location for the surface control valve is also highlighted in Figure 20.

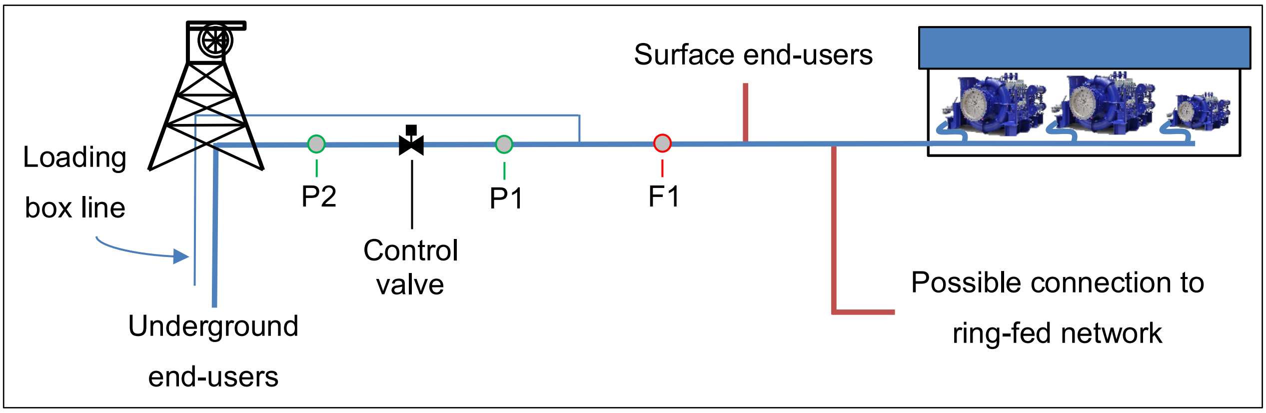


Figure 20 - An overview of the reticulation of a surface compressed air network and the possible end-users which might be present, the required instrumentation and ideal valve location for optimal surface control.

When investigating the possibility of implementing a hybrid control philosophy, it may be possible that a control valve is already installed on surface. In this instance, it is recommended that the procedure listed below is still followed to ensure optimal control of the surface control valve. Additionally, it is recommended that the existing control valve is checked via the process discussed in Section 2.4.2.1 to ensure that it is adequately specified for the desired control parameters.

If it is found that a surface control valve is not present at the existing site, the investigation begins by understanding the possible end-users which exist on surface or tie-off from the main surface line as shown previously in Figure 20. Typical surface end-users which can be found are: Mineral processing plants, fridge plants, as well as D-bar lifts. These end-users make use of compressed air for a variety of different purposes and operate continuously throughout the 24-hour mining cycle. Due to their pressure requirements of 500 kPa throughout the day, it is recommended that they tie-off prior to the surface control valve, such that they are not affected by the control of the surface control valve.

The second tie-off from the surface mainline, which one must be aware of, is a possible connection to a ring-fed compressed air network. It is common for multiple compressor houses to be connected in a ring-fed network to enable better compressor control as well as creating redundancy within the system as discussed in Section 1.6.2.2. It is recommended that this tie-off occur prior to the control valve installation location such that the control valve does not influence the operation of the ring-fed network and vice versa.

The final tie-off from the surface mainline to be aware of is an isolated loading box line. The loading boxes are usually actuated via a set of pneumatic cylinders which are operational throughout the 24-hour mining cycle. The loading boxes are responsible for transferring ore from underground or surface silos to either a skip or a surface locomotive. The skips then transport the ore from the underground silo to the surface silo, followed by the surface locomotives which transport the ore from the surface silo to the processing plant.

Transportation of ore from underground to the processing plant is seen as one of the main bottlenecks in deep-level mining logistics. Thus, the loading boxes must be able to operate throughout the 24-hour mining cycle and must tie-off prior to the surface control valve. To combat the loading boxes dependency on compressed air, several mining sites have converted their loading boxes from pneumatics to localised hydraulic power packs. Therefore, it is critical that the loading boxes' method of operation be considered when implementing surface control.

Due to the uniqueness of each mining operation, the site must be investigated to determine which tie-offs, discussed above, are present on the main surface compressed air line. It is critical that any end-users which require a constant pressure supply throughout the 24-hour mining cycle tie-off prior to the surface control valve. Thus, ensuring that the surface control valve can achieve the maximum operational efficiency when throttling underground end-users throughout their 24-hour pressure profile.

The second area to be investigated is the existing instrumentation on the main surface compressed air line. The instrumentation which is required to implement and quantify the benefits of surface control is depicted in Figure 20. The optimal instrumentation layout makes use of two pressure sensors and one flow meter.

The two pressure sensors are primarily used to control the main surface control valve. However, they perform a secondary function of ensuring the surface end-user's pressure requirements are met whilst also performing condition monitoring on the surface control valve and compressor house. A detailed description of the control methodology is shared later in Section 2.4.1. However, during the initial infrastructure investigation, it is only important to note if such instrumentation is present and operational.

The flow meter is primarily used to quantify the benefit achieved by implementing surface control and can be used to monitor the effect of the surface control daily. The data collected by the flow meter is used to develop a baseline for the shaft in question and is later compared to the actual consumption to quantify the benefit of surface control. The details regarding baseline development and quantification of the impact of surface control are discussed in Section 2.2.3. As with the pressure loggers, during the initial investigation it is only important to note if the flow meter is present and operational.

It is important to note that in standalone compressed air networks a flow meter is not critical, as the power consumption of the compressor house can be used to determine the benefit of surface control. However, in a ring-fed network it is critical to have a surface flow meter installed as compressed air may be imported to the shaft from other compressor houses on the ring. Alternatively, compressed air may be exported from the shaft's compressor house to other shafts on the ring. Thus, analysing the power consumption of the shaft's compressor house will not be a true reflection of the shafts' compressed air consumption in a ring-fed network.

In deep-level mining it is common practice to have a surface flow meter as well as a surface pressure sensor installed as shown by F1 and P1 in Figure 20. These instruments are utilised to perform condition monitoring of the existing compressed air supply network as well as monitoring the shafts' compressed air utilisation. Therefore, these instruments should be present on the respective deep-level mining site. If it is found that these instruments are present, it is recommended that their accuracy be verified prior to the implementation of surface control, thus, ensuring optimal control of the surface control valve.

After investigating the existing tie-offs and instrumentation present on the main surface compressed air line, the possible installation location of the surface control valve can be determined. The possible installation locations, following the optimal layout as shown in Figure 20, are anywhere downstream of the surface tie-offs until the first operational level underground. However, it is recommended that the control valve be installed on surface and not in the shaft barrel as this will complicate the installation and maintenance of the valve unnecessarily, whilst also exposing the valve to the harsh underground conditions.

Once the installation location on surface has been chosen, the site must be inspected to determine the existing compressed air line size. The existing line size will be used in conjunction with the flow and downstream pressure requirements to specify a control valve size. This process is also dependant on the type of valve chosen and is further discussed in Section 2.4.2.1.

The section above explains the necessary investigations required on the compressed air network prior to the implementation of a surface control valve. Figure 21 serves as a summary/checklist of all the information which must be collected when investigating the infrastructural requirements to implement a surface control valve.

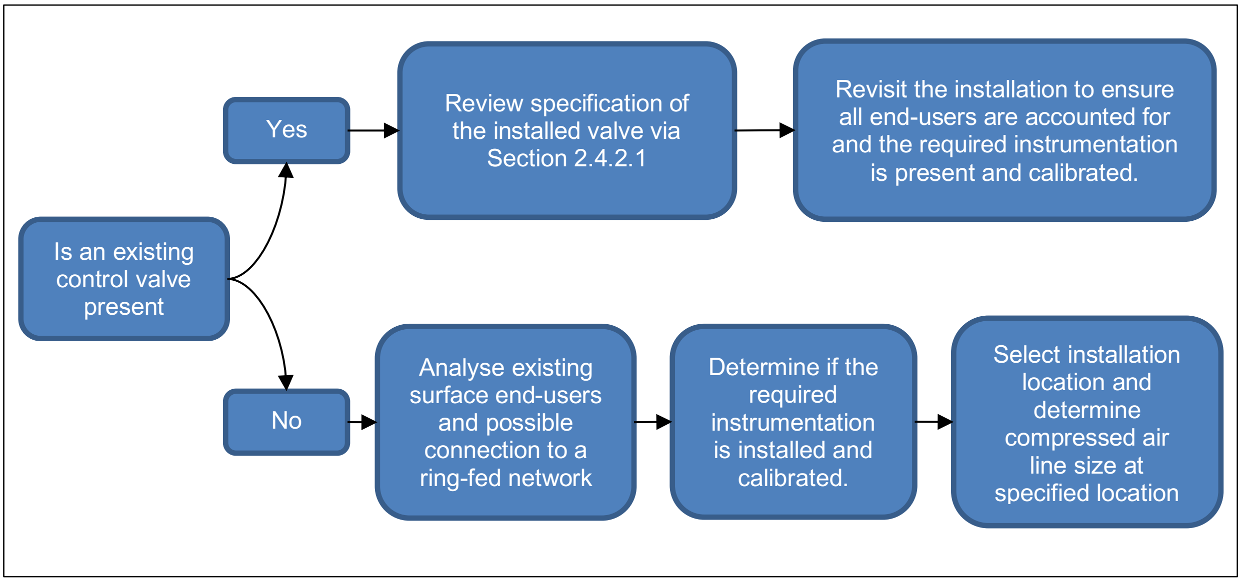


Figure 21 - Summary of infrastructure check prior to implementing the hybrid approach.

2.2.1.2 *Level control valves*

Following the investigation of the surface compressed air network, each of the operational mining levels underground are investigated. The investigation begins by determining how many mining levels are present at the respective mining site as well as determining which levels are currently active. Once this information has been gathered a detailed investigation must be completed at each of the active mining levels as per the process discussed below.

The two areas to be investigated, per active mining level, are: the end-users which must be satisfied by the reticulation network as well as the existing reticulation network. Figure 22 serves as an example of the ideal compressed air reticulation and instrumentation when a level control valve is installed. Each area of investigation is expanded on later in this section.

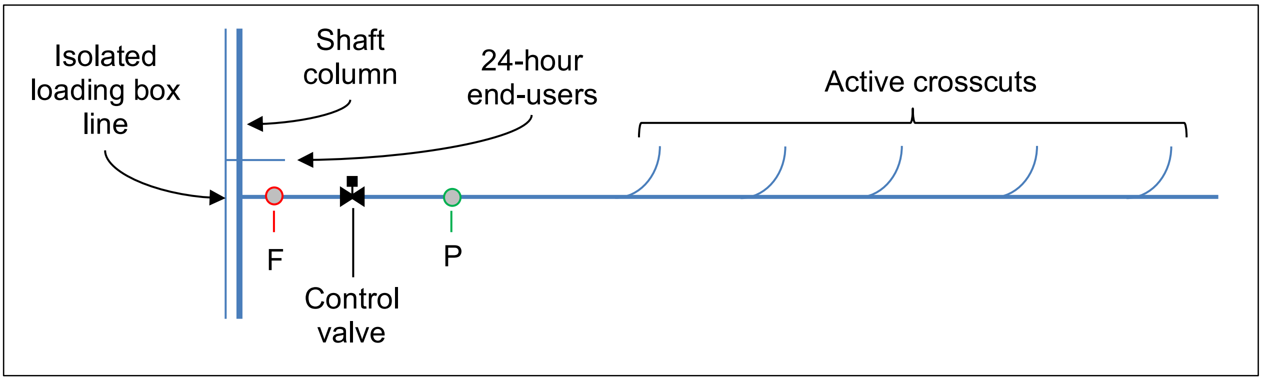


Figure 22 - An overview of the reticulation of an underground level's compressed air network, the possible end-users which might be present, the required instrumentation and ideal valve location for optimal level control.

As with surface control valves, if it is found that there is already a level control valve installed on some of the levels, it is recommended that the procedure listed below is still followed to ensure optimal control of the level control valve. Additionally, it is recommended that the existing control valve is checked via the process discussed in Section 2.4.2.1 to ensure that it is adequately specified for the desired control parameters.

Unlike the surface compressed air network, there are usually no underground end-users which require a constant pressure supply throughout the 24-hour mining cycle other than the loading box at shaft bottom. It is assumed that if the loading box operation is a concern, it would have been identified and resolved during the surface control valve investigation in Section 2.2.1.1.However, if the mining operation in question does have end-users who require a constant supply pressure throughout the 24-hour mining profile, which is above 200 kPa, it is recommended that these end-users tie off from the isolated loading box line as shown in Figure

22, thus ensuring they receive the pressures they require without inhibiting the optimisation of the level control valve.

The main end-users which must be taken into account are the active crosscuts. Majority of the unauthorised end-users are found in the crosscuts and the goal is to limit their negative impact by limiting the pressures supplied to them outside of the drilling shift via the level control valve. Therefore, the control valve must be located between the tie off from the shaft's compressed air column and the first active crosscut, as depicted in Figure 22, to ensure maximum impact of the level control valve.

The second area of investigation is the existing instrumentation. The instrumentation required to implement level valve control is a single pressure sensor. If a pressure sensor is found during the initial investigation it is recommended that this sensor's accuracy be verified, and location be noted. This sensor must be placed downstream of the control valve as it will be used to implement the pressure control profile on the level control valve by means of PID control.

It is also important to take note of any flow meters which are present on the respective level. Although the flow meters are not required to implement level valve control, they can be used to determine the distribution of compressed air across the different levels as well as developing baselines per level. This will be further discussed in Section 2.2.2 and Section 2.2.3. During the initial investigation it is only important to note if flow metering is present and verify its accuracy.

After investigating the end-users which are present, as well as the existing instrumentation, the optimal level control valve installation location, per active mining level, can be determined. The respective compressed air line size at the optimal installation locations must be noted such that the relevant control valves can be specified for the application. The details regarding the control valve specification are further discussed in Section 2.4.2.1.

2.2.1.3 Conclusion

Upon completion of the initial investigations on surface and underground the following information should be known and summarised in an engineering drawing:

1. Compressed air piping network and active levels on the respective mining site.
2. Existing control valves.
3. End-users which must be accounted for and the required infrastructure changes (if any).
4. Existing instrumentation as well as the required instrumentation.
5. Possible valve installation locations and associated compressed air line sizes.

2.2.2 Compressed air distribution

Once an understanding of the existing infrastructure has been determined, the next step is to determine the distribution of compressed air from surface to the different levels of the respective deep-level mining operation. The compressed air distribution will be used in Section 2.3.2 to determine the theoretical benefit of the hybrid control philosophy [20].

The different points at which the compressed air distribution must be determined are highlighted in Figure 23 by the grey arrows outlined in red. Each flow rate is denoted by $\dot{F}_X$ where $\dot{F}$ = flow and X = location of the measurement. To determine the theoretical benefit of hybrid control, a pressure measurement is also required as the flow rate is directly proportional to the supply pressure, shown previously in Figure 6. The location of the required pressure measurement is shown in Figure 23 as P1.

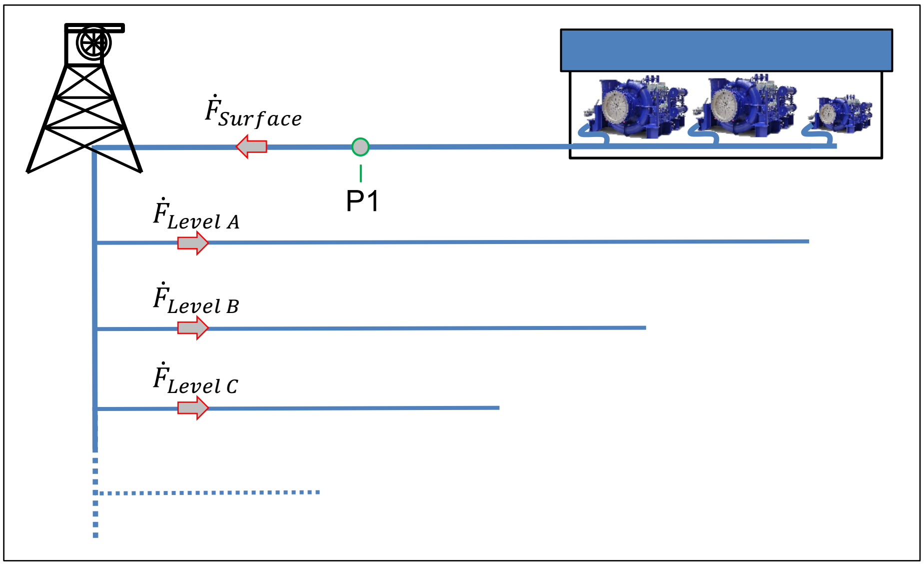


Figure 23 - Diagram depicting the compressed air distribution which must be determined.

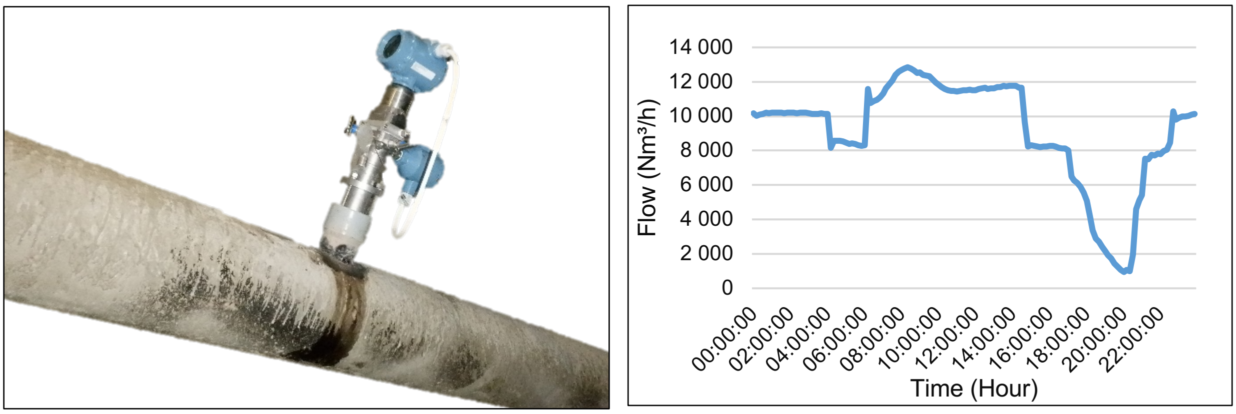
For the purpose of this study, it is assumed that a permanent flow meter instrument and pressure sensor are installed on the surface compressed air line. Thus, this data can be used to determine the surface compressed air flow rate and pressure profile over a 24-hour period.

The remaining requirement is to determine the compressed air distribution across the underground mining levels. There are three methods which can be used to determine the compressed air distribution, namely: permanent flow metering, portable flow metering and baseload testing. Each of the methodologies have different infrastructural requirements, advantages and disadvantages.

Due to the uniqueness of each mining operation one methodology may be more favourable than another, depending on the available infrastructure at the mining operation in question. In some instances, it may be beneficial to use a combination of two methodologies to achieve optimal results. Therefore, each methodology is discussed in detail such that the methodology / methodologies which best suit the requirements of the mining operation in question can be selected.

2.2.2.1 Permanent flow metering

In order to track and monitor compressed air distribution and usage, many mining operations have installed permanent flow meter instruments across the compressed air network. The permanent flow meters measure the compressed air flow rate at a specified time interval and write this data to a historian. The stored information is then used to monitor the compressed air consumption. An example of a permanent flow meter instrument and the data it would output over a 24-hour profile are shown in Figure 24 (a) and (b), respectively.



(a) (b)

Figure 24 – (a) Example of a permanent flow meter (b) A typical flow profile recorded by a permanent flow meter for a 24-hour mining cycle.

The steps to determine the compressed air distribution via permanent flow metering are as follows:

1. Determine the installation locations of permanent flow meters on the respective underground levels.
2. Ensure that the flow meters are operational and within an acceptable accuracy of ± 2%.
3. Select the required time interval at which the data must be extracted.
4. Select the total period for which data is required.
5. Extract the flow data from the historian at the specified time interval and period.
6. Combine all the flow profiles to determine the compressed air distribution.

Having completed the steps listed above, the compressed air distribution across the mining levels which are equipped with permanent flow meters can be determined. Figure 25 shows an example of the compressed air distribution recorded by permanent flow meters across multiple levels on a mining operation. The data is summarised as an average 24-hour weekday profile.

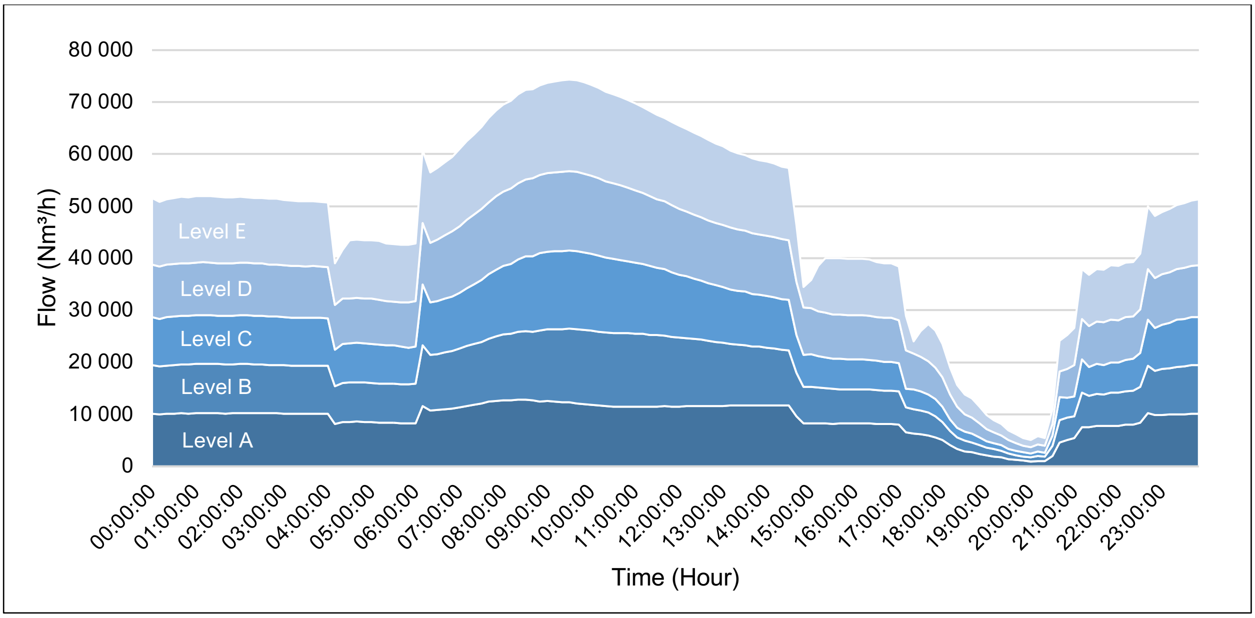


Figure 25 - Example of the compressed air distribution across a mining operation being measured on multiple levels by different permanent flow meters.

Using permanent flow meters is the most accurate method to determine the compressed air distribution as large data sets can be used to determine an accurate 24-hour average compressed air distribution profile. However, there are two risks which may be encountered using this approach, namely: absence of permanent flow metering or inaccurate flow measurements. If either of these issues are encountered, it is recommended that one of the alternative flow distribution methodologies, discussed in Section 2.2.2.2 and Section 2.2.2.3, be used.

2.2.2.2 Portable flow metering

The second methodology used to determine the compressed air distribution is by means of portable flow metering. Much like a permanent flow meter, a portable flow meter measures the compressed air flow rate and stores the data at a specified time interval. This data is stored locally on the portable flow meter memory and can be extracted and utilised at a later stage.

They key difference between permanent and portable flow metering is that a portable flow meter is a temporary installation and will only record data for as long as it is installed. Therefore, there is a smaller dataset to work with, resulting in reduced accuracy when compared to permanent flow metering.

The steps to determine the compressed air distribution using a portable flow meter are as follows:

1. Select the areas in which a portable flow measurement is required.
2. Install the portable flow meter in the first selected area on the compressed air network.
3. Select the time intervals at which the data must be recorded.
4. Specify the period for which the data must be recorded.
5. Record the data at the selected time interval and period.
6. Remove the flow meter and extract the data for the selected area.
7. Repeat steps 2- 6 for all the selected areas.
8. Combine all the flow profiles to determine the compressed air distribution.

Upon completion of the steps listed above, the compressed air distribution across the selected levels should be clearly defined, resulting in a 24-hour compressed air distribution profile similar to the example given in Figure 25.

The main risks to be considered when implementing portable flow metering are as follows:

1. Each flow meter must be manually installed and measured for the specified time interval. Thereafter the flow meter is removed and installed in the next location, resulting in a high resource intensity.
2. The flow meter must be manually installed and setup, leading to the possibility of human error, thus resulting in the possibility of reduced accuracy.
3. A reduced amount of data is available to determine the compressed air distribution when compared to permanent flow metering, resulting in reduced accuracy.

2.2.2.3 Baseload testing

The third and final methodology used to determine the compressed air distribution is by means of a baseload test. A baseload test is the fastest and crudest method used to determine the compressed air distribution. The infrastructure requirements to perform a baseload test are as follows:

1. Surface flow and surface pressure instrumentation.
2. Operational isolation valves per level (manual or automatic).

Once the infrastructural requirements have been addressed, the following steps can be followed to perform the baseload test, which will in turn determine the compressed air distribution:

1. Ensure isolation valves are open on surface and underground.
2. Abort control on any existing control valves.
3. Ensure the compressed air flow and pressure on surface are being recorded.
4. Ensure that the flow and pressure on surface are stable prior to starting the baseload test.
5. Close the isolation valve on the first underground mining level.
6. Record the time at which the valve was closed.
7. Wait until the surface flow and pressure stabilize – approximately 10-20 minutes.
8. Repeat steps 5 - 7 until all the underground mining levels have been isolated.
    a. If the pressure rises to the point that a compressor begins to surge, allow the compressor to switch off and wait for the flow and pressure to stabilize before continuing with the baseload test.
9. Extract the flow and pressure data from the historian for the period of the baseload test.

Upon completion of the baseload test, the extracted data can be plotted to show the resulting flow rates and pressure profiles, as highlighted by the example in Figure 26. The flow rate is depicted by the blue area and the pressure is depicted by the grey line. As each level is isolated, there is a clear reduction in the surface flow rate and an increase in the surface pressure.

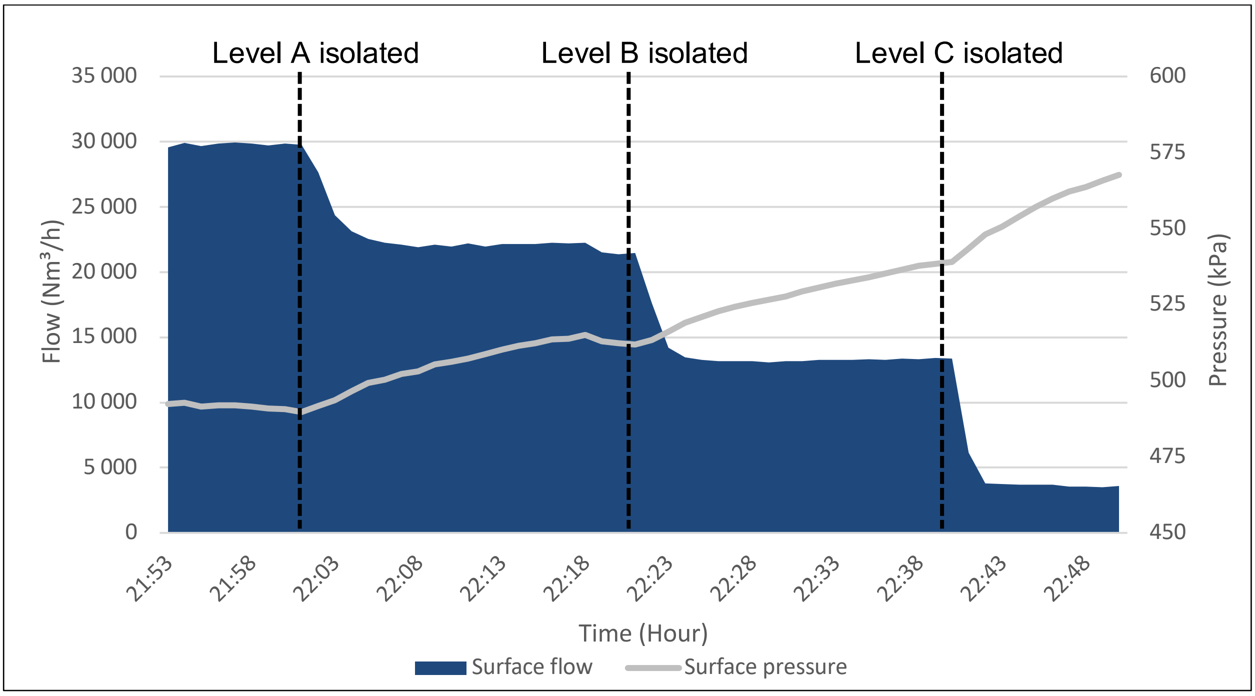


Figure 26 - Example of the surface flow and surface pressure profile over the baseload test period.

The following step in the baseload methodology is to process the baseload data such that the compressed air flow rate per level can be determined. To determine the flow rate per level, the surface flow rate before isolating the level is subtracted from the surface flow rate after isolating the level, as shown in Equation 1:

$$\dot{F}_{Level\,x} = \dot{F}_{Surface\,t_i} - \dot{F}_{Surface\,t_j} \qquad (1)$$

Where $\dot{F}$ = flow rate, x = the isolated level, t_i = time stamp before isolating level x and t_j = time stamp after isolating level x. The core principle behind Equation 1 is the law of the conservation of mass. For a detailed explanation on how Equation 1 is derived please see Annexure B.

Applying Equation 1 after each level is isolated allows us to determine each levels compressed air flow rate, thus leading to the compressed air distribution across the shaft in question for that instance in time. Each level's flow rate can then be calculated as a fraction of the surface flow rate at the start of the baseload test. This is referred to as the flow fraction. The process discussed above is applied to a theoretical example in Table 6 to further assist with understanding the necessary steps required.

Table 6 - Example of the process to determine each levels flow fraction.

Level	$\dot{F}_{Surface\,t_i}\ (Nm^3/h)$	$\dot{F}_{Surface\,t_j}\ (Nm^3/h)$	$\dot{F}_{Level\,x}\ (Nm^3/h)$	**Flow fraction**
A	29 731	22 266	7 465	29%
B	22 266	13 323	8 943	34%
C	13 323	3 544	9 779	37%

The flow fraction can then be extrapolated using the surface flow meter's data to determine each level's approximate flow rate throughout the 24-hour mining cycle. This is shown in Figure 27 where each level's flow profile is represented by a stacked area chart, relative to the surface flow profile which is represented by the dark blue line.

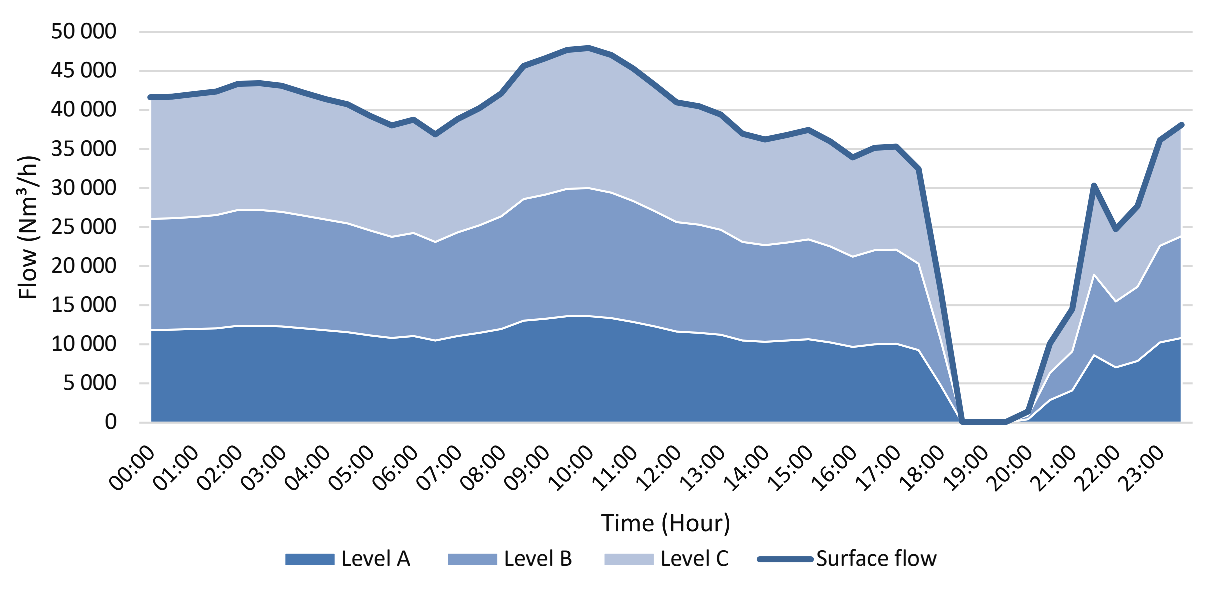


Figure 27 - Example of the extrapolation of each level's flow fraction to the surface flow rate.

Upon completion of the baseload methodology, the compressed air distribution across the selected areas should be clearly defined. This method is advantageous as it provides a reasonably quick analysis of the compressed air distribution with minimal infrastructural requirements, when compared to permanent and portable flow measurements. However, the main disadvantage of using the baseload methodology is that a baseload test represents the compressed air consumption for that level at that exact instance in time. Therefore, it is less accurate than permanent and portable flow measurements.

2.2.2.4 Conclusion

To determine the compressed air distribution across the active levels of the mining operation the three methodologies discussed above can be utilised. The compressed air distribution analysis is not limited to a single methodology and in certain instances a hybrid of two methodologies may yield the best results. Once the infrastructure analysis in Section 2.2.1 is completed, the methodology / methodologies which are most applicable to the compressed air network in question should be evident. Upon completion of determining the compressed air distribution, the following information should have been collected:

1. A 24-hour surface compressed air flow rate profile.
2. A 24-hour compressed air distribution profile from surface to each underground mining level. Also known as the flow fraction.
3. A 24-hour supply pressure profile corresponding to the surface and level flow rates.

2.2.3 Baseline development

The next step in the analysis of the existing compressed air network is to develop baselines of the compressed air network in question. The purpose of the baseline is to have a record of the compressed air flow rate and supply pressure, prior to the implementation of the hybrid control philosophy. The baseline is utilised for two purposes:

1. Determining the theoretical energy improvement of various hybrid control philosophies in Section 2.3.2.
2. Verification of the impact of the hybrid control philosophy upon implementation in Section 2.5.

In Section 2.2.2, it was assumed that a permanent flow meter and pressure sensor are installed and operational on the surface compressed air line of the compressed air network being investigated. Therefore, the surface flow rate and surface pressure will be utilised to develop the initial flow and pressure baselines. This information can be collected from the historian.

During the development of the baselines, it is recommended that the international performance measurement and verification protocol (IPMVP) documentation be consulted to ensure the baseline is accurate for the relevant application [61]. Baseline development is unique for each compressed air network, hence the IPMVP highlights the important aspects which should be considered. The critical questions to be addressed, when setting up a baseline, according to the IPMVP are:

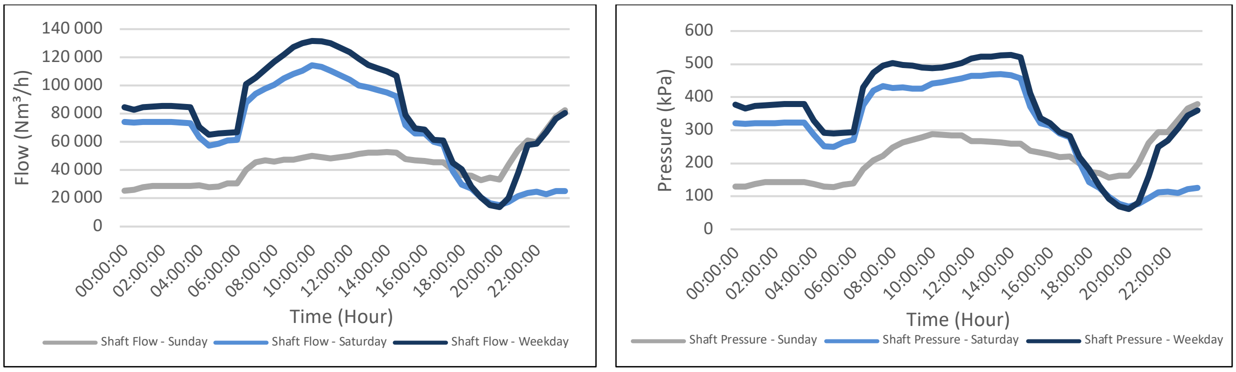
1. Measurement boundary
    a. What is the boundary at which the measurement and verification against the baseline is taking place?
2. Measurement period selection
    a. Are there any recent changes to the system which may impact the accuracy of the baseline at the system's current state?
    b. Are there any seasonal effects which must be accounted for?
    c. Are there different modes of operation for which different baselines should be developed?
3. Methods of adjustment
    a. Routine adjustments – is the baseline influenced by an external factor such as production and does it need to be scaled accordingly?

   b. Non-Routine adjustments – Upon implementation of the project, was there a change in the system which drastically impacted the accuracy of the baseline?

Each area in question, as listed above, must be addressed whilst developing the baselines for the relevant system. Therefore, a general baseline development procedure which can be used when implementing a hybrid control philosophy is as follows:

1. Measurement boundary
   a. It is assumed that an operational surface flow meter and pressure sensor are available. This will form the measurement boundary on which the baseline will be developed and measured against.
2. Measurement period selection
   a. Any operational changes or projects on the system in question will have an impact on the baseline. Therefore, it is recommended that the baseline be dated back to the implementation of the previous change to the system (project), such that it accurately represents the current operation, prior to the implementation of hybrid control.
   b. To account for seasonal effects, it is recommended that the baseline be developed for at least a 12-month period. However, this may not be possible due to implementation of a recent project. If this is the case, the maximum period prior to implementation of the previous project should be used as discussed in 2.a. above.
   c. In deep-level mining operations, the system has two different modes of operation, and these modes change depending on the day of the week. Therefore, three separate baselines must be developed for each baseline parameter, namely:
      i. Weekdays
      ii. Saturdays
      iii. Sundays
3. Methods of adjustment
   a. Compressed air consumption does show a correlation between the number of active authorised end-users and the total consumption. Therefore, the total volume of air consumed during the drilling shift can be used to scale for the number of end-users present.
   b. If any additional projects are implemented at a later stage, it is important to account for such projects using a non-routine baseline adjustment.

Using data from the historian, the methodology described above can be applied to the surface flow and surface pressure to develop baselines for the three periods in which the modes of operation differ. The resulting flow and pressure baselines should be similar to the examples shown in Figure 28. The dark blue line represents the weekday baseline profile, the light blue line represents the Saturday baseline profile, and the grey line represents the Sunday pressure profile. Figure 28 (a) highlights the various flow baselines and Figure 28 (b) highlights the various pressure baselines.



(a) (b)

Figure 28 - Examples of (a) surface flow and (b) surface pressure baselines developed using the recommended baseline methodology.

The surface flow and pressure baselines determined using the methodology above will be used for two applications. The surface flow and pressure baselines are used to determine the theoretical impact of the surface control valve in Section 2.3.2. The surface flow baseline is also used to verify the impact of the hybrid control philosophy, upon implementation in Section 2.5.

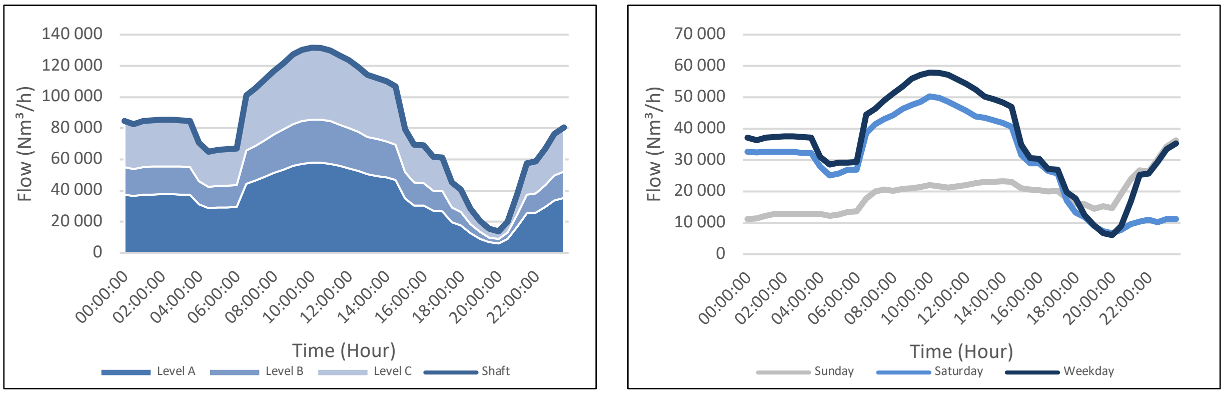
However, the surface flow baseline cannot be used to determine the theoretical impact of each level control valve. Therefore, a flow baseline per level needs to be determined.

The required level baselines are calculated by multiplying the surface flow baseline with the level's compressed air distribution / flow fraction, which was determined in Section 2.2.2. Each level's flow baseline is calculated using Equation 2 below:

$$\dot{F}_{LB} = \dot{F}_{SB} \times \beta_L \tag{2}$$

Where $\dot{F}_{LB}$ = level flow baseline, $\dot{F}_{SB}$ = surface flow baseline and β_L = flow fraction of the level in question. The level flow baselines can then be used to determine the theoretical flow reduction per level control valve in Section 2.3.2.

An example of the resulting flow baseline, using the methodology discussed above is shown in Figure 29. Figure 29 (a) shows all the level flow baselines for a weekday relative to the surface flow baseline, calculated using the flow fraction. Figure 29 (b) shows level A's baselines, extracted from Figure 29 (a) for weekdays, Saturdays and Sundays.



(a) (b)

Figure 29 - (a) Example of all the level flow baselines relative to the surface baseline, calculated using the flow fraction, (b) Example of the flow baselines of level A for weekdays, Saturdays and Sundays.

Lastly, it is assumed that each level's pressure baseline matches the surface pressure baseline, thus assuming that the effects of dynamic pressure drop and auto compression are negligible. This assumption is also made to account for a possible lack of instrumentation available underground.

2.2.4 Pressure demand requirements

The next step in analysing the existing compressed air network is to investigate the pressure demand requirements of the authorised compressed air end-users. This must be completed per level, per shift throughout the 24-hour mining cycle and will determine the relative minimum pressure requirements. In addition to the separate shifts, deep-level mining operations typically have two separate modes of operation as discussed in Section 2.2.3.

The two modes of operation are defined as the production mode and the maintenance mode. The production mode usually requires variable setpoints, for the various shifts, throughout the 24-hour mining cycle whilst the maintenance mode generally only requires enough pressure to sustain the refuge bays. However, the pressure demand requirements are unique to each mining operation and must be determined for both modes of operation.

The times at which the two modes of operation are active is not relevant at this point in time and are determined later in Section 2.2.5. The purpose of this section is purely to determine what the maximum end-users' pressure requirements are throughout each mode of operation.

This information can be gathered by consulting with the engineering and mining department at the relevant mining operation. The steps to gather and process this information are as follows:

1. Consult with the engineering and mining department.
2. Determine which authorised compressed air end-users are present during each shift.
3. Determine the minimum pressure requirement of each end-user.
4. Determine the minimum supply pressure which satisfies all end-users of each shift.
5. Repeat steps 1 - 4 for the separate shifts within the production mode of operation.
6. Repeat steps 1 - 4 for the maintenance mode of operation, no shifts.

When determining the maintenance mode requirement, it is important to remember that the maintenance mode does not operate in shifts and will have a single pressure requirement throughout the maintenance period.

An example of the pressure information which should be gathered for an active mining level is shown in Table 7. The minimum pressure requirement which satisfies all end-users for each shift is highlighted in red, thus leading to the production mode pressure requirements and the maintenance mode pressure requirement.

Table 7 - Example of the minimum pressure requirements per shift for a level, determined using the equipment present on the level.

Shift	Equipment	Pressure demand (kPa)	Minimum supply pressure (kPa)
Production pressure requirements			
Drilling shift	Rock drills	600	600
	Diaphragm pumps	450	
	Air whistles	150	
	Refuge bays	150	
Blasting shift	Refuge bays	150	150
Cleaning shift	Loaders	450	450
	Ore chutes	400	
	Air whistles	150	
	Refuge bays	150	
Shift changes	Refuge bays	150	150
Maintenance pressure requirements			
Maintenance shift	Refuge bays	150	150

The procedure discussed above must be completed for all active mining levels of the respective mining operation. Therefore, at the conclusion of Section 2.2.4 the pressure requirements throughout both modes of operation, for all the levels of the mining operation in question, should have been determined.

2.2.5 Shaft schedule

The final step to be conducted when analysing the existing compressed air network is to determine the operational logistics of the mining operation in question. This analysis is split into two sections, namely: analysis of the schedule for the modes of operation of the entire shaft and each shift's schedule within the production mode.

Deep-level mining operations typically follow a similar production mode and maintenance mode schedule. However, this is specific to the mining operation in question, and it is important that the operational logistics are determined from the relevant engineering and mining personnel. The operations are usually in production mode from Sunday night through to Saturday afternoon and then shift to maintenance mode for the period in between, from Saturday afternoon to Sunday night.

The times at which each mode of operation occurs will be utilised in Section 2.3.1 to develop a theoretical pressure profile for weekdays, Saturdays and Sundays. An example of a mining operation's modes of operation for each day of the week are shown in Table 8:

Table 8 - An example of the days and times at which each mode of operation is implemented.

Day of week	Operational mode	Duration of mode
Monday - Friday	Production mode	00:00 – 23:59
Saturday	Production mode	00:00 – 17:00
Saturday	Maintenance mode	17:00 – 23:59
Sunday	Maintenance mode	00:00 – 21:00
Sunday	Production mode	21:00 – 23:59

Once the modes of operation have been determined, the next step is to expand further into the production mode's operational schedule. During the production mode, personnel are transported from surface to their respective mining level according to the production modes shaft schedule. The shaft schedule determines the time at which each shift arrives and leaves their respective working area. The production shift schedule will later be combined with the pressure demand requirements to determine a 24-hour production pressure profile in Section 2.3.1. However, the critical task in this section is solely to determine the operational times of each shift. The shaft schedule information can be gathered from the engineer who is responsible for the man-winder and the shift times can be determined accordingly.

A simplified example of a shaft schedule during production mode is highlighted in Table 9. The times at which each shift is taken underground and retrieved from underground are shown for three example levels over a 24-hour production mining cycle.

Table 9 - Simplified example of a shaft schedule highlighting the difference in level schedules during the production mode of operation.

Time	Level	Shift down	Shift up
04:00 - 04:30	Level A	Drilling shift	Cleaning shift
04:30 - 05:00	Level B	Drilling shift	Cleaning shift
05:00 - 05:30	Level C	Drilling shift	Cleaning shift
11:30 - 12:00	Level A	None	Drilling Shift
12:00 - 12:30	Level B	None	Drilling Shift
12:30 - 13:00	Level C	None	Drilling Shift
21:00 - 21:30	Level A	Cleaning Shift	None
21:30 - 22:00	Level B	Cleaning Shift	None
22:00 - 22:30	Level C	Cleaning Shift	None

Upon completion of Section 2.2.5, the following information should have been gathered: the schedule of the operational modes as well as the detailed shift schedule for the production mode.

2.2.6 Conclusion

Upon completion of Section 2.2 – analysis of the existing compressed air network - all the information required to determine the theoretical benefit of a hybrid control philosophy should have been gathered. The information which should have been gathered is as follows:

1. An understanding of the compressed air network reticulation, active control valves, active mining levels, available instrumentation, end-users which must be accounted for and possible control valve installation locations.
2. The compressed air distribution from surface to underground levels.
3. Baselines of the existing compressed air flow, pressure and power consumption.
4. The pressure requirements per mining level for the two modes of operation.
5. The shaft schedule which determines:
    a. The schedule of operational modes.
    b. The shift schedule within the production schedule.

2.3 Theoretical analysis of a hybrid control philosophy

The purpose of the following section is to determine the theoretical benefit of a hybrid control philosophy and to select the optimal hybrid control valve layout which yields the greatest energy impact. The methodology is applied to weekdays, Saturdays and Sundays to account for the variability in the modes of operation. The methodology begins by determining the theoretical pressure profiles for each of the possible valve installation locations by combining the pressure demand requirements, of the end-users downstream of the valve, with the shaft schedule.

The theoretical pressure profiles and historic flow and pressure baselines are then used to determine the total energy impact of each control valve, across all modes of operation, by means of the ideal gas law. The energy impact of all the possible valve installation locations are then compared in order to select the hybrid control philosophy which maximises the energy efficiency of the respective mining operation, whilst minimising capital cost, required maintenance, project lead time and resource intensity.

2.3.1 Theoretical 24-hour pressure profiles

The first step in determining the theoretical benefit of a hybrid control philosophy is to develop a 24-hour pressure profile for weekdays, Saturdays and Sundays, across all possible valve installation locations on the respective mining operation. The three theoretical pressure profiles for each valve are determined by combining the minimum pressure demand requirements, of all the end-users downstream of the valve, with the shaft mode schedule and production schedule. Thus, generating three 24-hour pressure profiles for the valve in question which represent the minimum pressure demand requirements for weekdays, Saturdays, and Sundays.

When combining the end-user pressure requirements with the production schedule, it is assumed that each shift will only begin working approximately 2 hours after they go underground for their shift. This is done to account for traveling time from surface to the underground working area as well as the time needed to complete all safety checks prior to beginning with the assigned work. Therefore, each shift’s minimum pressure requirement must only be supplied approximately 2 hours after the shift arrives underground. This period is known as the change of shift and each pressure profile must be modified such that the change of shift times and pressure requirements are considered.

Due to the importance of the drilling shift and its impact on the production of the mining operation, maximum pressure must be supplied throughout the drilling shift. The pressure profile throughout the drilling shift will therefore be equal to the existing pressure baseline and will not be affected by the implementation of a control valve. The theoretical pressure profile for the production related drilling shift must therefore be updated for each control valve accordingly.

The procedure discussed above must be completed for all the possible valve installation locations identified in Section 2.2.1. The process is summarised as follows:

1. Select a valve location to be analysed.
2. Define the shaft's modes of operation for weekdays, Saturdays and Sundays from Section 2.2.5.
3. Derive the production mode's shift schedule, as per the shaft schedule identified in Section 2.2.5.
4. Derive the end-user's minimum pressure requirements, per operational mode, from Section 2.2.4.
5. Combine the operational schedule and shift schedule with their respective minimum end-user pressure requirements to generate three 24-hour pressure profiles.
6. Incorporate the change of shift times into the production pressure profile.
7. Incorporate the existing drilling shift pressure baseline into the production pressure profile.
8. Repeat steps 1 – 7 for all possible valve installation locations.

An example of a Saturday 24-hour pressure profile for a surface control valve is shown in Figure 30. During the production each of the shifts are shown by the light blue and dark blue areas. The change of shifts which take the traveling time and safety checks into account are shown by the grey areas. In this example the shift from the production mode to the maintenance mode at 17:00 is also highlighted.

The maintenance mode is shown using the green area. The corresponding pressure requirements of each shift are shown by the black line graph. The dotted red line shows the existing pressure baseline. During the drilling shift, no pressure control is implemented. Hence the pressure requirement and pressure baseline are equal to one another. Examples of the weekday, Saturday, and Sunday 24-hour pressure profiles can be found in Annexure D.

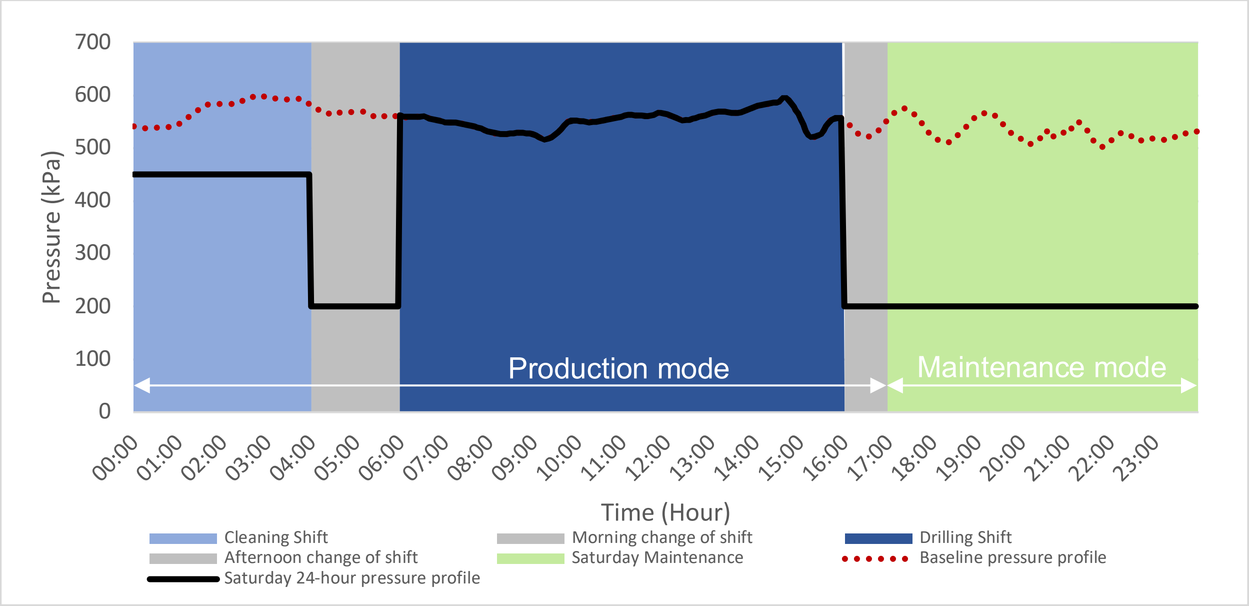


Figure 30 - Example of a Saturday 24-hour pressure profile which was developed using the methodology discussed above.

Upon completion of Section 2.3.1 a weekday, Saturday and Sunday theoretical pressure profile should have been developed for each of the possible valve installation locations identified in Section 2.2.1. The pressure profile should accommodate the different operational modes as well as the shifts within the production mode as shown in the example in Figure 30.

2.3.2 Theoretical energy impact

The purpose of this section is to quantify the annual theoretical energy impact which can be achieved by installing a control valve at each of the valve installation locations, identified in Section 2.2.1. As stated in Section 1.7.1, the purpose of a control valve is to further optimise the compressed air network by controlling the pressure supplied to the areas where a lower pressure demand exists.

The section begins by developing a theoretical energy improvement methodology which can be used to determine the annual energy impact of any control valve installation. Once the methodology has been discussed and is understood it can be applied to each of the possible valve installation locations identified in Section 2.2.1.

Due to the layout of a hybrid control philosophy, the application of the energy improvement methodology is split into two parts. The first part discusses the use of the methodology to determine the annual energy impact of a surface control valve alone. The second part discusses how the implementation of the surface control valve, upstream of the level control valves, is accounted for by adjusting the existing level baselines. Once the required baseline adjustments have been made, the theoretical annual energy impact methodology is applied, thus determining the annual energy impact of each level control valve.

2.3.2.1 Control valve energy impact methodology

The purpose of the following section is to develop a methodology which is used to determine the annual energy impact of implementing a control valve. To quantify the theoretical energy impact of a control valve, the following information is required:

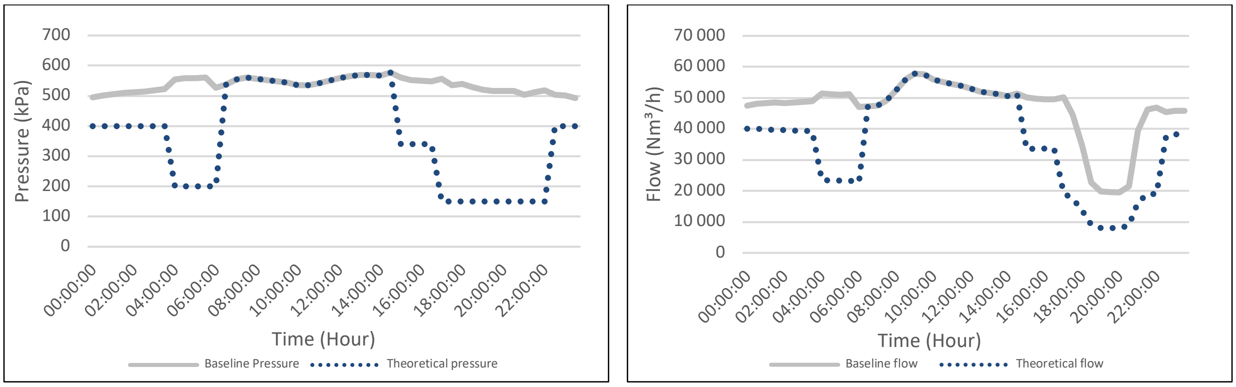
1. The 24-hour flow and pressure baselines of the relevant valve installation location.
2. The theoretical 24-hour pressure profiles which will be implemented by the control valve.

Using the above information, the ideal gas law can be used to determine the theoretical change in flow rate upon implementation of the theoretical 24-hour pressure profile. The impact of the theoretical pressure profile is calculated using Equation 3 below:

$$\dot{F}_T = \dot{F}_B \times \frac{p_T}{p_B} \tag{3}$$

Where $\dot{F}_B$ = baseline flow, p_B= baseline pressure, p_T = theoretical pressure and $\dot{F}_T$ = theoretical flow rate. For more information on the derivation of Equation 3 please see Annexure E.

An example of the theoretical change in flow rate, upon implementation of the theoretical 24-hour pressure profile, is shown in Figure 31. Figure 31 (a) shows the baseline pressure profile against the theoretical pressure profile. Figure 31 (b) shows the baseline flow profile against the theoretical flow profile, calculated using Equation 3.



(a) (b)

Figure 31 - (a) Example of the baseline pressure profile versus the theoretical pressure profile, (b) Example of the baseline flow profile against the theoretical flow profile.

Once the theoretical flow rate profile has been determined, the resulting power impact profile can be determined. The power impact profile is calculated by subtracting the theoretical flow rate from the baseline flow profile and then multiplying the difference by the power density of the relevant compressed air network, as shown in Equation 4.

$$P_I = \omega \, (\dot{F}_B - \dot{F}_T) \tag{4}$$

Where P_I = power impact, ω = power density, $\dot{F}_B$ = baseline flow and $\dot{F}_T$ = theoretical flow. See Annexure C for the process to determine the power density of the relevant compressed air network.

An example of the power impact calculation process is shown by means of Figure 32. The grey line shows the flow baseline prior to implementing the theoretical pressure profile and the dotted blue line shows the theoretical flow profile upon implementation of the theoretical pressure profile. The difference between the baseline and theoretical flow profile is then calculated and is shown as the light blue area between the flow baseline and the theoretical flow profile. The difference is then multiplied by the power density of the relevant compressed air network to calculate the power impact profile which is depicted by the blue bar chart in Figure 32.

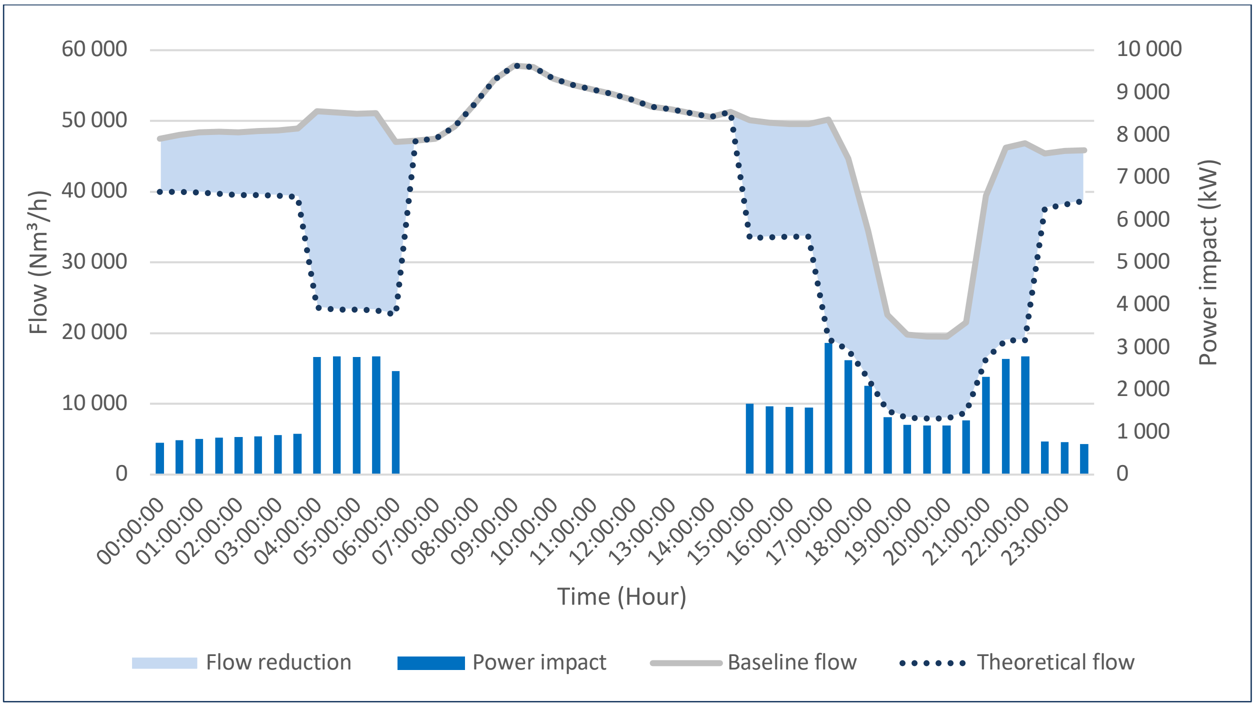


Figure 32 - Example showing the change in flow by implementing the theoretical pressure profile and the resultant power impact profile.

The next step is to calculate the annual energy impact of the power impact profile. First the average power consumption over the 24-hour period is determined. The average is then multiplied by 24 to determine the daily energy impact in kilowatt hours. The annual energy impact is then calculated by multiplying the daily energy impact by the number of days in a year which represent the mode of operation being analysed.

Due to the operational logistics of deep level mining operations, the energy impact methodology above must be performed for weekdays, Saturdays and Sundays to determine the total annual energy impact of the control valve in question.

2.3.2.2 Surface valve energy benefit

The first step in determining the annual energy impact of a hybrid control philosophy is to determine the energy impact of the surface control valve. When applying the annual energy impact methodology to the surface control valve the process is as follows:

1. Obtain the 24-hour surface flow and surface pressure baselines identified in Section 2.2.3.
2. Obtain the theoretical surface pressure profiles identified in Section 2.3.1.
3. Apply the annual energy impact methodology for the weekday, Saturday and Sunday operating conditions.

Upon completion of Section 2.3.2.2 the annual energy impact of the surface control valve for the various modes of operation should have been determined.

2.3.2.3 Level valve energy benefit

The next step is to analyse the energy impact of each of the possible level control valve installation locations. Due to the level control valves being downstream of the surface control valve, the pressure supplied to them is already controlled by the surface control valve. Therefore, the original level flow and pressure baselines developed in Section 2.2.3 must be adjusted to take the effect of the surface control valve into account.

The first step is to determine the new pressure baselines for the level control valves. Each level's pressure baselines are simply equal to the theoretical pressure profiles of the surface control valve as the surface control valve now determines what pressure is supplied to the underground levels. The impact of the surface control valve on the levels' flow baselines can then be calculated using the ideal gas law equation from the energy impact methodology above. Equation 5 is applied as follows:

$$\dot{F}_{LB_2} = \dot{F}_{LB_1} \times \frac{p_{ST}}{p_B} \tag{5}$$

Where $\dot{F}_{LB_2}$ = new level baseline flow, p_B= original baseline pressure, p_{ST} = surface valve theoretical pressure and $\dot{F}_{LB_1}$ = original level baseline flow.

Therefore, the steps required to determine the annual energy impact of each level control valve are as follows:

1. Adjust the existing level flow and level pressure baselines to account for the impact of the surface control valve.
2. Obtain the theoretical pressure profile, of the level in question, identified in Section 2.3.1.
3. Apply the annual energy impact methodology for the weekday, Saturday, and Sunday operating conditions.
4. Repeat steps 1 – 3 for all possible level control valve installation locations.

Upon completion of Section 2.3.2.3 the impact of the surface control valve on the level control valves' energy impact should have been accounted for. Additionally, the annual energy impact of each possible level control valve installation location should have been determined.

2.3.3 Selection of optimal hybrid layout

The final step in the theoretical analysis of the hybrid control philosophy is to select the hybrid control valve layout which has the maximum energy impact whilst minimising the capital cost, project lead time, maintenance requirements and resource intensity.

Although the capital cost, project lead time, maintenance requirements and resource intensities for the various hybrid layouts are unclear at this stage in the analysis, it can be assumed that they are directly proportional to the number of valves required. As the number of valves which are selected increases so do the capital costs, project lead time, maintenance requirements and resource intensities. However, the contribution of each valve is not equal.

Therefore, each valve can be analysed using a decision matrix to determine the combined impact of each of the above-mentioned factors. Using the decision matrix, each factor is rated on a scale from 1 to 10 where 1 represents a low impact and 10 represents a high impact. This process is repeated for all the possible valve installation locations. An example of the decision matrix is shown in Table 10:

Table 10 - Example of a decision matrix which rates the impact of capital cost, required maintenance, project lead time and resource intensity on a scale from 1-10.

Valve	Capital cost	Required maintenance	Project lead time	Resource intensity
Surface	10	2	1	3
Level A	5	8	6	6
Level B	6	4	6	4
Level C	5	6	6	7

Each factor then receives a weighting. The weighting determines how important each of the factors are to the relevant mining operation. The weighting is also done on a scale from 1 to 10 where 1 is the lowest level of importance and 10 is the highest level of importance. The weighting for each factor is dependent on the project in question and must be determined by consulting with the relevant mining and engineering personnel. Once the weighting for each factor is determined, the weighting is multiplied by the factor for each valve.

The factors for each valve are then summed to determine a rating which represents how well each valve meets the outlined requirements. A low rating represents a valve which meets the outlined requirements well and a high rating represents a valve which does not meet the requirements well. Implementing the weighting and summation to the decision matrix example in Table 10 results in the example shown in Table 11:

Table 11 - Example of the decision matrix once the weightings have been implemented and summed for each valve, highlighting how well the valves meet the outlined requirements.

Valve	Capital cost (W:10)	Required maintenance (W:5)	Project lead time (W:1)	Resource intensity (W:2)	Rating
Surface	100	10	1	6	117
Level A	50	40	6	12	108
Level B	60	20	6	8	94
Level C	50	30	6	14	100

Once the rating per valve has been calculated, each valve's rating is matched with its associated annual energy impact as determined in Section 2.3.2. It is important to note that for the purposes of this study, the primary goal is to maximise the energy impact whilst also minimising the rating. Thus, the primary method of selecting a layout is by means of energy impact and a by-product of the selection is the rating. Therefore, the valves are ranked from the highest energy impact to the lowest to streamline the selection process.

Table 12 shows an example of the annual energy impact for each valve with its associated ranking, ranked in terms of energy impact from highest to lowest.

Table 12 - Example of ranking the energy impact of each valve from highest to lowest with each valves associated rating.

Valve	Annual energy impact (MWh)	Rating
Surface	1000	117
Level B	600	94
Level A	300	108
Level C	50	100

The following step is to evaluate the different valve combinations which can be implemented. This is done sequentially, according to the energy impact of each valve. Therefore, if one valve is being analysed, the valve with the highest energy impact is selected, if three valves are being selected, the three valves with the highest energy impact are selected. The total energy impact and rating for each possible combination is then calculated.

To compare the different combinations, two base combinations must also be analysed, namely: 1) a surface valve alone and 2) level valves across all the levels with no surface valve. The surface valve alone serves as the base which has the highest energy impact for a single valve, representing the lower limit. The combination with level valves across all levels and no surface valve serves as the base with the highest possible energy impact for the maximum number of valves which can be selected, representing the upper limit. The resulting combinations and base combinations for the example in Table 12 are shown in Table 13:

Table 13 - Example of the combinations generated from Table 12.

Combination	Valves selected (In order of selection)	Total energy impact (MWh)	Total rating
1	Surface & Level B	1600	225
2	Surface, Level B & Level A	1900	319
Lower limit	Surface	1000	117
Upper limit	Level B, Level A & Level C	1950	302

The various combinations can then be plotted on a scatter plot which compares the total energy impact and total rating for each combination. The lower limit and upper limit are plotted on the scatter plot and a trendline is drawn between them to show the base energy impact and rating, which must be surpassed to add value over and above a surface valve alone or level valves across all the levels. Therefore, any hybrid valve combination which falls above the base energy impact and ranking line is achieving a greater energy impact and a lower ranking than surface control alone or level valves across all levels. The resulting scatter plot for the example shown in Table 13 is presented in Figure 33:

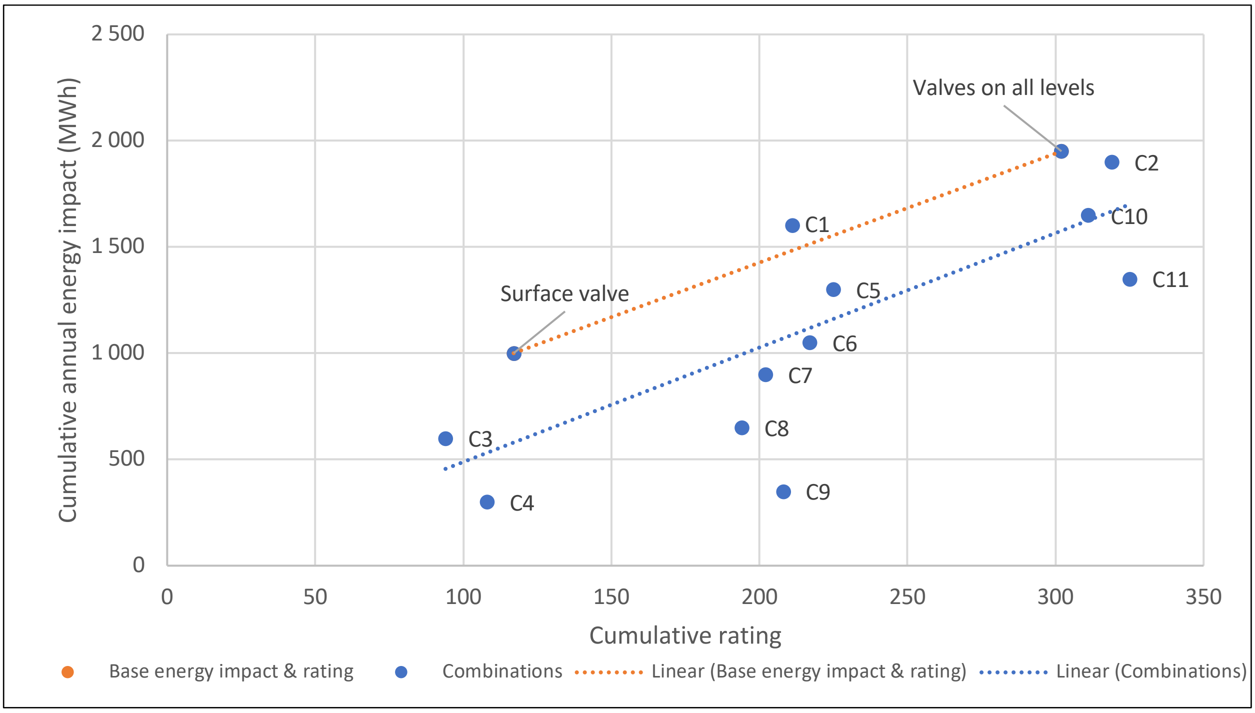


Figure 33 - Scatter plot showing example combinations (C1 & C2) against the upper and lower limit of a surface control valve alone and level valves across all levels as well as all the other possible scenarios and their respective energy impacts and ratings.

As a proof of concept, all the other possible valve combinations are added to Figure 33 and are depicted by C3 to C11. A trendline is drawn between all the possible combinations to show the average energy impact to maintenance ratio if the combinations are chosen at random. It is clearly shown in Figure 33 that first select combinations by ranking them in terms of energy efficiency achieves the best energy impact to ranking ratio for the number of valves selected. This is shown to be true for selection of a single valve: surface valve versus combinations C3 and C4, for selection of two valves: C1 versus C5 to C9 and for the selection of three valves: level valves on all levels versus C2, C10 and C11.

Therefore, for all future investigations the selection of possible valve combinations can be done by ranking the valves in terms of energy impact and selecting valve combinations from the highest energy impact to the lowest. For a single valve combination, the top ranked energy impact is selected, for two valves the top two ranked energy impacts are selected, etc.

The selected combinations are then evaluated by comparing their energy impact and rating to the base energy and impact rating trendline. The combination with the greatest increase in energy impact and reduction in rating, relative to the trendline, is the hybrid control philosophy which maximises energy impact whilst minimising capital cost, project lead time, maintenance requirements and resource intensity.

The examples from Figure 33 are compared in Table 14 to illustrate the comparison process. In the examples shown, combination 1 has the best overall energy impact and rating improvement relative to the base combinations with a total impact of 120. Therefore combination 1 is the optimal hybrid layout for the examples from Figure 33. Table 14 also highlights the negative impacts of the combinations which are not selected by ranking the energy impact first i.e. combinations C3-C11.

Table 14 - Comparison of all possible combinations showing if each combination improves the energy impact and rating relative to the base energy impact and rating of a surface control valve alone and level control valves across all levels.

Combinations	Energy impact	Cumulative rating	Energy impact improvement	Rating improvement	Total improvement
Surface valve	1000	117	0	0	0
C1	1600	211	117	23	120
C2	1900	319	-137	-27	-140
Valves on all levels	1950	302	0	0	0
C3	600	94	-282	-55	-287
C4	300	108	-654	-127	-666
C5	1300	225	-255	-50	-259
C6	1050	217	-464	-90	-472
C7	900	202	-536	-104	-547
C8	650	194	-745	-145	-759
C9	350	208	-1117	-218	-1138
C10	1650	311	-346	-67	-353
C11	1350	325	-718	-140	-732

Therefore, the steps to determine the optimal hybrid control philosophy are summarised as follows:

1. Analyse each possible valve installation location using a decision matrix to determine the cumulative impact of capital cost, required maintenance, project lead time and resource intensity per valve.
2. Weight each factor based on its importance to the mining operation in question.
3. Multiply each factor by its weighting and sum the factors for each valve to determine the overall rating for each valve installation.
4. Match each valve with its associated energy impact and its overall rating.
5. Rank the valves in terms of energy impact from highest to lowest.
6. Select the possible valve combinations using the ranked energy impacts.
7. Set the lower limit equal to a single surface valve installation.
8. Set the upper limit equal to level control valves on all levels.

9. Draw a trendline between the lower and upper limits.
10. Compare the valve combinations to the trendline to determine the combination which has the maximum energy and rating improvement.

2.3.3.1 Conclusion

Upon completion of Section 2.3.3 the hybrid control philosophy which maximises the annual energy impact and minimises capital cost, maintenance requirement, project lead time and resource intensity should have been identified and selected.

2.4 Hybrid control philosophy implementation

The purpose of the following section is to develop the methodology which will be used to implement the optimal hybrid control valve philosophy identified in Section 2.3.3. The methodology begins by describing the valve control philosophy which will be implemented on each of the control valves.

Thereafter, the necessary infrastructure required to implement the control strategy is investigated such that the optimal options for the mining operation in question can be selected. Once the infrastructural upgrades are completed, the procedure used to effectively implement the pressure control strategy is discussed.

2.4.1 Pressure control philosophy

The purpose of a control valve is to control the pressure downstream of the valve according to the theoretical pressure profile developed in Section 2.3.1. A control valve acts as a variable orifice: as the control valve position moves towards the closed position, the valve's orifice size decreases. In turn, the pressure downstream of the valve decreases as well. The typical infrastructure used to implement pressure control is shown by means of a cross section in Figure 34. The control valve, actuator and downstream pressure sensor are also shown in Figure 34 and will be used as a reference when discussing the pressure control philosophy.

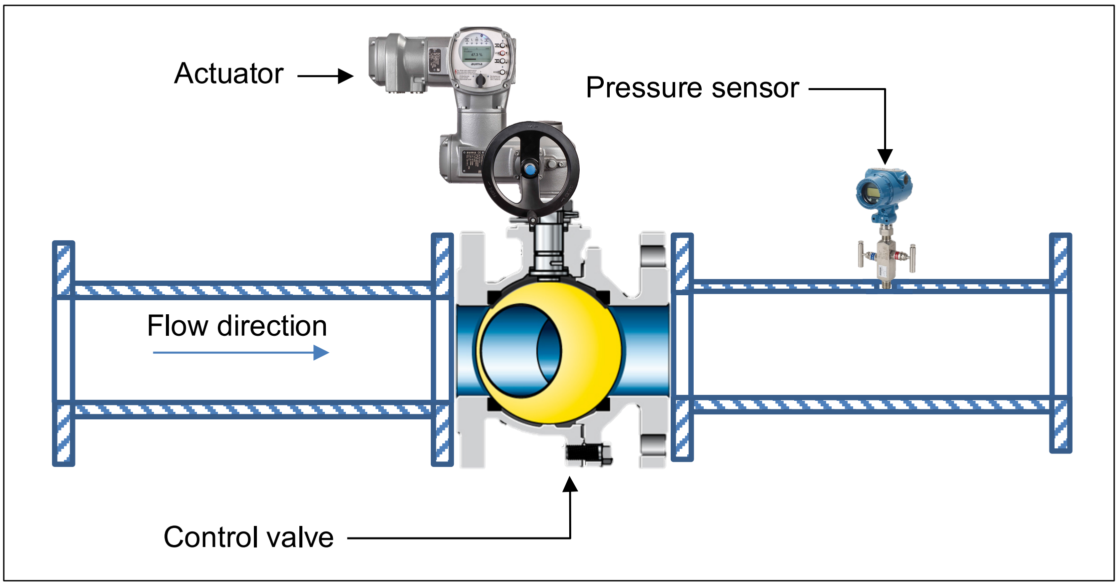


Figure 34 - Example of the typical infrastructure used to implement pressure control, adapted from [62-64].

The actuator and pressure sensor must be connected to a programmable logic controller (PLC) such that the valve position and downstream pressure can be read from the instruments into the

PLC as process variables. The theoretical pressure profile is then written manually into the PLC code and acts as the pressure setpoint. Pressure control can then be implemented by using a proportional-integral-derivative (PID) controller within the PLC [20]. The implementation of the PID methodology is as follows:

1. Read the valve's position, downstream pressure, and pressure setpoint from the PLC.
2. Calculate the difference between the downstream pressure and pressure setpoint, known as the error.
3. The PID controller then outputs a signal from the PLC to the actuator to adjust the control valve position until the error is within an acceptable limit and the pressure setpoint is satisfied.

The PID controller repeats steps 1-3 in a continuous feedback loop to ensure that the downstream pressure matches the theoretical pressure setpoint throughout the 24-hour mining profile.

2.4.2 Infrastructural upgrades

To implement the pressure control philosophy as discussed in Section 2.4.1 several infrastructure upgrades are required. The infrastructure to be upgraded or implemented, if it is not present, is as follows: control valves, actuators, and pressure sensors. The purpose of the following section is to investigate the different types of control valves, actuators and pressure sensors and in turn choose which options suit the respective mining operation best.

2.4.2.1 Control valves

The first and most important piece of infrastructure to be investigated is the control valve itself. There are a multitude of control valve types available which can be used as a control valve in a compressed air application. However, not all valves are equal and the major factors separating the control valve types are their operational characteristics, specifications, and associated prices.

Control valves typically have different characteristic flow profiles, namely:

- Quick opening
- Linear
- Equal percentage

The difference in the characteristic flow profiles is shown in Figure 35. The blue line shows quick opening valves which typically reach high flow rates at low valve percentages. The orange line shows linear flow valves which tend to have a linear relationship between flow percentage and valve percentage. Lastly, the grey line shows equal percentage valves which typically have a low flow rate percentage at low valve percentages and a high flow rate at high valve percentages.

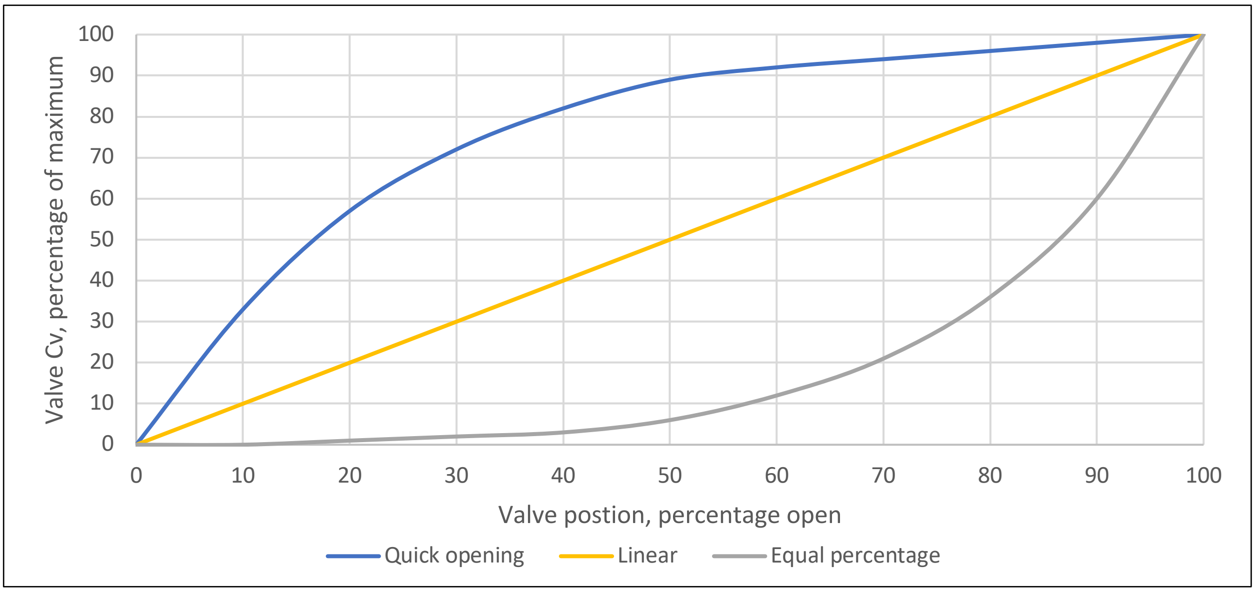


Figure 35 - Different characteristic flow curves for different categories of control valves, adapted from [65].

Studies conducted by Kriel, Fouché and van der Linde all recommend that valves with equal percentage flow characteristics be used for pressure control applications [20, 49, 55]. Therefore, for the purposes of pressure control, the valves which can be utilised are as follows:

- Linear globe valves with cage-style trim
- Segmented V-notch ball valves
- Eccentric butterfly valves

The different valves are compared in Table 15 such that the valve type which best suits the mining operations application can be selected. The factors used to compare each of the valves are the pressure drop over the valve when fully open, the control range and the associated cost.

Table 15 - Comparison of different control valves which can be used as control valves for compressed air [20, 49, 55].

Valve type	Pressure drop when fully open	Control range	Cost
Linear globe valve	High	High	High
Segmented V-notch ball valve	Moderate	Moderate	Moderate
Eccentric butterfly valve	Low	Moderate to low	Low

The pressure drop over the valve when fully open is an important factor to be considered as this will lower the pressure downstream of the valve during the drilling shift which will negatively affect production. Therefore, if supply pressure during the drilling shift is already an issue, a valve with a large pressure drop is not recommended.

The second factor to be considered is the control range. If the flow demand downstream of the valve tends to be volatile, then a valve with a broader control range should be selected. However, if the flow demand is relatively stable then a valve with a smaller control range can be chosen. The downstream demand of underground end-users typically does fluctuate over time as the number of mining crews increase or decrease. Therefore, a valve with a moderate control range is recommended to provide longevity to the control capabilities of the valve in question. However, it is important to note that if the control valve is correctly specified then all the valve types should satisfy the control range accordingly.

The final factor to be considered is the cost of each control valve. As shown in Table 15, the cost varies depending on the control range of the valve type. The greater the control range, the greater the cost of the valve. Therefore, the decision must be made to either have high capital costs in exchange for a better control range or reduce the capital cost and in turn reduce the control range of the valve in question.

Having gained an understanding of the different control valves which can be used for pressure control implementation, the next step is to specify the control valve such that it can meet the theoretical pressure profile requirements for the relative flow demands downstream of the valve. To specify the control valve, Nelprof simulation software is used.

The information required to specify each control valve is as follows:

- The compressed air line size at the valve location, as determined in Section 2.2.1
- The maximum supply pressure which will be experienced, usually 600 kPa
- Upper and lower flow requirements which must be satisfied
    - As determined in Section 2.3.2
- Upper and lower limits of the theoretical pressure profile for the valve in question
    - As determined in Section 2.3.2
- A starting valve size (usually the same as the line size) and valve type must be selected

Using this information, the following scenarios must be run through the simulation to ensure that the control valve is adequately specified for the required application:

1. The maximum flow and supply pressure to determine the pressure drop when the valve is 100% open [55].
2. The minimum flow at the minimum downstream pressure requirement, at a supply pressure of 600 kPa to determine the lower limit of control [55].
3. The maximum flow requirement at the maximum downstream pressure, at a supply pressure of 600 kPa to determine the upper limit of control [55].

The information from running scenario 1 should then be gathered and analysed. If the chosen valve type and size result in a large pressure drop at the maximum flow and pressure conditions, then it is recommended that an alternative valve type or increased valve size are chosen and the simulation is re-run until an acceptable pressure drop is achieved.

Once the pressure drop at 100% open has been addressed, scenario 2 and scenario 3 can be simulated. The resulting control valve percentage for the two scenarios listed above are subtracted from one another to determine the total control range for the valve in question.

When analysing the results from scenario 2, the important factor to consider is the lower control limit. A lower control limit less than 8% indicates that the chosen valve size or type is not optimal for the current flow and pressure conditions. The valve size must then be decreased, or the valve type must be changed to one with a better control range. The simulation should then be re-run to determine if the new selection satisfies the lower limit requirements.

When analysing the results from scenario 3, the important factor to be considered is the total control range. A large control range indicates that the chosen valve size or type suits the current flow and pressure conditions well. Therefore, the selected valve size and type is optimal for the relevant application. However, it is important to note that a valve with a large control range is optimal for the conditions which have been specified. If those conditions may be subject to change in the near future, it is recommended that the valve size be increased, or the valve type be changed such that a smaller control range is achieved, thus allowing greater flexibility to account for changes in flow demands in the future.

Upon completion of Section 2.4.2.1, a control valve type and size should have been simulated and selected for all the control valve installation locations which were selected for the optimal hybrid control philosophy in Section 2.3.3.

2.4.2.2 Actuators

Once the relevant valve sizes and valve types have been selected, a suitable actuator, which will be used to position the valve, must be selected. The main differentiating factor between actuators is the method of actuation, namely: pneumatic actuators and electrical actuators.

For the purposes of a hybrid control philosophy, pneumatic actuators are not suitable as they have a minimum pressure requirement of approximately 300 kPa [66]. The theoretical pressure profile during the maintenance period, on Saturdays and Sundays, is generally 200kPa, to supply the refuge bays, which is lower than the actuator's minimum supply pressure. Therefore, the actuators will not be operational and are not suitable for a hybrid control valve layout.

Therefore, the remaining option is to make use of electrical actuators. There are a multitude of electrical actuators which are appropriate for the implementation of a hybrid control philosophy. The important factors which must be considered when selecting an electrical actuator are the following:

1. The toque curve of the selected actuator must meet the torque requirements of the valve when controlling at the maximum flow requirement, with the minimum pressure demand requirement and the maximum supply pressure.
2. The required actuator supply voltage must be compatible with the underground supply voltage.
3. The actuator must be able to relay the valve position for the PID feedback loop as discussed in Section 2.4.1.
4. The actuator's communication methodology must be compatible with the communication method of the mining operation in question.

Thus, any electrical actuator which satisfies the conditions specified above will be suitable for the implementation of a hybrid control philosophy at the mining operation in question.

2.4.2.3 Pressure sensors

The final infrastructural upgrade which is to be decided on is the pressure sensors which will be used downstream of each control valve. Much like the electrical actuators, there are a multitude of pressure sensors which are appropriate for the implementation of a hybrid control philosophy. Thus, any pressure sensor which meets the following requirements can be selected:

1. The pressure sensor’s range must match the pressure ranges experienced on the relevant compressed air network.
2. The pressure sensor’s power supply must be compatible with the PLC’s power supply capabilities.
3. The pressure sensor must be able to relay the pressure to the PID feedback loop as discussed in Section 2.4.1.
4. The pressure sensor’s communication methodology must be compatible the communication method of the mining operation in question.

Thus, any pressure sensor which satisfies the conditions specified above will be suitable for the implementation of a hybrid control philosophy at the mining operation in question. It is also of critical importance that the pressure sensor is installed downstream of the control valve as shown previously in Figure 34.

2.4.3 Implementation of the theoretical pressure profile

Once the required infrastructural upgrades have been selected and implemented for the chosen hybrid control valve layout, the theoretical pressure profile must be implemented for each control valve at the mining operation in question. The pressure profiles were developed theoretically using the shaft schedule as well as the minimum pressure requirement of the equipment being utilised during each shift as discussed in Section 2.3.1.

The theoretical pressure profiles represent the ideal scenario where it was assumed that no pressure drop is experienced from the control valve to the end-users downstream of the control valve. However, due to the nature of the underground working environment this is not always true and large pressure drops can be experienced in some areas. To ensure that the production capabilities of the mining operation in question are not hindered, the theoretical pressure profile must be implemented incrementally until the theoretical pressure profile is reached.

It is recommended that the starting point for the incremental reductions be set to the current compressed air pressure baseline for the valve in question. The setpoints can then be reduced at a specified frequency and specified increments. For example, a 10 kPa reduction twice a week.

As the incremental setpoint reductions are being made, the control room must monitor any compressed air pressure complaints from underground working areas. If a complaint is received, then the pressure must be increased to the setpoint prior to the complaint being received. If no complaints are received, then the pressure setpoint must be continually reduced until the theoretical pressure profile is reached [22].

Once a compressed air complaint is received, it is recommended that an auditing team be sent to the area where the complaint originated from. The auditing team can then analyse the existing infrastructure and determine what the root cause of the insufficient pressure is. The pressure setpoints can then be adjusted according to the findings of the auditing team [22].

The procedure discussed above is summarised by the flow diagram shown in Figure 36.

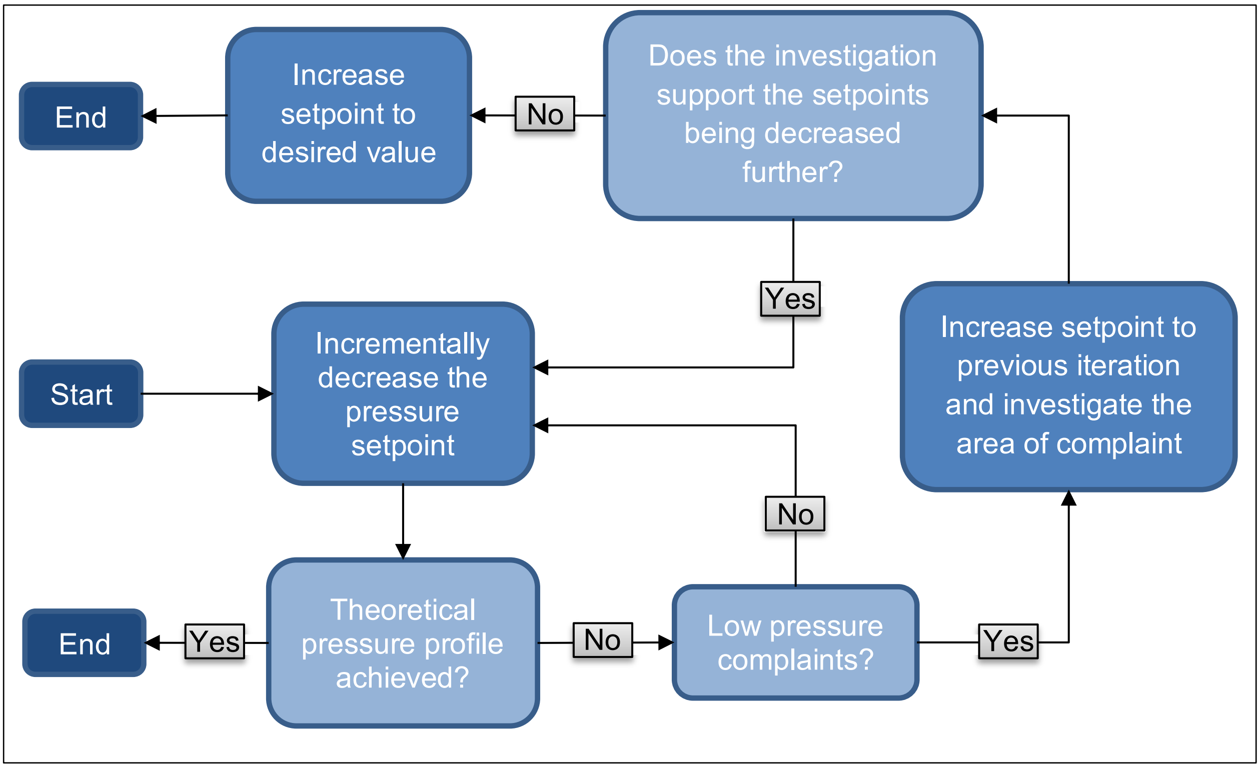


Figure 36 - Procedure used to implement theoretical pressure profile whilst ensuring that production is not hindered, adapted from [22].

Once the implementation procedure discussed in Figure 36 is complete, the hybrid control philosophy should be controlling the pressure supplied to the end-users downstream of each control valve as close to the theoretical pressure profile as possible.

2.4.4 Conclusion

Upon completion of Section 2.4 the control valves, actuators and pressure sensors which are used to implement the hybrid control philosophy should have been selected. The selected infrastructural upgrades are then implemented at the relevant mining operation such that the hybrid control philosophy can be employed. The theoretical pressure profile for each control valve within the hybrid control philosophy is then adopted using the procedure identified in Section 2.4.3 to ensure that the production of the shaft is not hindered.

2.5 Validation and verification

Once the infrastructural changes and theoretical pressure profiles are implemented, the methodology used to monitor the performance of the hybrid control philosophy is discussed. The purpose of the following section is to develop the methodology which will be used to quantify the energy impact of the implemented hybrid control philosophy and determine the accuracy of the theoretical analysis model developed in Section 2.3.2.

2.5.1 Validation

During the development of the baseline in Section 2.2.3, it was assumed that the measurement boundary for the hybrid control philosophy would be the compressed air flow rate which is measured by the surface flow meter. Therefore, the same measurement boundary and its associated flow baseline will be used to verify the energy impact of the hybrid control philosophy.

The information required to determine the energy impact of the hybrid control is as follows:

1. Surface compressed air baseline prior to implementation of the hybrid control philosophy
    a. Developed in Section 2.2.3
2. The historic surface flow consumption since the implementation of the hybrid control philosophy
    a. This information must be gathered from the historian

The primary step to determine the energy impact of the hybrid control philosophy is to perform a routine baseline adjustment to account for any changes in the number of active authorised compressed air end-users since the development of the baseline. Historically the volume of compressed air consumed during the drilling shift is directly proportional to the number of active authorised end-users [22].

Therefore, the drilling shift compressed air consumption will be used to scale the baseline accordingly. Baseline scaling must only be done for production related periods. The maintenance periods will remain unscaled and will be compared directly to the baseline. Equation 6 is used to determine the scaled baseline as follows:

$$\dot{F}_{SBS} = \dot{F}_{SB} \times \frac{V_{AD}}{V_{SBD}} \qquad (6)$$

Where F_{SBS} = scaled surface flow baseline, F_{SB} = surface flow baseline, V_{AD} = Actual volume of compressed air consumed in the drilling shift and V_{SBD} = volume of compressed air consumed during the drilling shift for the original surface baseline.

Once the baseline has been scaled, the power impact profile can be determined. The power impact profile is calculated by subtracting the actual compressed air flow profile from the scaled baseline flow profile. The difference is then multiplied by the power density of the compressed air network in question as shown in Equation 7:

$$P_I = \omega \, (\dot{F}_{SBS} - \dot{F}_A) \tag{7}$$

Where P_I = power impact, ω = power density, $\dot{F}_{SBS}$ = scaled surface flow baseline and $\dot{F}_A$ = actual flow.

An example of the baseline scaling and power impact calculation process is shown by means of Figure 37. The grey line shows the unscaled baseline which was developed in Section 2.2.3. The dashed blue line shows the scaled flow baseline, and the dotted blue line shows the actual flow profile upon implementation of the hybrid control philosophy.

The difference between the scaled baseline and actual flow profile is then calculated and is shown as the light blue area between the scaled flow baseline and the actual flow profile. The difference is then multiplied by the power density of the relevant compressed air network to calculate the power impact profile which is depicted by the blue bar chart in Figure 37.

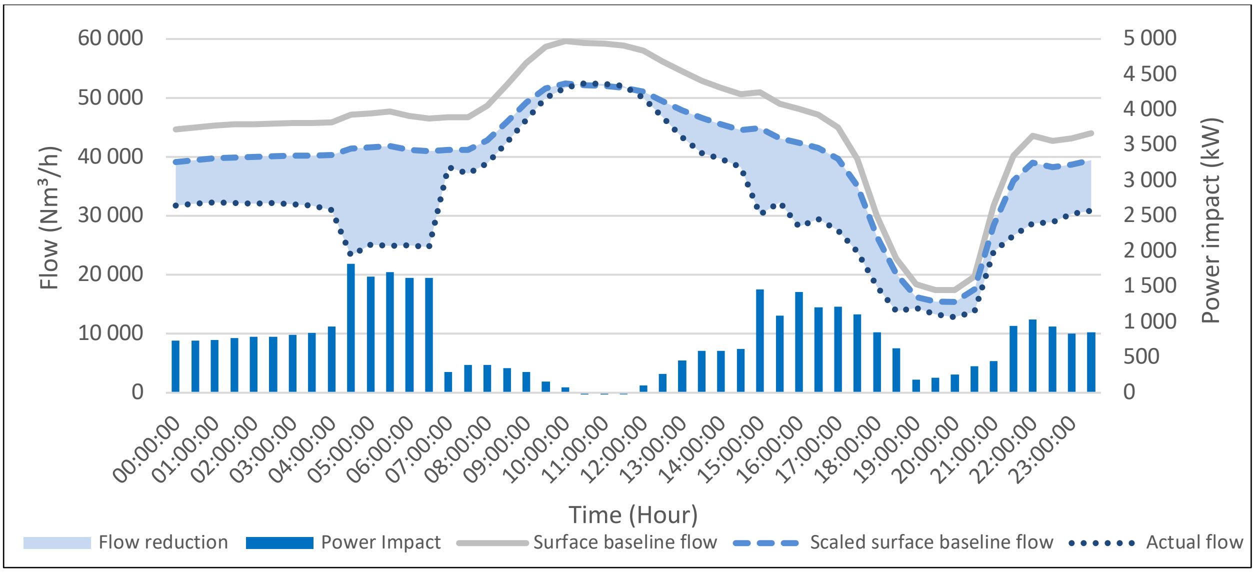


Figure 37 - Example showing the change in flow rate as a result of the implementation of the selected hybrid control philosophy. The example highlights the effect of scaling the baseline and the resultant power impact profile which is calculated by subtracting the actual flow rate from the scaled baseline flow rate.

The final step is to calculate the annual energy impact of the power impact profile. First the average power consumption over the 24-hour period is determined. The average is then multiplied by 24 to determine the daily energy impact in kilowatt hours. The annual energy impact is then calculated by multiplying the daily energy impact by the number of days in a year which represent the mode of operation being analysed.

The methodology described above must be used to calculate the annual energy impact for weekdays and On-Saturdays. The methodology described above can also be utilised to calculate the power impact for Off-Saturday and Sunday periods. However, the only difference is that the Saturday and Sunday baselines developed in Section 2.2.3 must not be scaled as the compressed air consumption on Off-Saturdays and Sundays is not production related.

2.5.2 Verification

Once the actual annual energy impact of the implemented hybrid control philosophy has been determined it can be compared with the theoretical annual energy impact which was calculated in Section 2.3.2 to verify the accuracy of the theoretical model. To determine the true impact of the theoretical model, there are two risks which must be accounted for:

1. If the initial theoretical pressure profile, identified in Section 2.3.1, could not be implemented in Section 2.4.3 due to constraints within the system, the theoretical analysis must be updated such that it aligns with the pressure profile that was actually implemented.
2. If there were large changes in the compressed air distribution between project identification and project implementation, a non-routine baseline adjustment must be implemented for the level flow consumptions and the theoretical model must also be updated accordingly.

Once the theoretical model has been adjusted to represent the state of implementation, it can be compared with the actual results to determine the percentage error of the theoretical model by means of Equation 8:

$$\%\, Error = \frac{|E_{TA} - E_A|}{E_A} \tag{8}$$

Where E_A = actual annual energy impact and E_{TA} = adjusted theoretical annual energy impact.

2.5.3 Conclusion

Upon completion of Section 2.5 the actual annual energy impact of the hybrid control philosophy should have been quantified and validated. The validated results were then compared with the theoretical energy impact, determined in Section 2.3.2, to quantify the percentage error of the theoretical model and verify the accuracy of the theoretical model.

2.6 Conclusion

In Chapter 2, the methodology which was used to determine the theoretical energy impact of a hybrid control philosophy was developed. The model was developed such that all the possible hybrid control valve layouts could be evaluated and the hybrid control philosophy which maximised the energy impact and minimised the capital cost, maintenance requirements, project lead time and resource intensity could be effectively identified and selected.

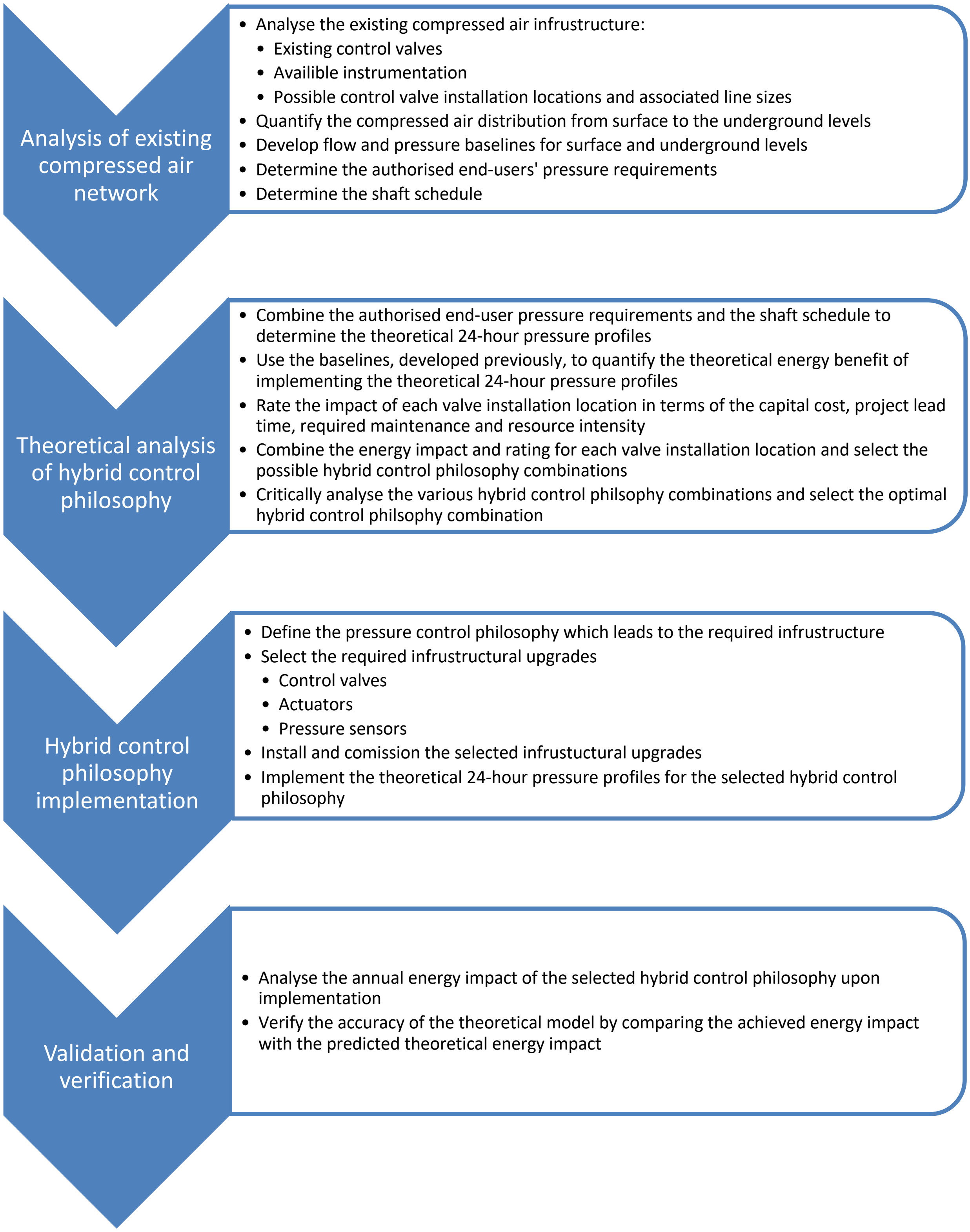
The methodology began with an investigation into the existing infrastructure of the mining operation in question. The methods used to assess the compressed air reticulation, existing control valves, available instrumentation, future control valve installation locations and current compressed air distribution were identified. Thereafter, the baseline methodology was developed according to the IPMVP standard. Additionally, the process to determine the authorised end-users' pressure requirements and existing shaft schedule of the mining operation in question was discussed.

The above information was then critically analysed such that the theoretical pressure profiles for each of the possible valve installation locations could be developed. The theoretical analysis used to determine the theoretical energy impact per valve installation was then identified. Thereafter, the optimal hybrid layout selection methodology was highlighted.

The following step in the process identified the pressure control philosophy as well as the methods used to select the required infrastructural upgrades such as the control valves, actuators and pressure sensors, ensuring that they met the pressure control philosophy's requirements and would be applicable to the mining operation in question. Thereafter, the process to implement the theoretical pressure profiles is discussed.

The final step in the methodology highlights how the achieved energy impact of the selected hybrid control philosophy was quantified and validated. Thereafter, the process used to verify the theoretical model's accuracy was presented.

The analysis methodology developed in Chapter 2 is summarised accordingly in Figure 38.



Analysis of existing compressed air network

- Analyse the existing compressed air infrustructure:
  - Existing control valves
  - Availible instrumentation
  - Possible control valve installation locations and associated line sizes
- Quantify the compressed air distribution from surface to the underground levels
- Develop flow and pressure baselines for surface and underground levels
- Determine the authorised end-users' pressure requirements
- Determine the shaft schedule

Theoretical analysis of hybrid control philosophy

- Combine the authorised end-user pressure requirements and the shaft schedule to determine the theoretical 24-hour pressure profiles
- Use the baselines, developed previously, to quantify the theoretical energy benefit of implementing the theoretical 24-hour pressure profiles
- Rate the impact of each valve installation location in terms of the capital cost, project lead time, required maintenance and resource intensity
- Combine the energy impact and rating for each valve installation location and select the possible hybrid control philosophy combinations
- Critically analyse the various hybrid control philsophy combinations and select the optimal hybrid control philsophy combination

Hybrid control philosophy implementation

- Define the pressure control philosophy which leads to the required infrustructure
- Select the required infrastructural upgrades
  - Control valves
  - Actuators
  - Pressure sensors
- Install and comission the selected infrustuctural upgrades
- Implement the theoretical 24-hour pressure profiles for the selected hybrid control philosophy

Validation and verification

- Analyse the annual energy impact of the selected hybrid control philosophy upon implementation
- Verify the accuracy of the theoretical model by comparing the achieved energy impact with the predicted theoretical energy impact

Figure 38 - Summary of the analysis methodology developed in Chapter 2.

CHAPTER 3 - RESULTS AND DISCUSSION

3.1 Preamble

A deep-level platinum mine in the North West province of South Africa, further referred to as Shaft A, was used as a case study for the implementation of a hybrid control philosophy. Shaft A is approximately 1400m deep and has 14 active working levels. In Chapter 3 the analysis methodology developed in Chapter 2 was applied to the case study in question.

The analysis of Shaft A began by gaining an understanding of the existing compressed air network in the following areas: the current compressed air infrastructure, and the compressed air distribution. This information was then used to develop the relevant baselines for Shaft A. Thereafter, the end-user’s pressure requirements and shaft schedule for Shaft A were determined.

Using the gathered information, the 24-hour pressure profiles for each control valve installation were determined and the theoretical analysis methodology was applied to determine the theoretical energy impact for each possible valve installation location. Thereafter, the optimal hybrid control philosophy was selected. The required infrastructural upgrades to implement the optimal hybrid control philosophy were then determined and implemented at Shaft A.

Once the infrastructural changes were complete, the theoretical pressure profiles were iteratively implemented on Shaft A and the energy impact upon implementation was validated. The actual energy impact was then compared with the predictions of the theoretical model and the theoretical model’s accuracy was verified.

3.2 Analysis of the existing compressed air network

The analysis of Shaft A began by gathering the necessary information which was later used to conduct the theoretical analysis in Section 3.3. The investigation gathered information regarding the existing compressed air infrastructure and compressed air distribution. Baselines of Shaft A’s surface flow and surface pressures were then developed. Lastly, the authorised end-users’ pressure requirements and the shaft schedule were determined.

3.2.1 Existing compressed air infrastructure

The analysis methodology described in Section 2.2.1 was applied to the compressed air network at Shaft A to determine the existing compressed air infrastructure. The analysis of the surface compressed air network and underground network were completed concurrently. The information gathered during the analysis is summarised in Figure 39.

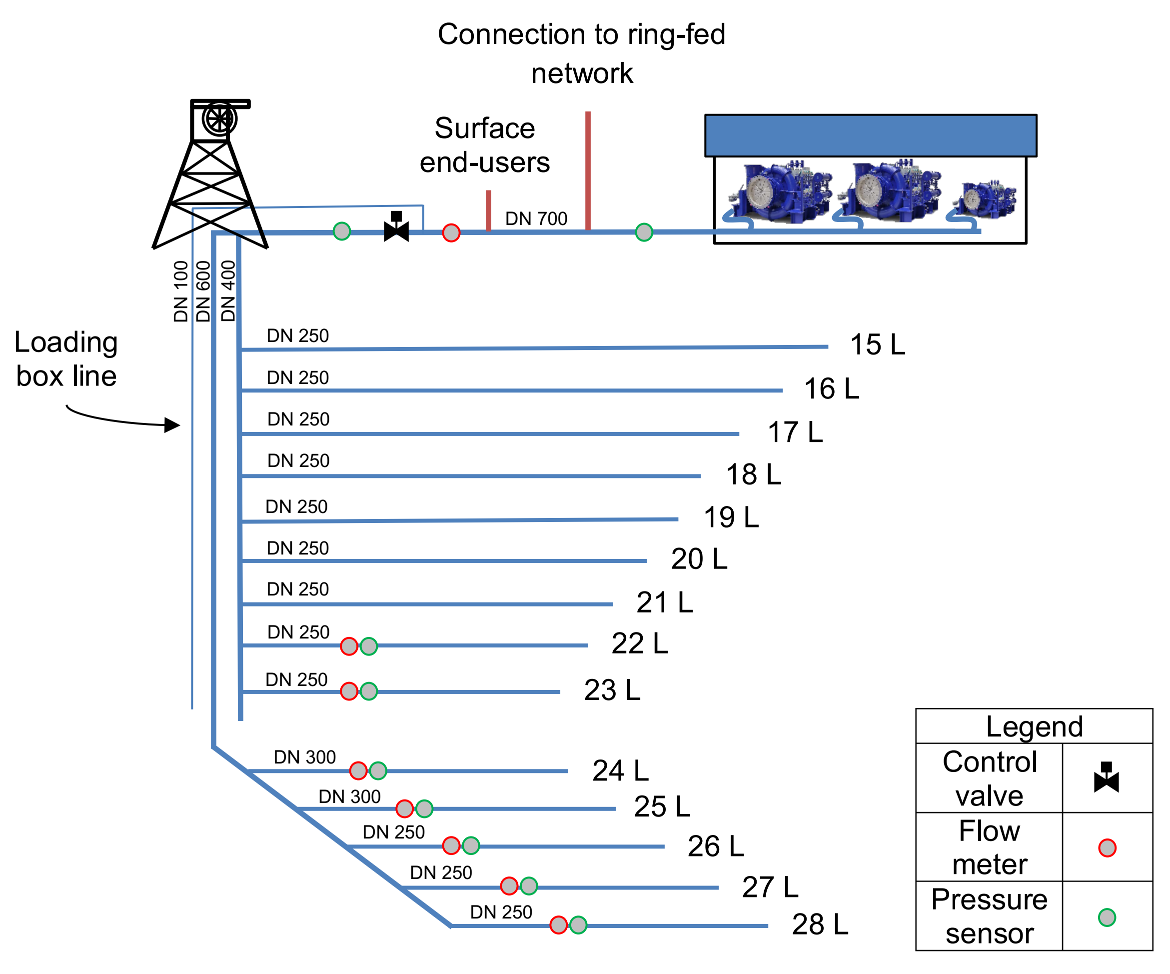


Figure 39 - A summary of the existing compressed air infrastructure at Shaft A.

Important findings from the infrastructural investigation were as follows:

A surface control valve was already installed on the shaft's main compressed air line. The surface valve was identified as a 700 mm triple eccentric butterfly valve with an electrical AUMA actuator and was already controlling the pressure supplied to underground end-users.

Three tie-offs prior to the surface control valve were also identified. These tie-offs were used for the following purposes: the first was a connection to a ring-fed compressed air network, the second was a tie-off to the fridge plant at Shaft A and the third was an isolated loading box line which supplied compressed air to the loading box at shaft bottom.

The analysis of the existing compressed air instrumentation revealed that Shaft A had two pressure sensors and a flow meter in place. The first pressure sensor and flow meter were located upstream of the control valve and the second pressure sensor was located downstream of the control valve. The identified instrumentation was re-calibrated to ensure accurate measurements.

Upon completion of the surface compressed air network investigation, it was concluded that no infrastructural changes were required. However, it was recommended that the analysis procedure be continued for the existing surface control valve to ensure that the maximum energy impact was being achieved. It was also recommended that the surface control valve specifications be reviewed (see Section 3.4.2.1) to ensure that it was adequately specified for the flow and pressure conditions of Shaft A.

When the underground compressed air network was investigated, 14 active mining levels, supplied by two separate compressed air lines, were identified. There were no control valves currently installed on any of the levels. Therefore, each level was marked as a possible installation location for a control valve. The relative line sizes at each possible installation location were noted.

Each level was then checked for equipment which required a constant supply pressure of 500kPa or greater throughout the 24-hour mining cycle. However, no end-users with such pressure requirements were found and thus no infrastructural changes had to be made.

Lastly, the existing instrumentation was investigated. Flow meters and pressure sensors were found from 22 Level to 28 Level. The existing flow meters had suffered severe damage from the harsh underground conditions and were no longer in working order. The decision was made to not replace the flow meters due to extensive lead times and high capital costs. The pressure sensors however were still operational, and their accuracy was verified using portable measuring equipment.

3.2.2 Compressed air distribution

The next step in the analysis methodology was to determine the distribution of compressed air from surface to each of the underground levels at Shaft A. In Section 2.2.2 three methodologies were discussed which could be used to determine the compressed air distribution, namely: permanent flow metering, portable flow metering and baseload testing.

The use of permanent flow metering was not a viable option at Shaft A, as the permanent flow meters which were present underground were not operational. Portable flow metering was considered the next best option to determine the compressed air distribution. However, due to a lack of available measuring points and the high resource intensity of portable flow metering measurements, it was decided that portable flow metering would not be pursued. Thus, the baseload testing methodology was used to determine the compressed air distribution from surface to the underground levels.

The baseload testing methodology discussed in Section 2.2.2.3 was applied to Shaft A. The existing surface control valve was aborted, and each of the levels were isolated sequentially from Level 15 to Level 28 until all the levels on Shaft A were isolated. The resulting change in surface flow as each level was isolated was calculated and normalised to 500 kPa, using the ideal gas law. The relevant flow fraction per level was then determined as shown in Table 16.

Table 16 - Summary of the flow rate and associated flow fraction per level at Shaft A, calculated using the baseload test methodology.

Level	Flow rate (Nm^3/h)	Flow fraction
15 Level	2 848	2.61%
16 Level	11 104	10.18%
17 Level	10 080	9.25%
18 Level	4 588	4.21%
19 Level	4 292	3.94%
20 Level	3 278	3.01%
21 Level	4 026	3.69%
22 Level	4 718	4.33%
23 Level	4 864	4.46%
24 Level	11 918	10.93%
25 Level	9 607	8.81%
26 Level	10 574	9.70%
27 Level	14 862	13.63%
28 Level	12 261	11.25%

The flow fractions were then extrapolated to a weekday 24-hour surface flow profile measured by the surface flow meter to show how the flow fraction could be used to determine the flow distribution from surface to each level. The extrapolation of the flow fractions is shown in Figure 40.

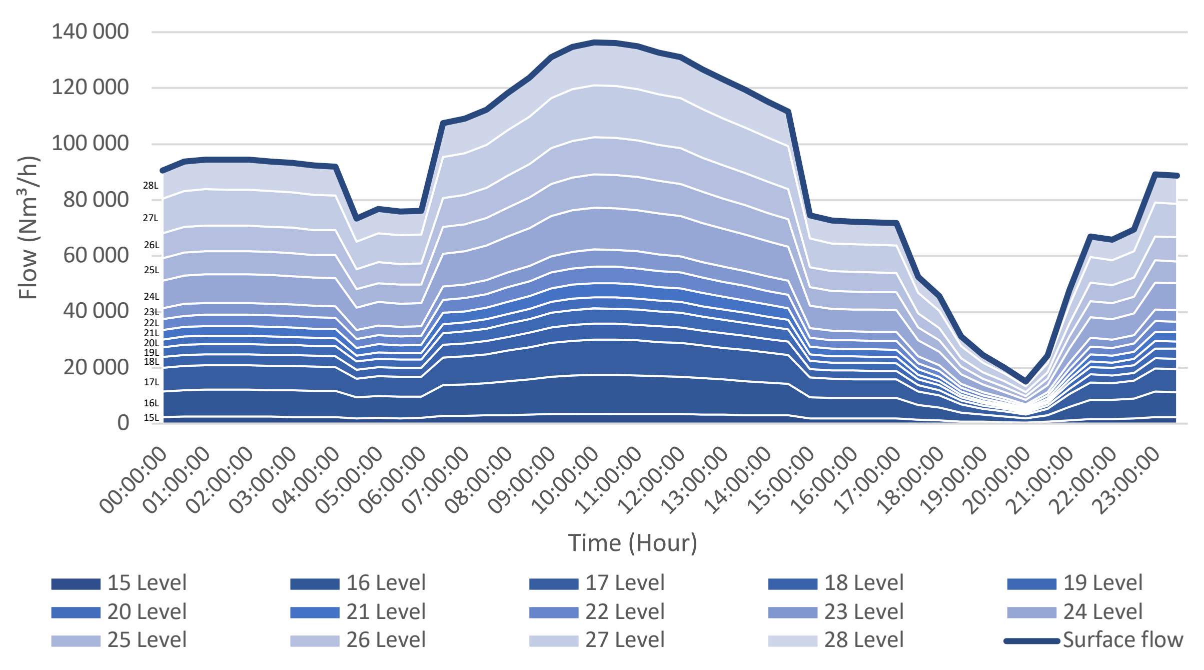


Figure 40 - Extrapolation of each level's flow fraction to the total surface flow measured by the surface flow meter.

3.2.3 Baseline development

Once the existing compressed air infrastructure and flow distributions per level at Shaft A were determined, the next step was to develop baselines of the existing compressed air flow rate and supply pressure prior to the implementation of the hybrid control philosophy. The baselines would later be used to determine the theoretical energy impact of the hybrid control philosophy in Section 3.3.2 and verify the impact of the hybrid control philosophy in Section 3.5.1.

The IPMVP baseline methodology discussed in Section 2.2.3 [61], was applied to Shaft A. The answers to the critical questions when developing the baseline for Shaft A were as follows:

1. Define the measurement boundary

During the initial investigations conducted in Section 3.2.1, it was found that Shaft A had a surface flow meter and two surface pressure sensors installed. As there was already an operational surface control valve in place, the effects of the control valve had the be considered when developing the baseline. Therefore, the surface flow meter was assigned as the flow measurement boundary to be used for the baseline development and the pressure sensor downstream of the control valve was assigned as the pressure measurement boundary to be used for the baseline development.

2. Define the measurement period selection

The important factors which had to be considered when defining the measurement period selection as per the methodology described in Section 2.2.3 were as follows: Operational changes or projects implemented on the system being measured, seasonal effects and different modes of operation.

The only major project which had been implemented on the compressed air network of Shaft A was the implementation of the surface control valve which dated back to August 2017. Therefore, the baseline could be developed for a full 12-month period to account for the possible impact of seasonal effects.

The second area to be addressed was the modes of operation at Shaft A. It was determined that Shaft A had different compressed air consumptions on Weekdays, Saturdays, and Sundays. The root cause of this was found to be the changes in operational modes from production modes into maintenance modes. Therefore, separate baselines had to be developed to represent the compressed air consumption on weekdays, Saturdays, and Sundays.

3. Define the methods of adjustment

Due to the correlation between the number of active authorised compressed air end-users and the compressed air consumption, it was decided that a routine baseline adjustment methodology would be adopted at Shaft A. Therefore, when the actual effects of the hybrid control philosophy were later determined, in Section 3.5.1, the baseline would be scaled according to the total volume of compressed air consumed during the drilling shift.

Therefore, the baseline for Shaft A was developed according to the IPMVP standard. The key take aways from the investigations above were the following:

- The surface flow meter and pressure sensor downstream of the control valve formed the measurement boundary.
- The baselines were developed using 12-months of historic data and separate baselines had to be developed to account for changes in operation modes. Thus, 12-month baselines were developed for weekdays, Saturdays, and Sundays.

- When the baseline was used to verify the impact of the hybrid control philosophy, routine baseline adjustments would be used to account for changes in the number of active end-users.

The baselines developed using the surface flow meter and surface pressure sensor were then calculated by extracting data from the historian. The resulting flow baseline profiles are shown in Figure 41 and the resulting pressure baseline profiles are shown in Figure 42. The dark blue line presents the weekday 24-hour baseline profile, the light blue line presents the Saturday 24-hour baseline profile, and the grey line presents the Sunday 24-hour baseline profile.

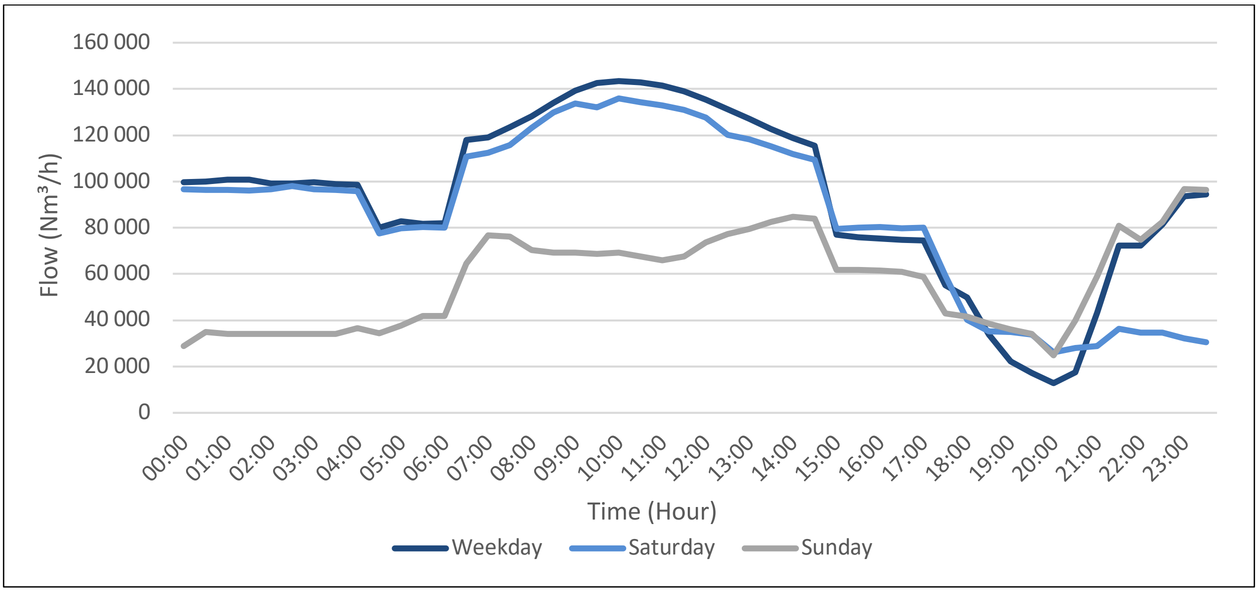


Figure 41 – Weekday, Saturday and Sunday flow baselines developed for Shaft A.

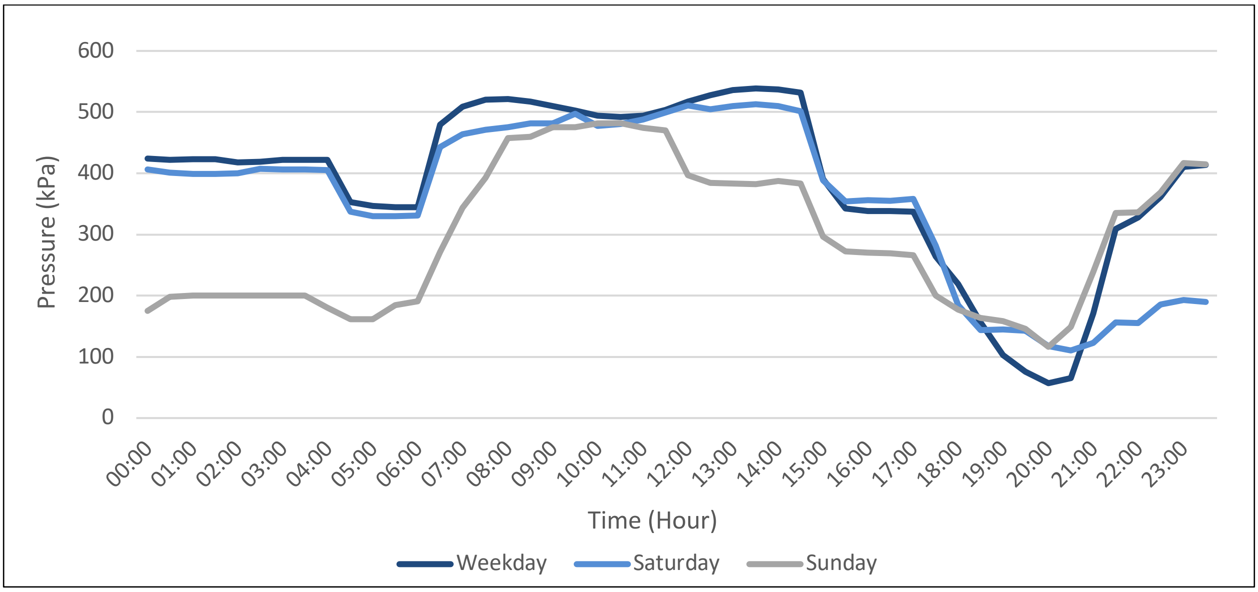


Figure 42 – Weekday, Saturday and Sunday pressure baselines developed for Shaft A.

The surface flow and surface pressure baselines were later used in Section 3.3.2 to determine the theoretical energy impact of improving the existing surface valve's pressure setpoints. However, the surface flow baseline could not be used to determine the theoretical energy impact of implementing a control valve on each level.

Therefore, flow baselines were developed for each level using the surface flow baselines and the flow fractions which were determined in Section 3.2.2. The pressure baselines for each level were assumed to be equal to the existing surface pressure baselines, as the supply pressure to all the levels is determined by the existing control valves' pressure setpoints. The resulting flow baselines for 28 Level at Shaft A are shown in Figure 43 for illustration purposes. All the levels' flow baselines can be viewed in Annexure F.

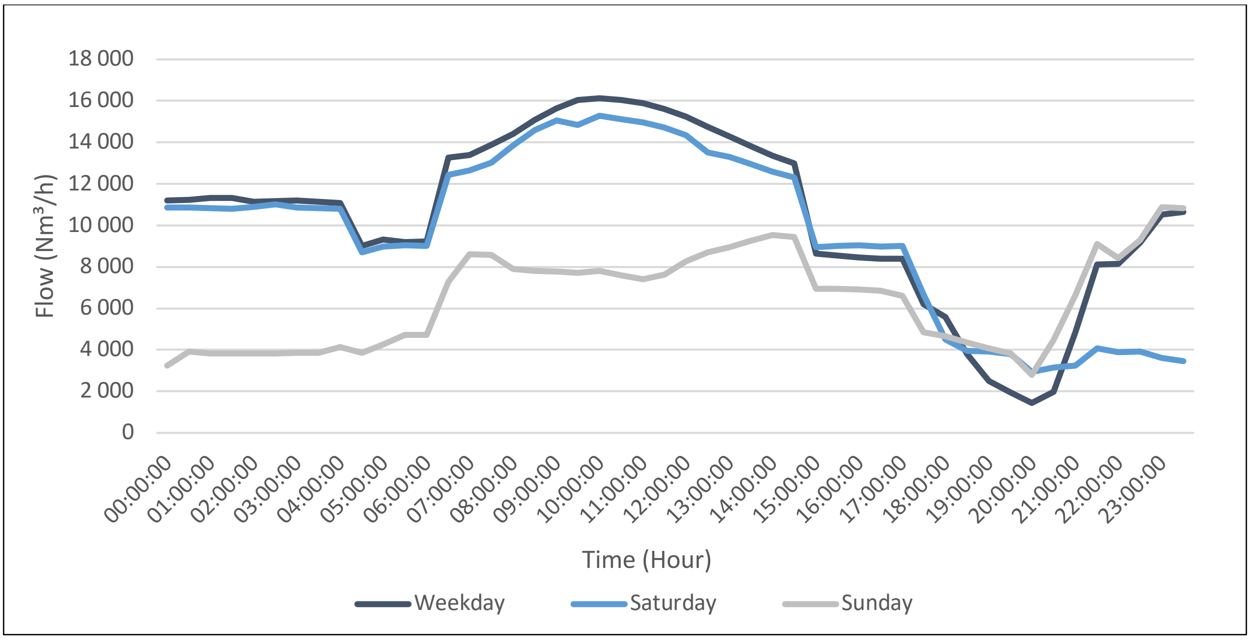


Figure 43 - The weekday, Saturday, and Sunday flow baselines for 28L.

3.2.4 Pressure demand requirements

The next step in the analysis of the existing compressed air network was to determine the minimum pressure requirements of the end-users which were present throughout the two modes of operation, namely: the production mode and the maintenance mode. The engineering and mining personnel at Shaft A were consulted to determine the pressure requirements for the two modes of operation. The production mode had various shifts in which different authorised end-users were present and the maintenance mode had a single pressure requirement throughout the maintenance period.

When investigating the production mode's pressure requirements, it was found that all the levels had the same pressure requirements for each shift, except for 28 Level. 28 Level was running an extended production shift which required additional pressure for the explosive charge up process. When investigating the maintenance mode's pressure requirements, it was found that only the refuge bays were required to be pressurised to ensure the safety of underground personnel.

The resulting end-users' pressure requirements for the production mode and the maintenance mode are highlighted in Table 17. Table 17 is split into three sections, the first presents the production mode requirements for all levels excluding 28 Level, the second presents the production mode requirements for 28 Level alone and the third presents the maintenance mode requirements for all the levels combined.

Table 17 - Summary of the authorised end-users pressure requirements across all levels at Shaft A for the production mode and the maintenance mode.

Shift	Equipment	Pressure demand (kPa)	Minimum supply pressure (kPa)
15 level to 27 level production pressure requirements			
Drilling shift	Rock drills	600	600
	Diaphragm pumps	400	
	Chain saw	400	
	Ore chutes	350	
	Air whistles	150	
	Anfo loaders	340	
	Refuge bays	200	
Blasting shift	Refuge bays	200	200
Cleaning shift	Loaders	370	370
	Ore chutes	350	
	Air whistles	150	
	Refuge bays	200	
Shift changes	Refuge bays	200	200
28 level production pressure requirements			
Drilling shift	Rock drills	600	600
	Diaphragm pumps	400	
	Chain saw	400	
	Ore chutes	350	
	Air whistles	150	
	Anfo Loaders	340	
	Refuge bays	200	

Extended production	Anfo loaders	340	340
	Refuge bays	200	
Blasting shift	Refuge bays	200	200
Cleaning shift	Loaders	370	370
	Ore chutes	350	
	Air whistles	150	
	Refuge bays	200	
Shift changes	Refuge bays	200	200
Maintenance pressure requirements			
Maintenance shift	Refuge bays	200	200

3.2.5 Shaft schedule

The final step in the analysis of the existing system was to determine the operational logistics of Shaft A. The analysis was split into two sections where the schedule for the modes of operation were investigated first and thereafter the schedules for each shift within the production mode were investigated. The engineering and mining personnel at Shaft A were consulted to determine their operational logistics.

It was determined that Shaft A planned to follow a bi-weekly schedule. In the first week, the production mode ran from Sunday night through to Saturday evening, the maintenance mode then ran from Saturday evening through to Sunday night. In the second week, the production mode ran from Sunday night through to Friday evening, the maintenance mode then ran from Friday evening through to Sunday night. The additional maintenance time in the second week was used to perform large maintenance tasks which required excessive downtime.

However, if there was no major maintenance planned for the second week, the maintenance shift on a Saturday would be swapped for an additional production shift. When the historic schedule was analysed, it was found that three out of the four Saturdays in a month were used for production and a single Saturday was used for large maintenance tasks. The Saturdays which were used for production related purposes are referred to as “On-Saturdays” and the Saturdays which were used for maintenance related purposes are referred to as “Off-Saturdays”.

Therefore, the schedule for the modes of operation, which were later used to determine Shaft A’s theoretical pressure schedules in Section 3.3.1, were determined as a monthly overview shown in Table 18. The first section of Table 18 highlights the three weeks of operation in which each Saturday is an On-Saturday and the second section of Table 18 highlights the single week of operation in which the Saturday is an Off-Saturday.

Table 18 - Overview of the monthly production and maintenance mode schedules for Shaft A.

Day of week	Operational mode	Duration of mode
3 weeks with On-Saturdays		
Monday - Friday	Production mode	00:00 – 23:59
On-Saturday	Production mode	00:00 – 17:00
On-Saturday	Maintenance mode	17:00 – 23:59
Sunday	Maintenance mode	00:00 – 21:00
Sunday	Production mode	21:00 – 23:59
1 week with Off-Saturdays		
Monday - Friday	Production mode	00:00 – 17:00
Friday	Maintenance mode	17:00 – 23:59
Off-Saturday	Maintenance mode	00:00 – 23:59
Sunday	Maintenance mode	00:00 – 21:00
Sunday	Production mode	21:00 – 23:59

Following the investigation of the schedules for the modes of operation, the shift schedules within the production mode of operation were investigated. It was found that the mining personnel at Shaft A were taken to and from their underground working areas for each shift according to the schedule of the service winder and the man winder. A summary of the winder schedules for each shift is presented in Table 19.

Table 19 – A summary of Shaft A's production mode schedule per level, per shift.

Time	Service winder	Man winder	Shift down	Shift up
Morning shift				
03:50 - 04:10	15L	28L	Drilling shift	Cleaning shift
04:10 - 04:50	16L	26L & 27L	Drilling shift	Cleaning shift
04:50 - 05:10	17L	25L	Drilling shift	Cleaning shift
05:10 - 05:30	18L	24L	Drilling shift	Cleaning shift
05:30 - 05:50	19L	22L	Drilling shift	Cleaning shift
05:50 - 06:10	20L	23L	Drilling shift	Cleaning shift
06:10 - 06:30	21L	-	Drilling shift	Cleaning shift
Afternoon shift				
11:30 - 11:50	15L	27L	-	Drilling shift
11:50 - 12:30	16L	26L	-	Drilling shift
12:30 - 12:50	17L	25L	-	Drilling shift

12:50 - 13:10	18L	24L	-	Drilling shift
13:10 - 13:30	19L	28L	-	Drilling shift
13:30 - 14:00	20L	23L	-	Drilling shift
14:00 - 14:30	21L	-	-	Drilling shift
Night Shift				
20:30 - 20:50	15L & 16L	27L & 28L	Cleaning Shift	-
20:50 – 21:10	17L & 18L	26L & 27L	Cleaning Shift	-
21:10 – 21:30	19L & 20L	24L & 25L	Cleaning Shift	-
21:30 – 21:40	21L	22L & 23L	Cleaning Shift	-

3.3 Theoretical analysis of hybrid control philosophy at Shaft A

Upon completion of the analysis of the existing system, all the information required to determine the theoretical energy impact of a hybrid control philosophy at Shaft A had been acquired. The analysis began by determining theoretical pressure profiles for each of the valve installation locations identified at Shaft A, as well as the existing surface control valve, as per Section 3.2.1.

The theoretical energy impact of implementing the theoretical pressure profiles was then investigated. The energy impact of improving the existing surface control valve's pressure setpoints was the first point of order. Thereafter, the additional benefit of level valves downstream of the surface control valve were investigated.

Once the theoretical energy impacts of each valve had been determined, the expected capital cost, maintenance requirement, project lead time and resource intensities per valve installation location were analysed. The possible hybrid control valve layouts were then compared such that the hybrid control layout with the greatest energy impact and minimum capital cost, maintenance requirement, project lead time and resource intensity could be selected.

3.3.1 Theoretical 24-hour pressure profiles

The first step in the theoretical analysis was to develop theoretical 24-hour pressure profiles for weekdays, On-Saturdays, Off-Saturdays and Sundays for each of the control valve installation locations. Following the methodology described in Section 2.3.1, each valve's 24-hour pressure profile was determined by combining the end-users' pressure requirements for each shift with the shaft schedule. The recommended 2-hour buffer between the shift going underground and receiving their requested supply pressure was then accounted for. Lastly, the pressure during the drilling shift was set equal to the baseline pressure for all production periods (weekdays and On-Saturdays) as no control would be present throughout the drilling shift.

The resulting weekday 24-hour pressure profile for each possible valve location is highlighted in Table 20. The remaining 24-hour pressure profiles for On-Saturdays, Off-Saturdays and Sundays for each possible valve location are shown in Annexure G.

Table 20 - Summary of the 24-hour weekday pressure profiles for each possible control valve installation location.

Time	Surface	15L	16L	17L	18L	19L	20L	21L	22L	23L	24L	25L	26L	27L	28L
00:00	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
00:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
01:00	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
01:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
02:00	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
02:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
03:00	370	200	200	200	370	370	370	370	370	370	370	370	200	200	200
03:30	370	200	200	200	200	200	200	370	200	370	200	200	200	200	200
04:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
04:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
06:00	479	200	200	200	200	200	200	200	200	200	200	200	200	479	479
06:30	509	509	200	509	200	200	200	200	200	200	200	200	200	509	509
07:00	521	521	521	521	521	200	200	200	200	200	200	200	200	521	521
07:30	522	522	522	522	522	522	522	200	522	200	200	522	522	522	522
08:00	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517
08:30	510	510	510	510	510	510	510	510	510	510	510	510	510	510	510
09:00	502	502	502	502	502	502	502	502	502	502	502	502	502	502	502
09:30	494	494	494	494	494	494	494	494	494	494	494	494	494	494	494
10:00	492	492	492	492	492	492	492	492	492	492	492	492	492	492	492
10:30	495	495	495	495	495	495	495	495	495	495	495	495	495	495	495
11:00	504	504	504	504	504	504	504	504	504	504	504	504	504	504	504
11:30	517	200	517	517	517	517	517	517	517	517	517	517	517	517	517
12:00	528	200	200	528	528	528	528	528	528	528	528	528	528	200	528
12:30	536	200	200	200	536	200	200	536	200	536	536	536	536	200	340
13:00	539	200	200	200	200	200	200	200	200	200	539	539	539	200	340
13:30	537	200	200	200	200	200	200	200	200	200	537	537	537	200	340
14:00	532	200	200	200	200	200	200	200	200	200	200	200	200	200	340
14:30	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
15:00	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
15:30	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
16:00	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
16:30	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
17:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
17:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:30	370	370	370	370	370	200	200	200	200	200	200	370	370	370	370
23:00	370	370	370	370	370	370	370	200	370	200	370	370	370	370	370
23:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370

3.3.2 Theoretical energy impact

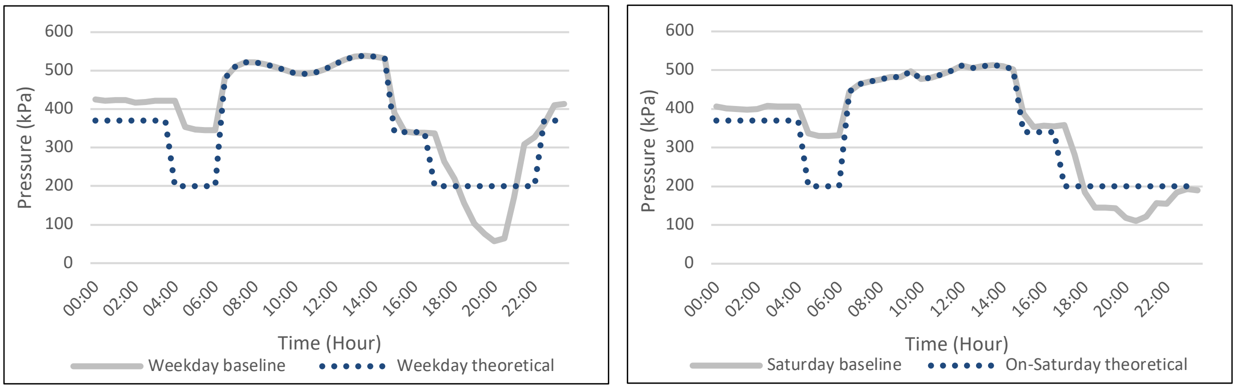
The pressure profiles developed in Section 3.3.1 could then be used to determine the theoretical energy impact that would be achieved if each theoretical pressure profile was implemented. The analysis methodology described in Section 2.3.2 was used to quantify the theoretical energy impact for each possible valve installation location. The first area of analysis was the energy impact as a result of improving the existing surface control valve's pressure setpoints, followed by an analysis of the energy impact for each possible level control valve installation location.

3.3.2.1 Surface control valve theoretical energy impact

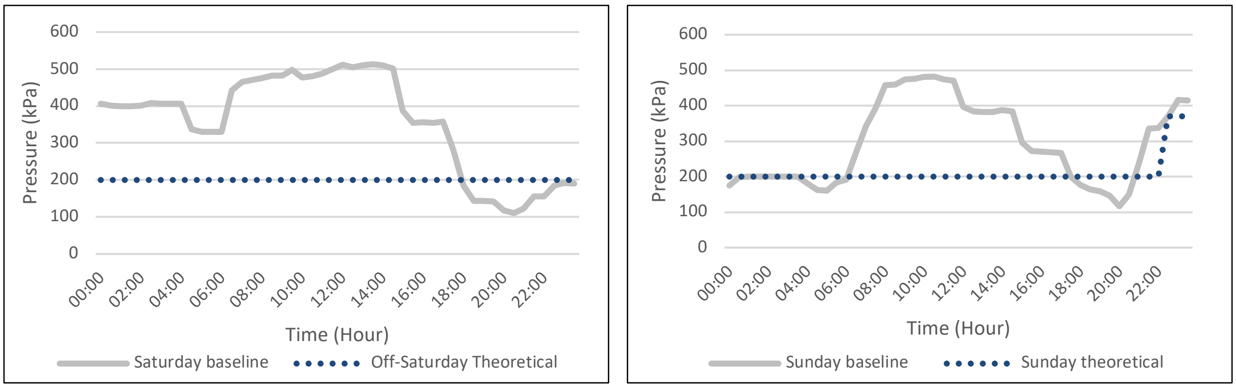
The first area which was investigated was the potential energy impact of improving the existing surface control valve's 24-hour pressure setpoints. This was seen as low hanging fruit since the surface control valve at Shaft A was already operational and the optimisation of the pressure setpoints would come at no additional cost or maintenance to the existing system.

When comparing the surface control valve's theoretical pressure profiles and current pressure baselines, there were several notable differences. The surface control valve's existing pressure setpoints were a single 24-hour production pressure profile which remained the same throughout all the days of the week. Therefore, the weekday and On-Saturday pressure setpoints could be slightly adjusted, with the largest difference occurring in the change of shift pressure setpoints. However, the major pressure profile change was observed on the Off-Saturday, and Sunday pressure profiles.

The difference in the current 24-hour pressure baselines and theoretical 24-hour pressure profiles for weekdays, On-Saturdays, Off-Saturdays, and Sundays is shown in Figure 44. The current 24-hour baseline pressure profiles are represented by the grey line and the proposed theoretical 24-hour pressure profiles are represented by the dotted blue line.



(a) (b)



(c) (d)

Figure 44 – (a) Weekday pressure baseline versus theoretical weekday pressure profile, (b) Saturday pressure baseline versus theoretical On-Saturday pressure profile, (c) Saturday pressure baseline versus theoretical Off-Saturday pressure profile, (d) Sunday pressure baseline versus theoretical Sunday pressure profile

It was noted in Figure 44 that the baselines were below the theoretical pressure profiles during certain periods. This was due to the surface control valve being closed for some of the periods which make up the baseline. It was standard practice at Shaft A to isolate the compressed air when there were no mining personnel underground. Therefore, the pressure supplied to the underground working areas was sometimes zero, resulting in the baseline dipping below the theoretical pressure profile.

Due to the pressure baselines being developed over a 12-month period, it was assumed that the frequency of the isolation of the surface control valve, for the various operational modes, would remain the same going forward. Thus, the areas in which the baseline pressure dipped below the theoretical pressure profile were excluded from the energy impact calculation process.

The theoretical power impact of implementing the theoretical pressure profiles on the surface control valve was then determined using the methodology discussed in Section 2.3.2.2. The resulting theoretical flow reduction and power impact profile for weekdays are highlighted in Figure 45. The theoretical flow reductions and power impact profiles for On-Saturdays, Off-Saturdays and Sundays can be found in Annexure H.

In Figure 45, the grey line shows the weekday flow baseline prior to implementing the theoretical weekday pressure profile and the dotted blue line shows the theoretical weekday flow profile upon implementation of the theoretical weekday pressure profile. The difference between the baseline flow profile and theoretical flow profile was calculated and is shown as the light blue area between the flow baseline and the theoretical flow profile. The difference was then multiplied by the power density of the compressed air network, which Shaft A is connected to, and the theoretical power impact profile was determined as shown by the blue bar chart in Figure 45.

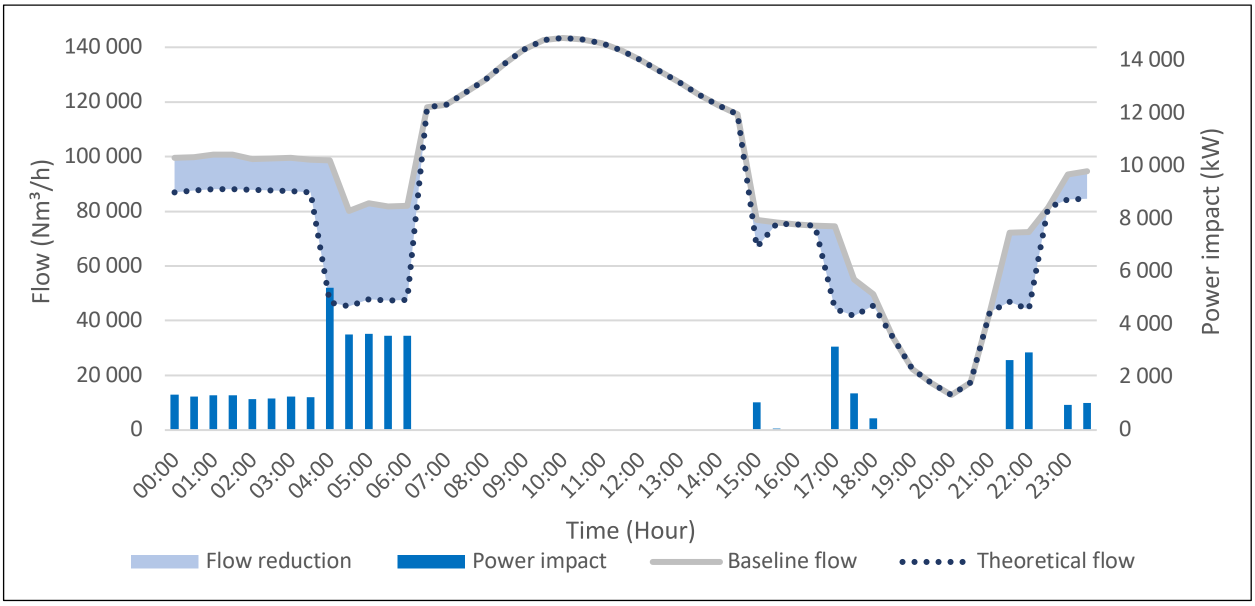


Figure 45 - The theoretical change in flow and resultant theoretical power impact upon implementation of the theoretical pressure profile on the surface control valve at Shaft A for weekdays only.

The daily theoretical energy impact for each of the modes of operation was then determined and extrapolated to quantify the annual theoretical energy impact of the theoretical pressure profile for the surface control valve at Shaft A. During the analysis it was assumed that a quarter of the Saturdays were Off-Saturdays, and the remaining Saturdays were On-Saturdays. Additionally, all public holidays were excluded from the analysis.

The resulting theoretical daily energy impact as well as the theoretical annual energy impact for each mode of operation are shown in Table 21. The resulting theoretical annual energy impact of implementing the theoretical pressure profile on the surface control valve at Shaft A was estimated at 9.37 GWh.

Table 21 - Summary of the daily and annual theoretical energy impact of implementing the theoretical pressure profiles on the surface control valve for the various modes of operations at Shaft A.

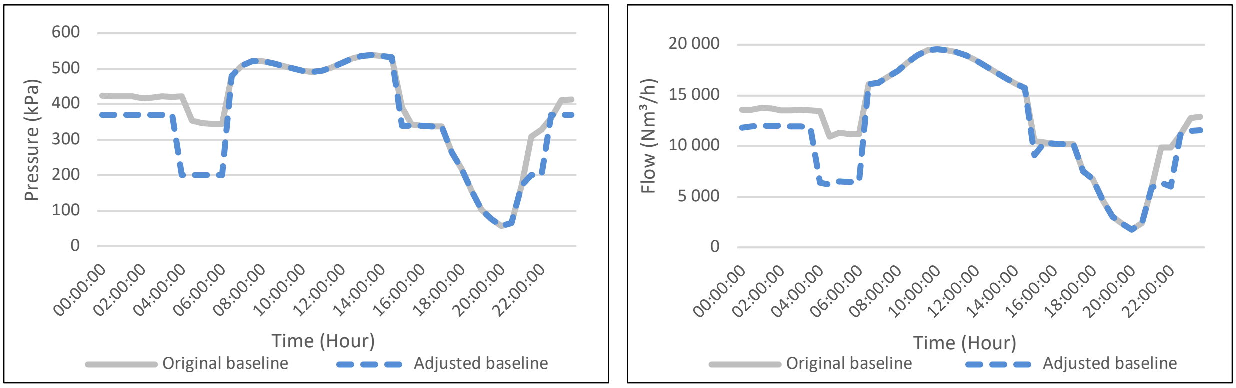
Mode of operation	Number of days	Daily energy impact (kWh)	Annual energy impact (kWh)
Weekday	252	21 784	5 489 611
On-Saturday	38	14 077	534 911
Off-Saturday	12	103 650	1 243 805
Sunday	50	42 066	2 103 302
Totals	352	181 577	9 371 630

3.3.2.2 Level control valves theoretical energy impact

The next step in the process was to determine the theoretical energy impact of each possible level control valve by applying the methodology described in Section 2.3.2.3. Due to the level valves being downstream of the surface valve, the pressure supplied to them is already controlled by the surface control valve. Therefore, the original level flow and pressure baselines developed in Section 3.2.3 had to be adjusted to take the effect of the surface control valve into account.

The theoretical surface flow profiles and theoretical surface pressure profiles, as determined previously in Section 3.3.2.1, were used to perform non-routine baseline adjustments on all the existing level flow and pressure baselines as per the methodology discussed in Section 2.3.2.3. The adjustments to 27 Level's weekday pressure and flow baselines are shown in Figure 46 for illustrative purposes.

The original baselines are presented by the grey line and the adjusted baselines are presented by the dashed blue line. Figure 46 (a) shows the difference between the original weekday pressure baseline and the adjusted weekday pressure baseline. Figure 46 (b) shows the difference between the original weekday flow baseline and the adjusted weekday flow baseline.



(a) (b)

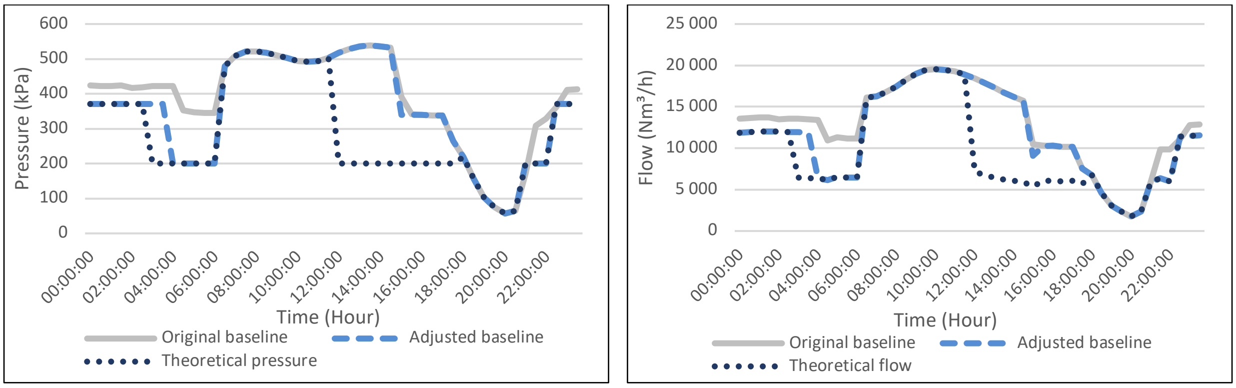
Figure 46 - (a) 27 Level's adjusted weekday pressure baseline versus original pressure baseline, (b) 27 Level's adjusted weekday flow baseline versus original flow baseline,

The updated level flow and pressure baselines were then used to determine the theoretical change in flow rate upon implementation of the theoretical pressure profile by means of the ideal gas law. This was done for all the possible level control valve installation locations for each of the various modes of operation.

For illustrative purposes, 27 Level's theoretical weekday pressure profile and its impact on the theoretical weekday flow profile are highlighted in Figure 47. Additionally, the original flow and pressure baselines are included such that the impact of the surface control valve is made evident.

The grey line represents the original baselines, the dashed blue line represents the adjusted baselines, and the dotted blue line represents the theoretical pressure and flow profiles. Figure 47 (a) presents the original weekday pressure baseline, adjusted weekday pressure baseline and the theoretical weekday pressure profile. Figure 47 (b) presents the original weekday flow baseline, adjusted weekday flow baseline and the impact of the theoretical pressure profile on the theoretical weekday flow profile.

The difference between the original baselines and the adjusted baselines highlights the impact of adjusting the surface control valve's pressure setpoints. The difference between the adjusted baselines and the theoretical pressure and flow profiles highlights the theoretical impact of 27 Level's control valve over and above the surface control valve. It is clear from Figure 47 that a level control valve only has an impact on the flow profile if its pressure profile differs from the surface control valve's pressure profile.



(a) (b)

Figure 47 - (a) 27 Level's original pressure baseline, adjusted pressure baseline and theoretical pressure profile, (b) 27 Level's original flow baseline, adjusted flow baseline and theoretical flow profile.

The theoretical power impact of implementing the theoretical pressure profiles on all the possible level control valve locations was then determined using the methodology discussed in Section 2.3.2.3. The resulting theoretical weekday flow reduction and power impact profile for 27 Level are highlighted in Figure 48 for illustrative purposes.

In Figure 48 the original weekday flow baseline is highlighted by the grey line, the adjusted weekday flow baseline is highlighted by the dashed blue line and the theoretical weekday flow profile upon implementation of the theoretical weekday pressure profile is highlighted by the dotted blue line. The difference between the original baseline and adjusted baseline illustrates the impact of the surface control valve and how it was accounted for. The difference between the adjusted flow baseline and the theoretical flow profile was then determined and is highlighted by the light blue area between the adjusted baseline and theoretical flow profile. The difference was then multiplied by the power density of the compressed air network, which Shaft A is connected to, and the theoretical power impact profile of 27 Level was determined as shown by the blue bar chart in Figure 48.

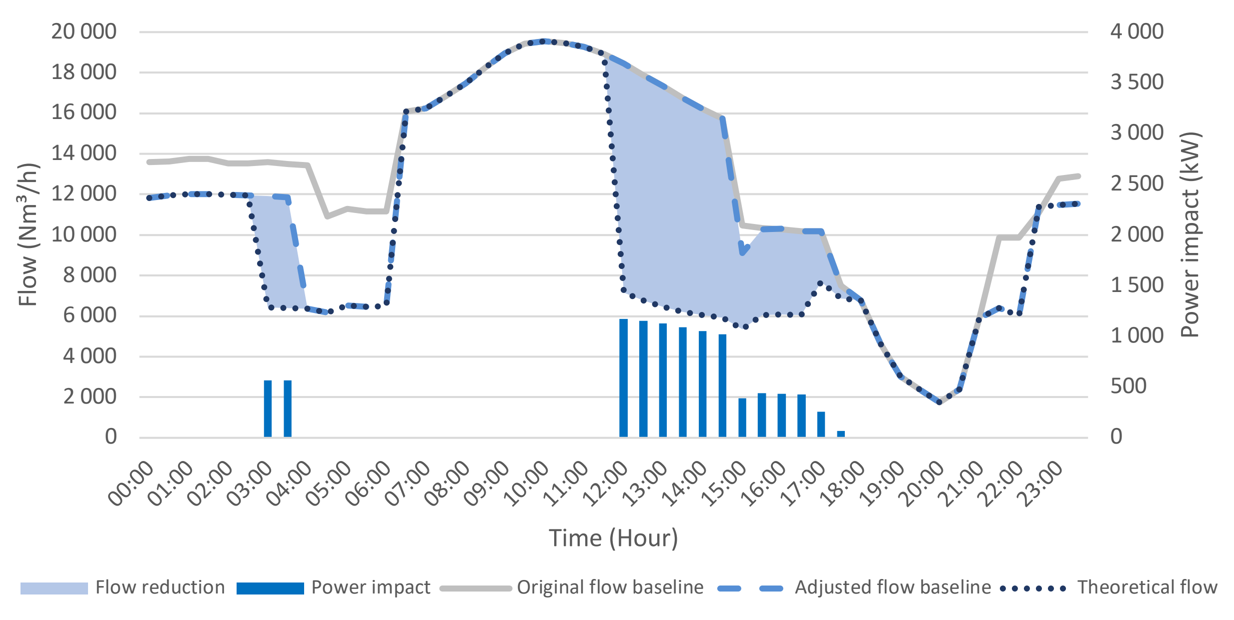


Figure 48 - Illustration of calculating the power impact of implementing the theoretical pressure profile for 27 Level at Shaft A.

The process to determine the power impact profiles as discussed above, which was illustrated for 27 level at Shaft A, was conducted on all the possible level control valve locations at Shaft A for all the modes of operation, namely: weekdays, On-Saturdays, Off-Saturdays and Sundays. The daily theoretical energy impact for each of the modes of operation was then determined and extrapolated to quantify the annual theoretical energy impact of the theoretical pressure profile for each of the possible control valve locations at Shaft A. During the analysis it was assumed that a quarter of the Saturdays were Off-Saturdays, and the remaining Saturdays were On-Saturdays. Additionally, all public holidays were excluded from the analysis.

The resulting theoretical energy impact per day for each mode of operation as well as the annual energy impact for each possible level control valve location are highlighted in Table 22. The resulting theoretical annual energy impact of implementing the theoretical pressure profiles on all the possible level control valve locations was estimated at 10.31 GWh. The level with the largest theoretical annual energy impact was 27 Level which was estimated at 1.4 GWh.

Table 22 - Summary of the daily and annual theoretical energy impact per possible level control valve installation location for the various modes of operation.

Level	Weekday energy impact (kWh)	On-Saturday energy impact (kWh)	Off-Saturday energy impact (kWh)	Sunday energy impact (kWh)	Annual energy impact (kWh)
15	1 222	759	0	0	345 220
16	4 709	2 941	0	0	1 330 845
17	3 322	2 422	0	0	955 918
18	1 422	1 035	0	0	409 032
19	1 797	1 071	0	79	509 321
20	1 373	818	0	61	389 060
21	1 677	946	0	154	476 665
22	1 976	1 177	0	87	559 964
23	2 026	1 143	0	186	575 896
24	3 922	2 707	0	220	1 132 112
25	2 559	2 066	0	0	746 191
26	3 017	2 428	0	0	879 392
27	4 961	3 587	0	0	1 426 033
28	1 867	2 213	0	0	578 883
Total	35 852	25 313	0	787	10 314 532

It was also noted in Table 22 that all the level valves had no energy impact on the Off-Saturdays and minor energy impacts on Sundays. This was because the surface control valve's theoretical pressure profile matched the level control valves theoretical pressure profiles for these modes of operation as shown in Annexure G. Therefore, the level control valves would add little to no benefit over and above the existing surface control valve.

3.3.3 Selection of optimal hybrid layout

The final step in the theoretical analysis of a hybrid control philosophy at Shaft A was to select the hybrid control valve layout which maximised the energy impact whilst minimising the capital cost, maintenance cost, project lead time and resource intensity. The optimal hybrid control valve layout was selected using the methodology described in Section 2.3.3.

The primary step in analysing the possible valve installation locations was to setup the decision matrix which estimated the cumulative impact of the capital cost, required maintenance, project lead time and resource intensity for each of the control valve locations. Each factor was rated on a scale from 1 to 10 where 1 represents the minimum impact and 10 represents the maximum impact. Each factor was then also weighted according to its importance at Shaft A. The factors were then multiplied by their weighting and summed together to determine the total rating per control valve.

The first area which had to be analysed were the capital costs of each possible control valve. The surface valve received a capital cost rating of 0 as it was already installed an operational. The remainder of the control valves received a rating of 5 as they would all be a midsize control valve.

The required maintenance for each control valve was then analysed. The surface control valve received a rating of 2 as it was located on surface and was not exposed to harsh underground conditions. Each level control valve received a rating of 6 as they were planned to be installed underground where they would be exposed to harsh conditions and would require more maintenance than a surface control valve.

The third area of investigation was the project lead time for each control valve installation. The surface control valve received a rating of 1 as the surface control valve was already installed, however the pressure setpoints needed to be updated accordingly which would take some time. The control valves from 15 Level to 23 Level received a rating of 6 as each of these control valves would need to be ordered and installed. The control valves from 24 Level to 28 Level received a rating of 8 as they also needed to be ordered and installed, however their installations were more complicated as the valve installation locations were in the return airway of Shaft A which is not easily accessible.

The final area of investigation was the resource intensity of each control valve installation. The surface control valve received a rating of 3 as it was easily accessible on surface and the operation of the valve could be easily monitored. The control valves from 15 Level to 23 Level received a rating of 4 as they were located underground and would be more difficult to monitor than the surface control valve. The control valves from 24 Level to 28 Level received a rating of 6 as they were also located underground but were in the return airway and thus would be the most difficult to monitor.

The final step of the decision matrix was to give each factor a weighting depending on the factor's importance to Shaft A. The primary area of concern for Shaft A was the capital cost as limited capital was available. Therefore, capital cost got a maximum rating of 10. The second largest area of concern was the resource intensity as the engineering and instrumentation personnel at Shaft A were already operating at maximum capacity. Any additional daily tasks would negatively impact the efficiency of the personnel. Thus, the resource intensity received a weighting of 5. The required maintenance and project lead time were of least concern to Shaft A and received a rating of 2 and 1 accordingly.

Each factor was then multiplied by its weighting and the sum of all the weighted factors generated a rating for each possible control valve. A low rating indicated that the control valve met Shaft A's requirements well, whilst a high rating indicated that the control valve did not meet Shaft A's requirements well. The resulting decision matrix is presented in Table 23.

Table 23 - Summary of the ratings of the various factors for each control valve installation location as well as the total weighted rating.

Valve	Capital cost (W:10)	Required maintenance (W:2)	Project lead time (W:1)	Resource intensity (W:5)	Rating
Surface	0	2	1	3	20
15L	5	6	6	4	88
16L	5	6	6	4	88
17L	5	6	6	4	88
18L	5	6	6	4	88
19L	5	6	6	4	88
20L	5	6	6	4	88
21L	5	6	6	4	88
22L	5	6	6	4	88
23L	5	6	6	4	88
24L	5	6	8	6	100
25L	5	6	8	6	100
26L	5	6	8	6	100
27L	5	6	8	6	100
28L	5	6	8	6	100

Once the ratings for each of the control valve installation locations had been determined, the next step was to match each control valve's rating with its theoretical annual energy impact and rank the control valves according to their theoretical annual energy impact. The ranked energy impacts and associated ratings per possible control valve installation are presented in Table 24.

Table 24 - Summary of each control valve installations energy impact and rating, ranked according to energy impact.

Valve	Energy impact (kWh)	Rating
Surface	9 371 630	20
27L	1 426 033	100
16L	1 330 845	88
24L	1 132 112	100
17L	955 918	88
26L	879 392	100
25L	746 191	100
28L	578 883	100
23L	575 896	88
22L	559 964	88

19L	509 321	88
21L	476 665	88
18L	409 032	88
20L	389 060	88
15L	345 220	88

The information in Table 24 was then used to develop various hybrid control valve combinations. As per the methodology described in Section 2.3.3, the combinations were selected sequentially using the ranked energy impacts. Additionally, the two base combinations were determined which represent the lower and upper energy impacts. The lower limit was represented by the selection of the surface control valve alone and the upper limit was represented by the selection of level control valves across all levels. The various combinations are summarised in Table 25 in which the selected control valves, cumulative energy impact and cumulative rating are highlighted.

Table 25 - Summary of valve combinations and their associated cumulative energy impacts and ratings.

Combination	Selected valve locations	Cumulative energy impact (kWh)	Cumulative rating
Lower limit	Surface	9 371 630	20
C1	Surface, 27L	10 797 663	120
C2	Surface, 27L, 16L	12 128 508	208
C3	Surface, 27L, 16L, 24L	13 260 620	308
C4	Surface, 27L, 16L, 24L, 17L	14 216 538	396
C5	Surface, 27L, 16L, 24L, 17L, 26L	15 095 929	496
C6	Surface, 27L, 16L, 24L, 17L, 26L, 25L	15 842 121	596
C7	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L	16 421 004	696
C8	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L	16 996 900	784
C9	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L, 22L	17 556 864	872
C10	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L, 22L, 19L	18 066 185	960
C11	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L, 22L, 19L, 21L	18 542 850	1 048
C12	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L, 22L, 19L, 21L, 18L	18 951 882	1 136
C13	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L, 22L, 19L, 21L, 18L, 20L	19 340 941	1 224
C14	Surface, 27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L, 22L, 19L, 21L, 18L, 20L, 15L	19 686 162	1 312
Upper limit	27L, 16L, 24L, 17L, 26L, 25L, 28L, 23L, 22L, 19L, 21L, 18L, 20L, 15L	19 686 162	1292

The cumulative energy impact and the cumulative rating were then plotted on a scatter plot which compared the various hybrid control valve layouts at Shaft A. The lower limit and upper limit were also plotted on the scatter plot and a trendline was drawn between them. The trendline highlights the base energy impact and ranking which must be surpassed for a hybrid control valve layout to add value over and above a surface control valve alone and level valves across all levels. Thus, any hybrid control valve layout at Shaft A which was above the trendline achieved a greater energy impact and rating than the upper and lower limits. The resulting scatter plot of the various combinations and the upper and lower limits are presented in Figure 49.

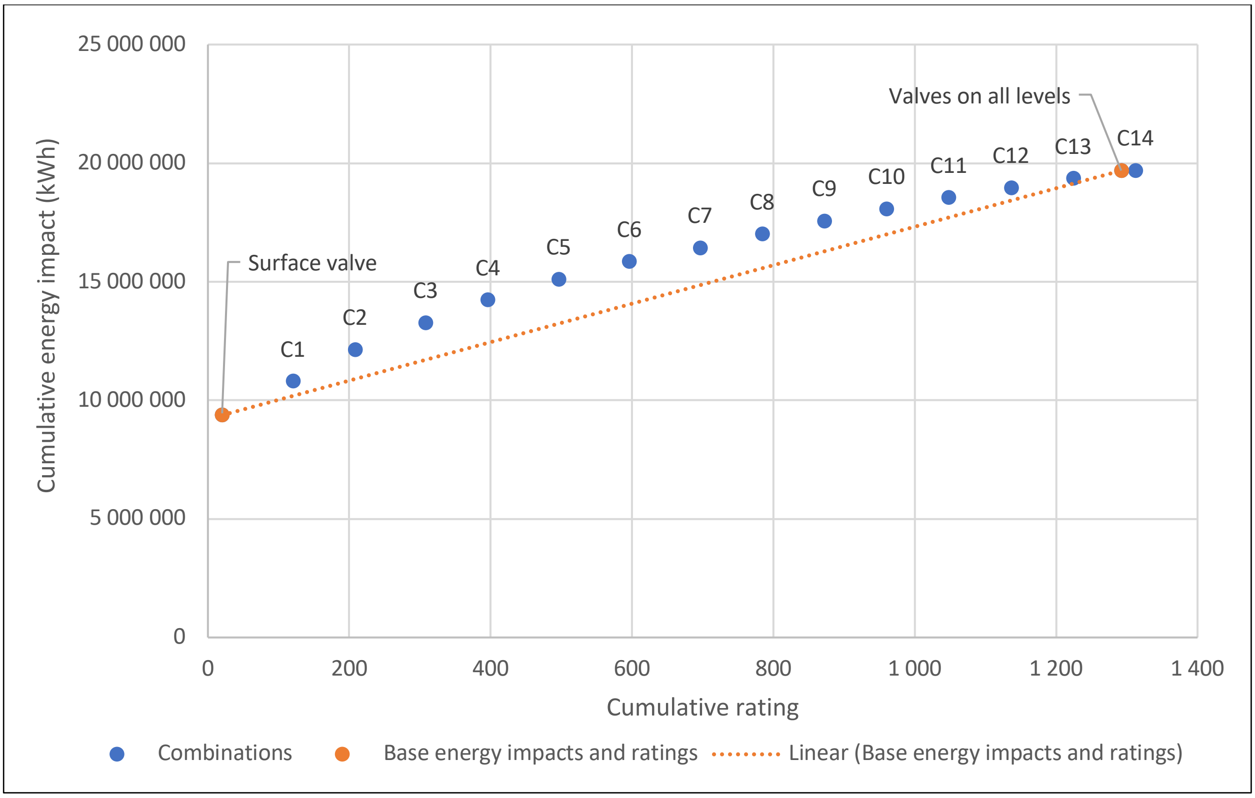


Figure 49 - Scatter plot of the cumulative energy impact versus the cumulative rating for the various hybrid control philosophy combinations compared to the upper and lower limit of a surface control valve alone and level valves across all levels.

It is clear from Figure 49 that all the possible combinations, except combination 14, add value over and above a surface control valve alone and level valves across all levels. Thus, any hybrid control valve layout from combination 1 to combination 13 were suitable choices. However, the goal of this study was to determine the optimal hybrid control valve layout.

To select the layout which maximised energy impact and minimised capital cost, project lead time, required maintenance and resource intensity, each combination was evaluated by comparing them with the base energy impact and rating trendline. The change in energy impact and rating were then determined for each of the hybrid control valve layouts. The two factors were then combined such that a total improvement factor could be determined. The results of the analysis process are highlighted in Table 26.

Table 26 - Comparison of the hybrid control valve combinations at Shaft A.

Combinations	Energy impact (kWh)	Cumulative rating	Energy impact improvement	Rating improvement	Total improvement
Surface valve	9 371 630	20	0	0	0
C1	10 797 663	120	615 142	76	615 142
C2	12 128 508	208	1 232 403	152	1 232 403
C3	13 260 620	308	1 553 624	192	1 553 624
C4	14 216 538	396	1 795 958	221	1 795 958
C5	15 095 929	496	1 864 459	230	1 864 459
C6	15 842 121	596	1 799 759	222	1 799 759
C7	16 421 004	696	1 567 752	193	1 567 752
C8	16 996 900	784	1 430 064	176	1 430 064
C9	17 556 864	872	1 276 444	157	1 276 444
C10	18 066 185	960	1 072 181	132	1 072 181
C11	18 542 850	1 048	835 262	103	835 262
C12	18 951 882	1 136	530 710	65	530 710
C13	19 340 941	1 224	206 186	25	206 186
C14	19 686 162	1 312	-162 178	-20	- 162 178
Valves on all levels	19 686 162	1 292	0	0	0

Analysis of the results presented in Table 26, clearly highlighted that the hybrid control valve layout which maximised the energy impact and minimised capital cost, required maintenance, project lead time and resource intensity was combination 5. Combination 5 consisted of the existing surface control valve in conjunction with control valves on Levels 16, 17, 24, 26 and 27. The expected annual energy impact of combination 5 was 15.1 GWh.

The selected hybrid control valve layout was then presented to the engineering and mining personnel at Shaft A. Upon presentation of the hybrid control valve layout, the decision was made to not install control valves on 16 Level and 17 Level as these areas were soon to be mined out and no mining activities would take place on these levels within the next two years. Therefore, the decision was made to rather place the control valves on 25 Level and 28 Level as mining activities were set to increase in these areas in the years to come.

This decision would result in a reduced immediate energy impact but would allow for greater long-term energy impact and long-term sustainability of the hybrid control philosophy. Thus, the selected hybrid control valve layout for Shaft A was the surface control valve in conjunction with control valves on Levels 24, 25, 26, 27 and 28. The expected annual energy impact of the selected hybrid control philosophy was estimated at 14.1 GWh, thus sacrificing 1 GWh of immediate energy improvement for greater long-term sustainability and long-term energy impact.

3.4 Hybrid control valve implementation

Once the optimal hybrid control philosophy at Shaft A had been selected by the relevant engineering and mining personnel, the next step was to implement the hybrid control philosophy. The implementation process began by understanding the valve control philosophy as described in Section 2.4.1. The control philosophy highlighted that the required infrastructure for each of the valve installation locations was as follows: a control valve, a suitable actuator, and a pressure sensor downstream of the control valve.

Each of the infrastructural upgrades was analysed according to the methodology described in Section 2.4.2. The selected control valves, actuators and pressure sensors were then purchased and installed at Shaft A. Additionally, the existing surface control valve was analysed to ensure that it was adequately specified for the flow and pressure conditions at Shaft A. Thereafter the theoretical pressure profiles were implemented according to the methodology described in Section 2.4.3. The details of each process are shared as follows.

3.4.1 Pressure control philosophy

It was noted in Section 3.2.1 that there was already an active surface control valve present at Shaft A. The pressure control methodology of the surface control valve was investigated, and it was found that the existing pressure control methodology matched the methodology recommended in Section 2.4.1. Therefore, no changes to the existing pressure control methodology had to be made.

When analysing the control philosophy, it was noted that control valves, actuators, and pressure sensors were required to implement the control philosophy on the level control valves. Thus, the required infrastructure had to be specified and installed such that the pressure control philosophy could be implemented accordingly.

3.4.2 Infrastructural upgrades

The following step in implementing the hybrid control philosophy was to specify which control valves, actuators and pressure sensors would be selected for the implementation of the hybrid control philosophy at Shaft A. Additionally, it was recommended during the initial infrastructure investigations in Section 3.2.1 that the surface control valve’s specifications be revisited to ensure that it was adequately specified for the flow and pressure conditions of Shaft A.

3.4.2.1 Control valve selection

The first area of investigation was the specification of the control valves which would be used for pressure control on Levels 24, 25, 26, 27 and 28. As per the methodology described in Section 2.4.2.1, the following information was collected for each of the control valve installation locations and used as input data to specify the control valves, using the NelProf software:

- The compressed air line size at the valve location
- The maximum supply pressure which will be experienced
- Upper and lower flow requirements which must be satisfied
- Upper and lower limits of the theoretical pressure profile for the valve in question

The gathered information for each of the control valve installation locations is summarised in Table 27.

Table 27 – Summary of the information used as input data for the NelProf simulation.

Control valve	Line size (mm)	Max pressure (kPa)	Upper flow (Nm³/h)	Lower flow (Nm³/h)	Upper pressure (kPa)	Lower pressure (kPa)
24 Level	300	600	14 000	3 100	400	200
25 Level	300	600	11 700	2 500	400	200
26 Level	250	600	13 000	2 700	400	200
27 Level	250	600	18 000	3 800	400	200
28 Level	250	600	15 000	3 200	400	200

Each possible control valve installation location was then simulated using the input conditions and the following factors were monitored, based on the requirements specified in the methodology in Section 2.4.2.1:

- Pressure drop over the valve when fully open
- Lower valve control limit
- Upper valve control limit
- Total control range

The simulation was run for two valve types, namely: 250 mm eccentric butterfly valves and segmented V-notch ball valves. Linear globe valves were excluded due to their excessive capital costs and Shaft A already had limited capital available. The results of the simulation are shown in Table 28.

Table 28 - Summary of the NelProf simulation results for each possible valve installation location.

Control valve	250 mm Butterfly valve				250 mm Segmented ball valve			
	ΔP Open (kPa)	Lower limit	Upper limit	Control range	ΔP Open (kPa)	Lower limit	Upper limit	Control range
24 Level	0.5	8%	19%	11%	4.00	24%	44%	20%
25 Level	0.5	7%	16%	9%	3.00	21%	39%	18%
26 Level	0.5	8%	17%	10%	3.00	22%	42%	20%
27 Level	0.5	10%	23%	12%	4.00	28%	50%	22%
28 Level	0.5	9%	20%	11%	3.00	25%	45%	21%

When analysing the results from Table 28, it was clear that the butterfly valve's lower limit of control was on or below the limit of 8%, as discussed in Section 2.4.2.1, and the control range was less than 12%. This indicated that smaller butterfly valves would be required. However, this was not possible due to the concerns of pressure drop when fully open. Thus, butterfly valves were not a feasible option for this application.

When analysing the segmented ball valve's results, the lower limit of control was well above the limit of 8%. Additionally, the control range for each valve was approximately 20%, indicating that the control valves were well suited to the current application and would be able to tolerate an increase and a decrease in compressed air demand and still be able to control accordingly. Therefore, the 250mm V-notch segmented ball valves were selected for the implementation of the theoretical pressure profiles from Level 24 to Level 28 at Shaft A.

Lastly, the existing surface control valve was also checked to ensure that it was adequately specified for the flow and pressure conditions at Shaft A. The current surface control valve is a 700 mm triple eccentric butterfly control valve. The input data used for the simulation regarding the existing surface control valve is highlighted in Table 29.

Table 29 - Input conditions to analyse the existing surface valve at Shaft A

Control valve	Line size (mm)	Max pressure (kPa)	Upper flow (Nm^3/h)	Lower flow (Nm^3/h)	Upper pressure (kPa)	Lower pressure (kPa)
Surface	700	600	140 000	40 000	400	200

The simulation was then run through the Nelprof simulation software, and the same factors used to monitor the level control valves were analysed. The simulation results are presented in Table 30.

Table 30 - Outputs of the NelProf simulation software for the existing surface valve at Shaft A

Control valve	ΔP Open (kPa)	Lower limit	Upper limit	Control range
Surface	4	5.5%	10.4%	4.9%

It is clear from the simulation results that the 700 mm triple eccentric butterfly control valve is not adequately specified for the flow and pressure conditions at Shaft A as it achieved a lower limit of 5.5% which exceeded the recommended lower limit of 8%, as discussed in Section 2.4.2.1. Additionally, the control range was extremely low at only 4.9%. It was therefore recommended that the surface control valve be re-evaluated and that an alternative control valve be put in its place. Unfortunately, due to capital constraints this was not completed at Shaft A at the time of writing.

3.4.2.2 Actuator selection

After the level control valves had been specified, the next step was to select a suitable actuator for each control valve application. In Section 2.4.2.2 it was concluded that pneumatic actuators would not be suitable due to their minimum pressure requirement of 300 kPa. Therefore, only electrical actuators were considered.

The instrumentation department at Shaft A had a standard for electric actuators used for control applications which had to be adhered to. The standard indicated that the actuator had to be an AUMA electrical actuator with a 525 V electric supply and 4-20 mA communications. Therefore, the flow, pressure and valve specifications for each valve location were given to Auma actuators and they supplied a suitable actuator which met the torque requirements of each level control valve.

3.4.2.3 Pressure sensor selection

The final step was to specify the pressure sensors which would be used for each level control valve. Fortunately, from 24 Level to 28 Level pressure sensors were already present, as determined previously in Section 3.2.1. The existing pressure sensors were installed downstream of the proposed valve installation locations and therefore no pressure sensors had to be selected or installed at Shaft A.

3.4.2.4 Installation of level valves at Shaft A

Once the required segmented ball valves and actuators arrived at the Shaft, they were installed from 24 Level to 28 Level and were commissioned accordingly. Figure 50 shows the segmented ball valve and Auma actuator which were installed on 25 Level. Two reducers had to be made up for the installation as the line size on 25 Level was 300 mm and the control valve was a 250 mm.

Figure 50 - Segmented V-notch ball valve installed on 25 level at Shaft A.

The Supervisory Control and Data Acquisition (SCADA) view for Shaft A highlights the installed level control valves and pressure sensors from 24 Level to 28 Level as shown in Figure 51. Once the control valves had been installed and commissioned, the system was now ready to implement the theoretical pressure profiles that were determined in Section 3.3.1.

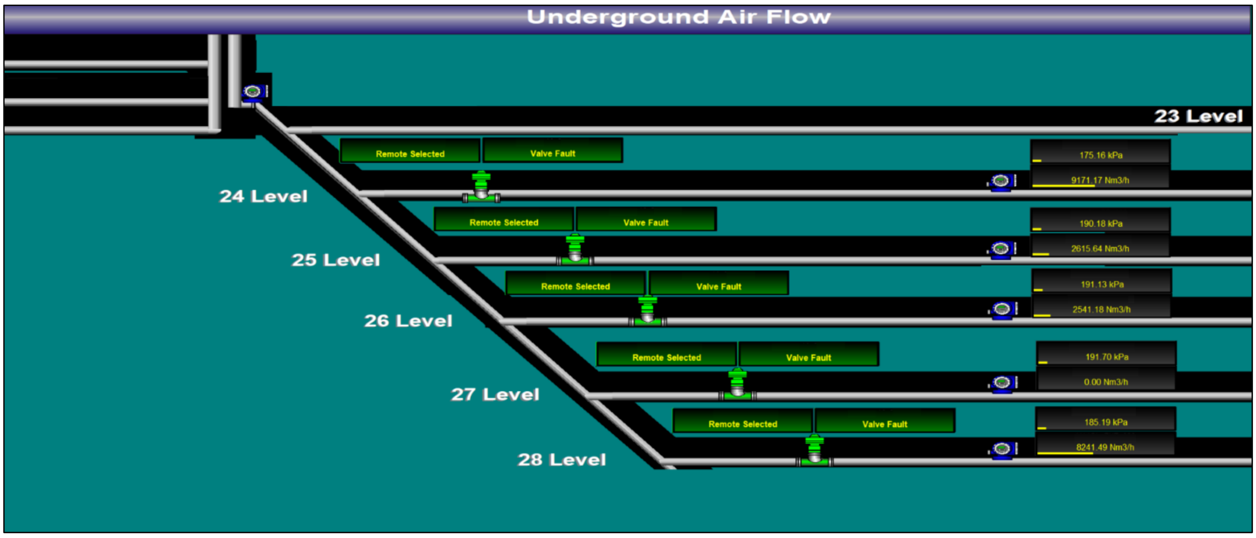


Figure 51 - SCADA view of Shaft A's compressed air reticulation, highlighting the level control valves installed from 24 Level to 28 Level.

3.4.3 Implementation of theoretical pressure profiles

The final step to fully commission the hybrid control philosophy at Shaft A was to implement the theoretical pressure profiles for each of the control valves as per the methodology discussed in Section 2.4.3. The implementation of the theoretical pressure profiles began with the surface control valve at Shaft A as it was already installed and operational. Once the level control valves had been installed and commissioned, the implementation of the level control valve's theoretical pressure profiles began.

Due to the nature of the underground compressed air network, the pressure setpoints were gradually decreased by 10 kPa twice a week, starting at the pressure baseline value. The setpoints were continuously decreased until the theoretical pressure profile was reached or until a complaint was received.

The control room at Shaft A was assigned with the responsibility to take note of any compressed air pressure complaints. When a complaint was received, the following information was noted such that the auditing team could perform a follow up audit of the area of concern:

- The time of the complaint
- The level from which the complaint originated
- The person reporting the issue and the compressed air equipment which was in use at the time

The control room would then relay the gathered information to the auditing team such that the auditing team could visit the area and determine the reason for the complaint. If the complaint was deemed valid, the pressure setpoint reductions were halted. However, if the complaint was deemed invalid, the setpoint reductions continued as normal. This process was repeated until the control valve setpoints had been reduced as far as reasonably possible.

3.5 Validation and verification

Once the hybrid control philosophy had been implemented at Shaft A, the final step was to validate the hybrid control philosophy's energy impact and determine the accuracy of the theoretical model which was developed in Section 3.3. The methodology developed in Section 2.5 was used to validate the hybrid control philosophy and verify the accuracy of the model.

The first area which was investigated was the energy impact of the hybrid control philosophy. This analysis was broken up into two sections, namely: the surface control valve optimisation and the implementation of the hybrid control philosophy. The analysis of the surface control valve optimisation was conducted first such that the energy impact of solely improving the surface control valve's pressure setpoints could be quantified. Thereafter, the additional impact of implementing the hybrid control philosophy, over and above the surface control valve optimisation, was quantified.

The final area of investigation was to verify the accuracy of the theoretical model. The methodology discussed in Section 2.5 was applied and the predicted energy impact was compared with the achieved energy impact, thus determining the accuracy of the theoretical model.

3.5.1 Energy impact of the hybrid control philosophy

Upon implementation of the hybrid control philosophy, the next step was to determine the energy impact which was achieved. During the initial investigation of Shaft A, it was determined that there was an existing surface control valve in place. As per the recommendation in Section 3.2.1, the existing shaft schedule and end-users' pressure requirements were analysed, and it was determined that the surface control valve's pressure setpoints could be further optimised to increase the surface control valve's energy impact.

Therefore, the analysis of the energy impact was separated in two parts. The first area of importance was to determine the energy impact of optimising the surface control valves pressure setpoints. Thereafter, the additional energy impact of implementing the hybrid control philosophy could be determined.

3.5.1.1 Energy impact of surface control valve optimisation

The energy impact of the improvement of the existing surface control valve's pressure setpoints was quantified using the methodology described in Section 2.5. During the development of the baselines in Section 3.2.3, the surface flow meter was used as the measurement boundary. Thus, the same measurement boundary was used to validate the impact of the surface control valve setpoint optimisation.

According to the methodology described in Section 2.5, two sets of information were required to determine the energy impact of the surface control valve setpoint optimisation, namely:

1. The surface compressed air flow baseline prior to the implementation of the setpoint changes.
2. The historic surface compressed air flow profiles following the implementation of the surface control valve setpoint optimisation.

The surface control valve setpoints were optimised approximately three months prior to the implementation of the hybrid control philosophy. Thus, these three months of historic data were gathered from the historian when determining the energy impact of the surface control valve setpoint optimisation. The baselines to which the historic data was compared, were developed previously in Section 3.2.3.

Using the collected information, the power impact profile of the surface control valve setpoint optimisation was determined as follows. The existing baseline, as developed in Section 3.2.3, was scaled according to the methodology described in Section 2.5. The scaled baseline was then compared to historic data measured by the surface flow meter after implementing the theoretical surface control valves pressure setpoints.

The difference between the scaled baseline and the historic compressed air flow was then calculated. This difference was multiplied by the power density of the compressed air network at Shaft A and the actual power impact profile was determined. This process was completed for weekdays and On-Saturdays. The analysis of Off-Saturdays and Sundays was completed using the same methodology, however the baselines were not scaled as the compressed air consumption during these periods was not production related.

The resulting flow reductions and associated power impact profiles for each of the modes of operation are presented in Figure 52, Figure 53, Figure 54 and Figure 55. Figure 52 presents the flow reduction and power impact for weekdays, Figure 53 presents the flow reduction and power impact for On-Saturdays, Figure 54 presents the flow reduction and power impact for Off-Saturdays and Figure 55 presents the flow reduction and power impact for Sundays.

The format used to present the flow reductions and power impacts is the same for Figure 52, Figure 53, Figure 54 and Figure 55. The grey line highlights the unscaled baseline which was developed in Section 3.2.3. The dashed light blue line highlights the scaled flow baseline, and the dotted dark blue line shows the actual flow profile upon implementation of the surface control valve optimisation.

The flow reduction, depicted by the difference between the scaled baseline and actual flow profile was then calculated and is shown as the light blue area between the scaled flow baseline and the actual flow profile. The difference was then multiplied by the power density of the compressed air network a Shaft A to calculate the power impact profile which is depicted by the blue bar chart. Any areas in which the flow increased rather than decreasing are highlighted by the orange area.

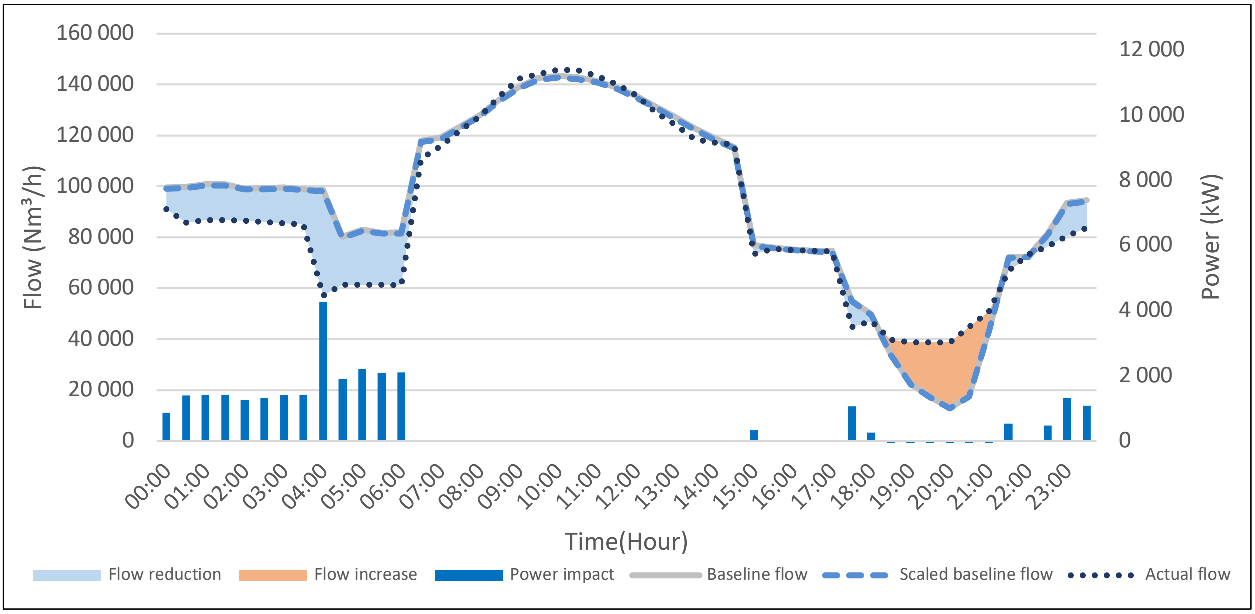


Figure 52 – The achieved weekday flow reduction and power impact upon optimisation of surface control valve pressure setpoints

When analysing achieved weekday flow reduction and power impact, shown in Figure 52, it is clear that the largest flow reduction was achieved throughout the cleaning shift and morning change of shift. A small flow reduction was also achieved during the afternoon shift, however this flow reduction was almost negligible.

Additionally, it was noted that there was an increase in flow during the blasting shift which was caused by the surface control valve not being isolated during the blasting shift. The frequency of the isolation of the surface control valve is entirely dependent on the mining personnel at Shaft A and is independent of the surface control valve pressure setpoints. Thus, the blasting shift was excluded from the power impact calculation.

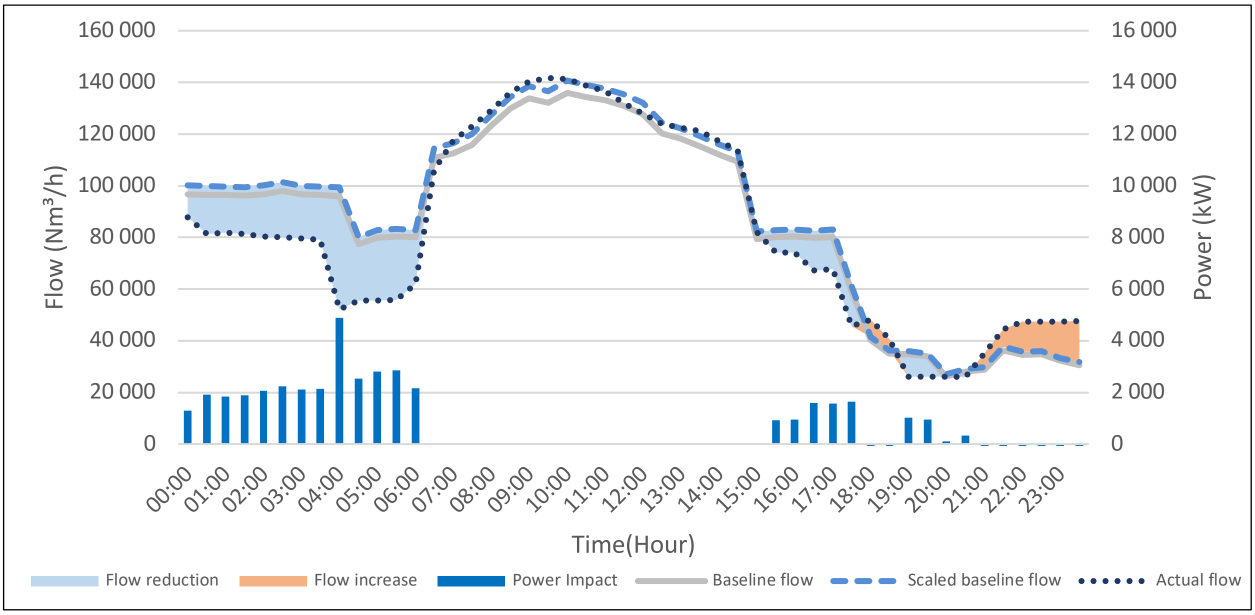


Figure 53 - The achieved On-Saturday flow reduction and power impact upon optimisation of surface control valve pressure setpoints.

Analysis of the impact of the surface control valve optimisation for On-Saturdays, as shown in Figure 53, revealed that the largest flow reduction was achieved during the cleaning shift and morning change of shift. The flow reduction during the afternoon shift was slightly higher than that of the weekday due to the lower pressure setpoints. Additionally, it was noted that there was a flow increase from 21:00 onwards. This was again caused by a change in the frequency of the isolation of the surface control valve during maintenance periods relative to the baseline.

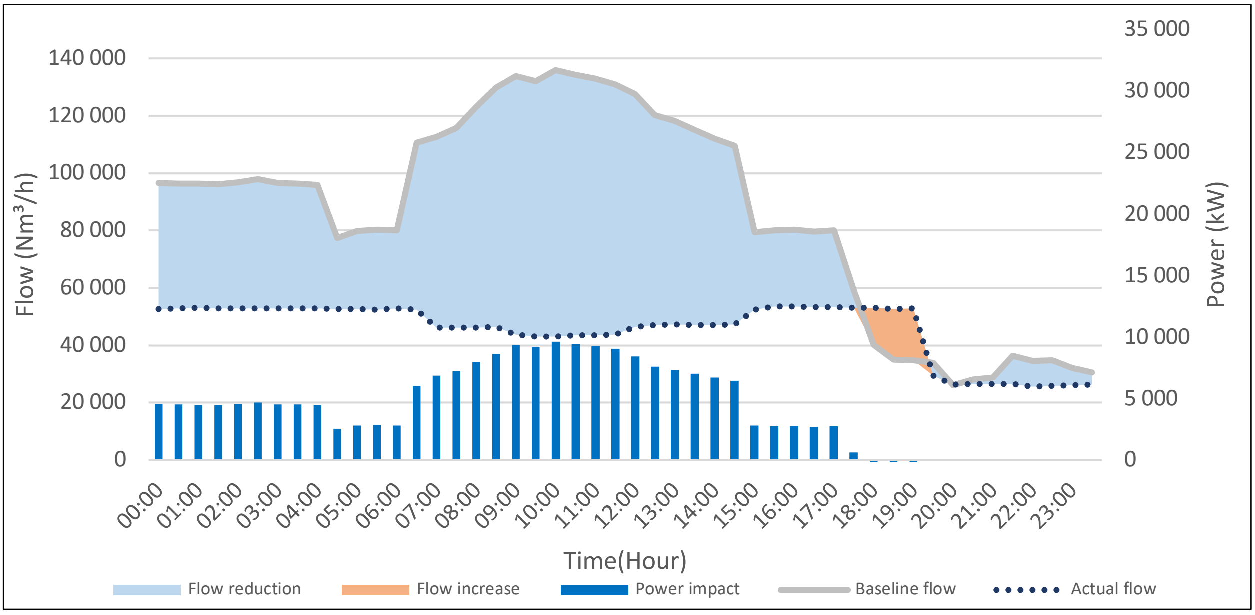


Figure 54 - The achieved Off-Saturday flow reduction and power impact upon optimisation of surface control valve pressure setpoints.

Analysis of the impact of the surface control valve optimisation for Off-Saturdays, as shown in Figure 54, highlighted a large flow reduction was achieved throughout majority of the 24-hour mining cycle, specifically from 00:00-18:00. The reason for this was that Shaft A originally had a single 24-hour production pressure profile which was used for all the modes of operation, leading to excessive compressed air consumption. Upon implementation of the theoretical pressure profile, Shaft A was supplied with 200 kPa throughout the 24-hour mining cycle, thus leading to the large reduction in compressed air consumption.

Additionally, it was noted that after 18:00 the actual consumption exceeds the baseline until approximately 19:00 where it dips below the baseline until 23:59. This was again caused by the isolation frequency of the surface control valve which is independent of the pressure setpoints. Therefore, this period was also excluded from the power impact calculation.

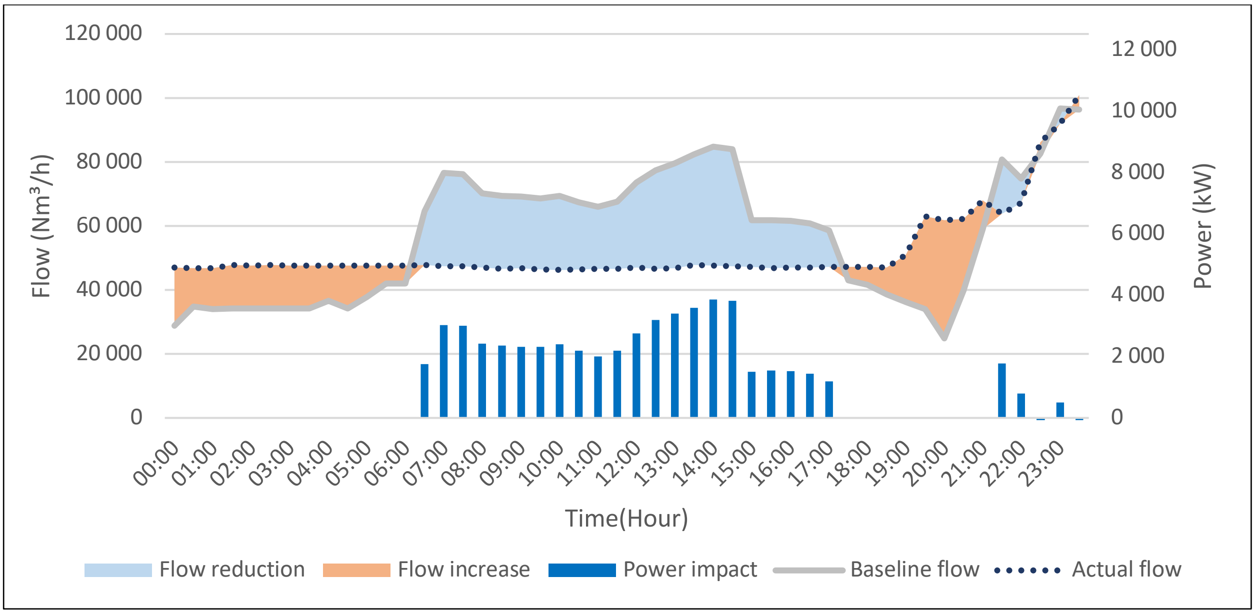


Figure 55 –The achieved Sunday flow reduction and power impact upon optimisation of surface control valve pressure setpoints.

Analysis of the surface control valve's optimised setpoints for Sundays, as shown in Figure 55, highlighted that a substantial flow reduction was achieved from 06:00-17:00. The excessive flows shown in the baseline from 06:00-17:00 were caused by the single 24-hour production pressure profile that was originally used by Shaft A. Thus, the optimised pressure setpoints resulted in a reduction in compressed air consumption for this period.

However, it is clear from Figure 55 that the flow had increased from 00:00-06:00 and 17:00-21:00. The cause of this was again the isolation frequency of the surface control valve. Therefore, these periods were excluded from the power impact calculation.

The effect of the optimised pressure profile can clearly be seen in Figure 55 as the actual consumption was steady throughout the day until the start of the cleaning shift on Sunday night. Therefore, when the isolation valve is not isolated, the optimised surface control valve setpoints lead to a significant reduction in compressed air consumption compared to the original 24-hour production pressure profile.

It is evident from Figure 52, Figure 53, Figure 54 and Figure 55 that the optimisation of the surface control valves pressure setpoints led to a significant reduction in flow across all the modes of operation. This in turn led to a power impact profile for each of the modes of operation. The power impact profiles were used to determine the daily energy impact as per the methodology discussed in Section 2.5. The daily energy impacts were then extrapolated to determine the annual energy impact of optimising the surface control valve's pressure setpoints. The resulting daily and annual energy impacts achieved for the various modes of operation are summarised in Table 31.

Table 31 - Summary of the daily and annual energy impact achieved by optimising the surface control valves pressure setpoints.

Mode of operation	**Number of days**	**Daily energy impact (kWh)**	**Annual energy impact (kWh)**
Weekday	252	14 045	3 539 403
On-Saturday	38	19 339	734 867
Off-Saturday	12	103 565	1 242 785
Sunday	50	27 987	1 399 357
Totals	352	164 936	6 916 411

It is clear from Table 31 that the largest daily energy impact was achieved on Off-Saturdays and the lowest daily energy impact was achieved on weekdays. However, due to the large number of weekdays in a year the annual energy impact of the weekdays surpassed all the other modes of operation, contributing an annual energy impact of 3.54 GWh.

A total annual energy impact of 6.92 GWh was achieved by optimising the surface control valve's pressure setpoints at Shaft A. This is a significant energy impact, especially considering that it came at no additional capital cost to Shaft A.

It is important to note the annual energy impact in Table 31 is solely determined by means of the flow reduction at Shaft A. In order for the energy impact to be realised, it is critical that effective supply side management is implemented on Shaft A's compressed air network as highlighted previously in Section 1.6.

3.5.1.2 Energy impact of hybrid control philosophy

Upon completion of analysing the annual energy impact of the surface control valve, the annual energy impact of the hybrid control philosophy at Shaft A was determined using the methodology discussed in Section 2.5. The analysis procedure remained the same as the one used for the surface control valve. The measurement boundary was defined as the surface flow meter at Shaft A and the baseline developed in Section 3.2.3 was used to validate the impact of the hybrid control philosophy. Thus, the energy impact represents the total energy impact of the surface control valve in conjunction with the level control valves.

The total energy impact of the hybrid control philosophy was then subtracted from the optimised surface control valve's energy impact, as determined in Section 3.5.1.2, to quantify the additional energy impact of the hybrid control valve layout alone. Therefore, it was assumed that the energy impact of the surface control valve remained the same during the period in which the hybrid control philosophy was implemented.

It was also assumed that the hybrid control valve layout would have no energy impact during Off-Saturdays and Sundays as the level control valves' theoretical pressure profiles did not differ from the surface control valve's pressure setpoints for these periods. Thus, the energy impact of the hybrid control philosophy was only determined for weekdays and On-Saturdays.

When analysing the impact of the hybrid control valve layout, three months of historic data was extracted from the historian. The data was extracted for the three months after the hybrid control philosophy was fully implemented and the pressure setpoints for each of the control valves had been finalised.

Once the historic data had been extracted, the scaled baselines for weekdays and On-Saturdays were determined. The scaled baselines were then compared with the historic data to determine the flow reduction which was achieved by the hybrid control valve layout. The flow reductions were then multiplied by the power density of the compressed air network at Shaft A to determine the power impact profiles.

The resulting flow reductions and associated power impact profiles for the weekdays and On-Saturdays are presented in Figure 56 and Figure 57. Figure 56 presents the flow reduction and power impact profiles of the hybrid control philosophy for weekdays, Figure 57 presents the flow reduction and power impact profiles for On-Saturdays.

The format used to present the flow reductions and power impacts is the same for Figure 56 and Figure 57. The grey line highlights the unscaled baseline which was developed in Section 3.2.3. The dashed light blue line highlights the scaled flow baseline, and the dotted dark blue line shows the actual flow profile upon implementation of the hybrid control philosophy.

The difference between the scaled baseline and actual flow profile was then calculated and is shown as the light blue area between the scaled flow baseline and the actual flow profile. The difference was then multiplied by the power density of the compressed air network at Shaft A to calculate the power impact profile which is depicted by the blue bar chart. Any areas in which the flow increased rather than decreasing are highlighted by the orange area.

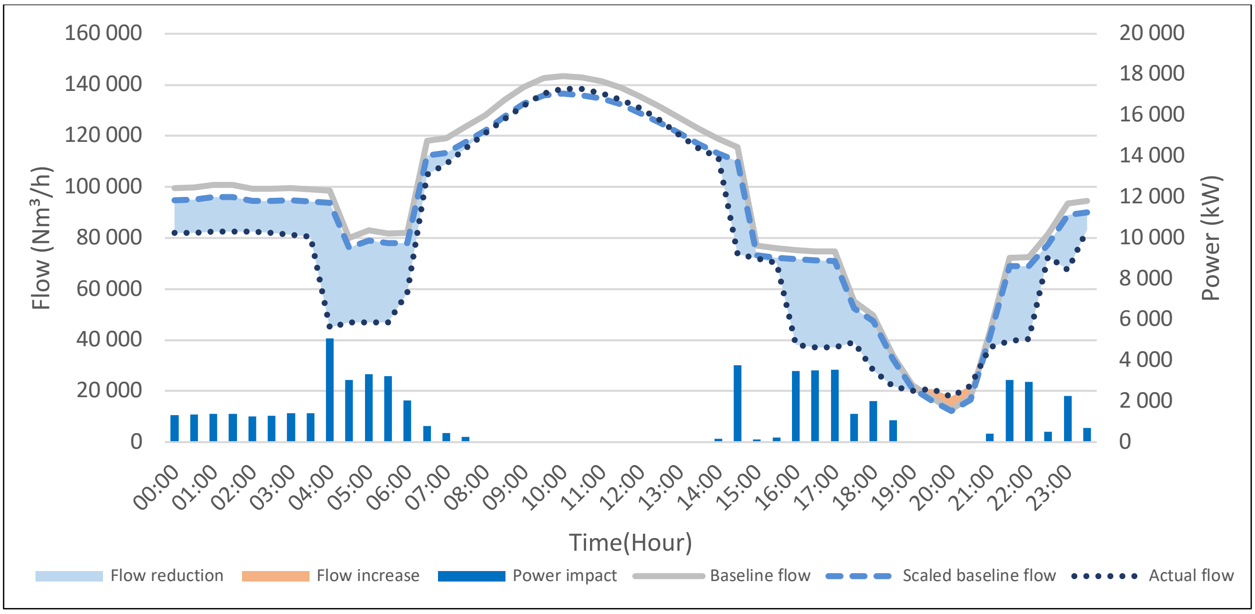


Figure 56 - The achieved weekday flow reduction and power impact upon implementation of the hybrid control philosophy at Shaft A.

When analysing the flow reduction and power impact for weekdays, as shown in Figure 56, there is a clear flow reduction for all periods outside of the drilling shift and blasting shift. The level control valves reduced the flow significantly from 14:00-23:59 due to the pressure on Levels 24 to 28 being throttled further than the surface control valve's pressure setpoints.

Additionally, there were slight reductions at the start and end of the drilling shift when compared to the baseline. The reductions were a result of matching the level's pressure profiles with the level schedules at Shaft A, something which is not possible with a surface control valve alone. This effect would be further exaggerated on a Shaft where there are large differences in the level schedules.

A slight increase in flow was noted during the blasting shift. As stated previously in Section 3.5.1.1 this was due to the isolation frequency of the surface control valve and was excluded from the power impact calculation.

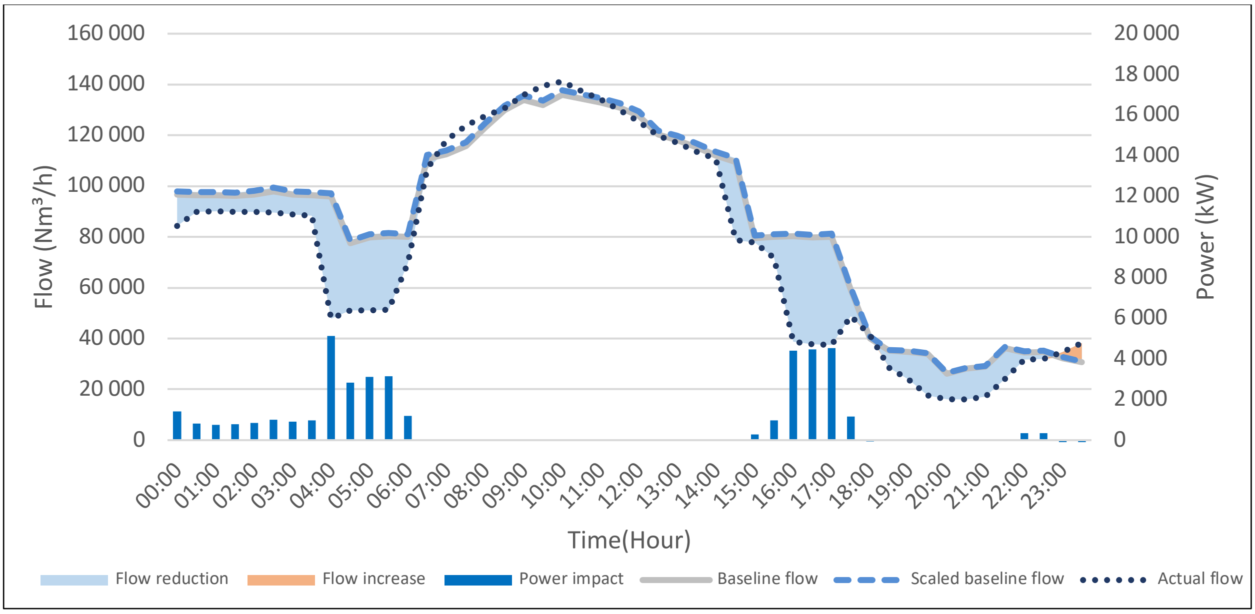


Figure 57 - The achieved On-Saturday flow reduction and power impact upon implementation of the hybrid control philosophy at Shaft A.

Analysis of the flow reduction and power impact for On-Saturdays, as shown in Figure 57, also revealed a flow reduction across all areas outside of the drilling shift. The most notable flow reduction was achieved in the afternoon shift which again was caused by the level control valves throttling the pressure further than the surface control valve.

As with the analysis of the weekday profile in Figure 56, a slight flow reduction was noted at the end of the drilling shift due to the schedules of the levels at Shaft A. Additionally, it was noted that the flow had been reduced during the blasting shift relative to the baseline. This was again due to the isolation frequency of the surface control valve and was excluded from the power impact calculation.

It is clear from Figure 56 and Figure 57 that the hybrid control philosophy further reduced the compressed air consumption when compared to the surface control valve alone. Using the power profiles developed in Figure 56 and Figure 57, the daily energy impact of the hybrid control philosophy was determined for weekdays and On-Saturdays. The daily energy impacts were then extrapolated to determine the annual energy impact of the hybrid control philosophy. The resulting daily and annual energy impacts are presented in Table 32. As stated previously in this section, it was assumed that the energy impacts for Off-Saturdays and Sundays would remain unchanged.

Table 32 - Summary of the daily and annual energy impact achieved upon implementation of the hybrid control philosophy at Shaft A.

Mode of operation	Number of days	Daily energy impact (kWh)	Annual energy impact (kWh)
Weekday	252	29 116	7 337 116
On-Saturday	38	23 592	896 487
Off-Saturday	12	103 565	1 242 785
Sunday	50	27 987	1 399 357
Totals	352	184 260	10 875 745

From Table 32 it is clear that the hybrid control philosophy had a significant energy impact for weekdays and On-Saturdays when compared to the surface control valve alone. The hybrid control philosophy achieved a total annual energy impact of 10.88 GWh.

The hybrid control philosophy's energy impacts could then be compared with the annual energy impacts of the surface control valve alone. The comparison of the annual energy impacts of the optimised surface control and the hybrid control is presented in Figure 58.

The grey bar chart presents the annual energy impact achieved by optimising the existing surface control valve at Shaft A. The blue bar chart presents the annual energy impact achieved by implementing the hybrid control philosophy at Shaft A. The difference between the blue and grey bar chart highlights the additional annual energy impact which was achieved by implementing the hybrid control philosophy.

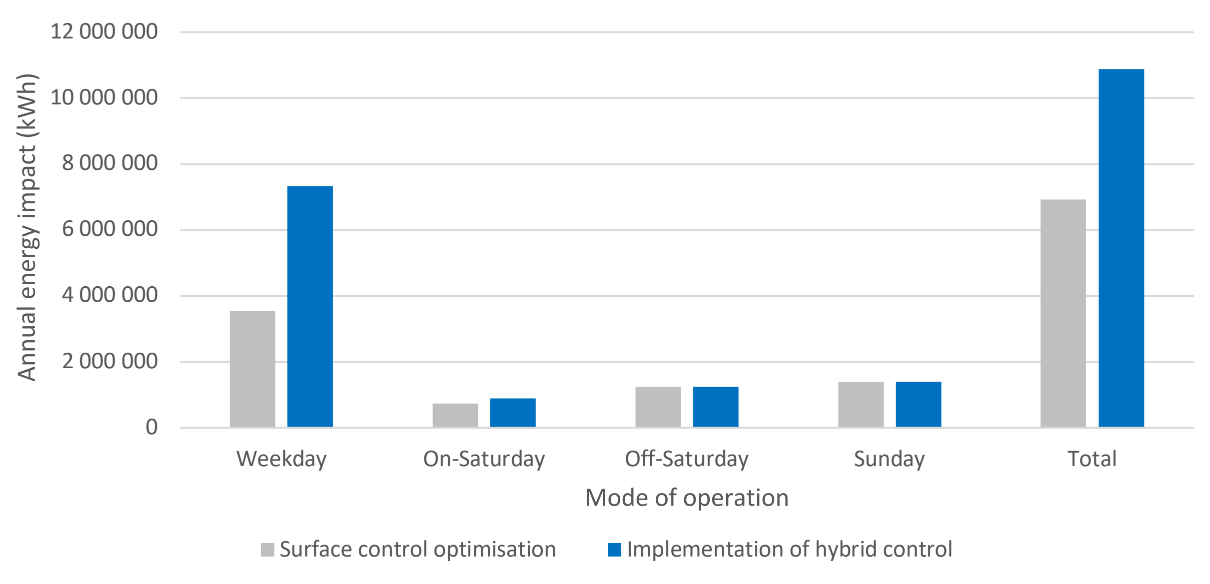


Figure 58 – Annual energy impact achieved by optimising the surface control valve versus the annual energy impact of implementing the hybrid control philosophy at Shaft A.

When comparing the surface control valve and the hybrid control philosophy, the most notable increase in energy impact was achieved for the weekdays. The hybrid control philosophy increased the annual weekday energy impact from 3.54 GWh to 7.34 GWh resulting in an additional annual weekday energy impact of 3.8 GWh. A minor annual energy impact increase of 161 MWh was achieved for On-Saturdays.

The cumulative effect of the weekdays and On-Saturdays upon implementation of the hybrid control philosophy increased total annual energy impact from 6.92 GWh to 10.88 GWh. Thus, the additional annual energy impact of the hybrid control philosophy was 3.96 GWh.

3.5.2 Verification of theoretical model

The final step of the methodology discussed in Section 2.5 was to verify the accuracy of the theoretical model which was used to determine the theoretical energy impact of the hybrid control philosophy. To quantify the accuracy of the theoretical model, the theoretical energy impact of the hybrid control philosophy for Shaft A, determined in Section 3.3.3, was compared with the actual energy impact which was achieved in Section 3.5.1.

The analysis was split into two sections. The first analysed the accuracy of the theoretical model's prediction for the optimisation of the surface control valve, further referred to as Case 1. The second analysed the accuracy of the theoretical model's prediction of the additional energy impact brought about by the hybrid control philosophy, further referred to as Case 2. The resulting accuracies for Case 1 and Case 2 are highlighted in Table 33.

Table 33 - Summary of the accuracies of the theoretical models predicted annual energy impact versus the achieved annual energy impact for Case 1 and Case 2.

Case	Theoretical models energy impact prediction (kWh)	Achieved energy impact (kWh)	Difference (kWh)	Percentage error (%)
Case 1	9 371 630	6 916 411	2 455 219	35.5
Case 2	4 762 611	3 959 334	803 277	20.3

It is clear from Table 33 that the percentage errors were rather high, and it appeared that the theoretical model did not predict the energy impact of implementing the theoretical pressure profiles within a reasonable accuracy. However, the high percentage errors were due to the fact that the theoretical pressure profiles and the implemented pressure profiles were not equal.

During the implementation of the theoretical pressure profiles in Section 3.4.3, not all the theoretical pressure profiles could be achieved due to complaints from underground end-users.

This resulted in a discrepancy between the theoretical flow reduction and the actual flow reduction, leading to the difference in the theoretical energy impact and the actual energy impact.

Therefore, the theoretical energy impacts for Case 1 and Case 2 had to be updated such that the theoretical pressure profiles aligned with the pressure profiles that were actually implemented. This reduced the error of the theoretical flow profiles versus the actual flow profiles which in turn reduced the error of the energy impacts.

For illustrative purposes, the adjustment process discussed above is performed for the optimisation of the surface control valve for weekdays. The difference in the baseline weekday pressure profile, theoretical weekday pressure profile and the achieved weekday pressure profile is highlighted in Figure 59.

The grey line presents the baseline pressure profile, the dashed light blue line shows the theoretical pressure profile, and the dark blue dotted line shows the implemented pressure profile. The discrepancy between the theoretical pressure profile and the implemented pressure profile is highlighted by the red area.

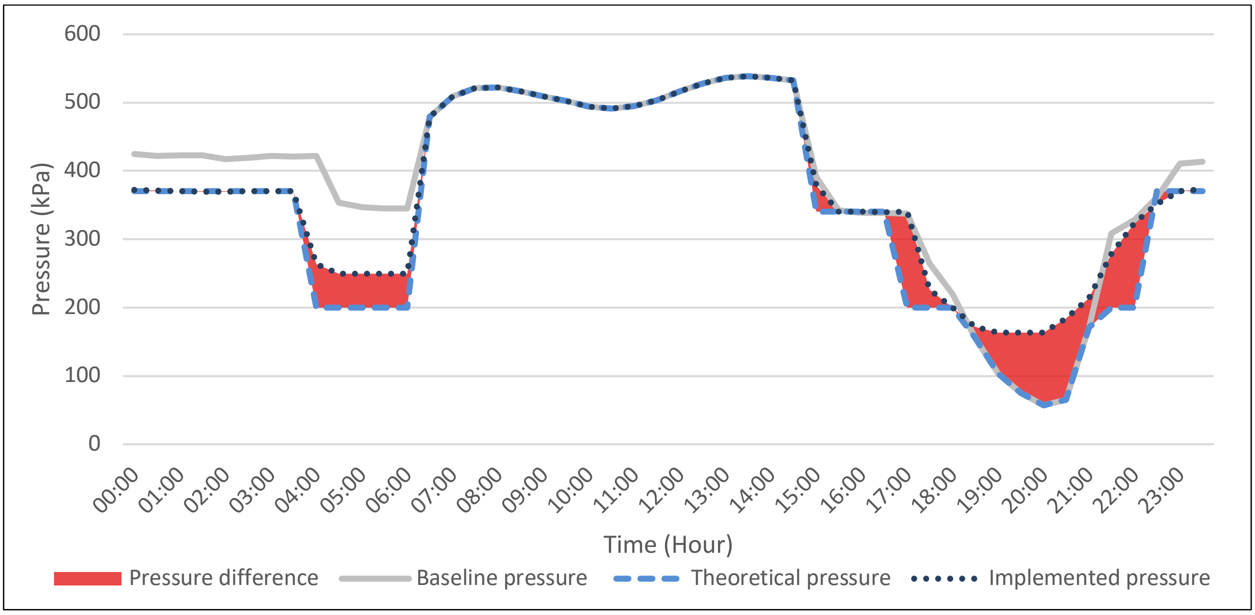


Figure 59 - Comparison of the baseline weekday pressure profile, theoretical weekday pressure profile and the implemented weekday pressure profile for the surface control valve optimisation.

The difference between the theoretical weekday pressure profile and the implemented weekday pressure profile causes the discrepancy between the theoretical weekday flow profile and the actual weekday flow profile. This in turn leads to the error when predicting the annual energy impact. The difference in the baseline weekday flow profile, theoretical weekday flow profile and the achieved weekday flow profile is highlighted in Figure 60.

The grey line presents the baseline flow profile, the dashed light blue line shows the theoretical flow profile, and the dark blue dotted line shows the actual flow profile. The discrepancy between the theoretical flow profile and the actual flow profile, which is leading to the error of the theoretical weekday annual energy impact, is highlighted by the red area.

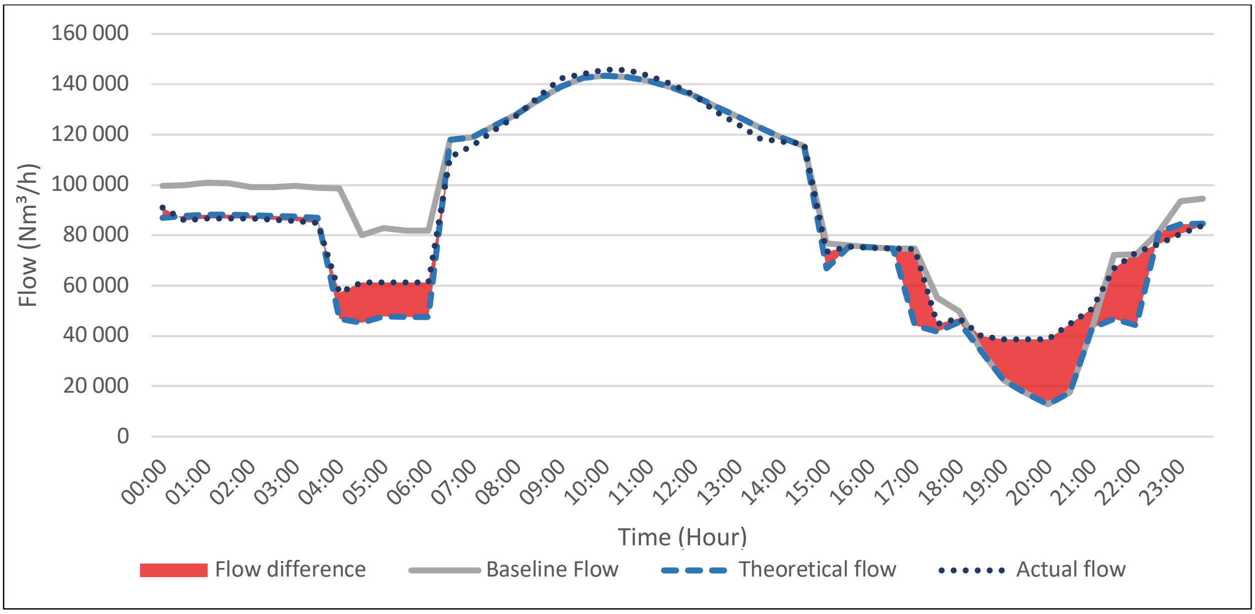


Figure 60 - Comparison of the baseline weekday flow profile, theoretical weekday flow profile and the actual weekday flow profile for the surface control valve optimisation.

It is clear from Figure 59 and Figure 60 that there is a correlation between the difference in pressure profiles and the difference in flow profiles. To account for the discrepancy between the theoretical flow profile and the actual flow profile, the implemented pressure profile as shown in Figure 59 was used to redevelop the theoretical flow profile. Thus, the theoretical flow was now calculated such that it matched the pressure setpoints which were actually implemented, further referred to as the adjusted theoretical flow. The difference between the baseline weekday flow, adjusted weekday theoretical flow and actual weekday flow is highlighted in Figure 61.

The grey line presents the baseline flow profile, the dashed light blue line shows the adjusted theoretical flow profile, and the dark blue dotted line shows the actual flow profile. The discrepancy between the adjusted theoretical flow profile and the actual flow profile, is highlighted by the red area.

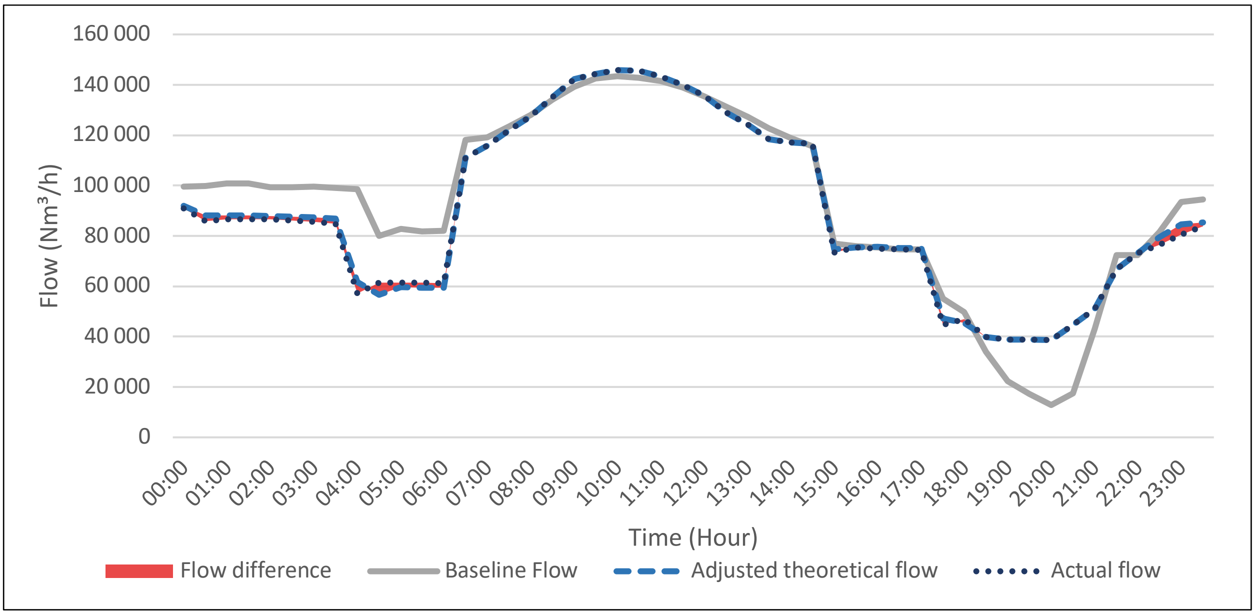


Figure 61 - Comparison of the baseline weekday flow profile, adjusted theoretical weekday flow profile and the actual weekday flow profile for the surface control valve optimisation.

It is clear from Figure 61 that adjusting the theoretical flow profile to match the implemented pressure profile has greatly reduced the discrepancy between the theoretical flow profile and actual flow profile, thus reducing the error between the theoretical weekday energy impact and the actual weekday energy impact.

The process described above was applied to the weekdays, On-Saturdays, Off-Saturdays and Sundays for both Case 1 and Case 2. The updated theoretical annual energy impacts for Case 1 and Case 2 were then used to redetermine the percentage error of the theoretical model as highlighted in Table 34.

Table 34 - Summary of the accuracies of the adjusted theoretical models predicted annual energy impact versus the achieved annual energy impact for Case 1 and Case 2.

Case	Theoretical models energy impact prediction (kWh)	Achieved energy impact (kWh)	Difference (kWh)	Percentage error (%)
Case 1	7 171 207	6 916 411	254 793	3.7
Case 2	4 043 051	3 959 334	83 716	2.1

The updated theoretical energy impacts drastically improved the percentage error of the theoretical model. Case 1's percentage error decreased from 35.5% to 3.7% and Case 2's percentage error decreased from 20.3% to 2.1%. Therefore, when the theoretical model is updated such that it represents the state of the pressure setpoints upon implementation, the theoretical annual energy impact can be predicted with an error of less than 5%.

3.6 Conclusion

In Chapter 3 the feasibility of implementing a hybrid control philosophy on a deep-level platinum mine in the North West province of South Africa was investigated. The analysis methodology developed in Chapter 2 was applied to Shaft A such that the optimal hybrid control philosophy could be identified and selected.

Initial investigations of the compressed air reticulation at Shaft A revealed that an existing surface control valve was in place and operational. Additionally, 14 active mining levels on which selected level control could be implemented were identified. The necessary information to determine the possibility of implementing level control on each of the identified areas was gathered and baselines of the existing compressed air flows and pressures were developed.

The minimum pressure requirements of the authorised compressed air end-users were then determined for each of the identified levels. This information was combined with the shaft schedule at Shaft A such that theoretical 24-hour pressure profiles could be developed per level for the various modes of operation at Shaft A.

Using the gathered information, the theoretical energy impact of implementing the theoretical 24-hour pressure profiles was determined. This analysis was split into two sections. The first analysed the energy impact of optimising the existing surface control valves pressure setpoints and thereafter the additional benefit of implementing various hybrid control philosophies was determined.

The various hybrid control philosophies were then critically analysed and the hybrid control philosophy which maximised the energy impact and minimised the capital cost, project lead time, required maintenance and resource intensity was identified and selected. Thereafter, the necessary infrastructural upgrades to implement the selected hybrid control philosophy at Shaft A were selected and commissioned such that the identified theoretical 24-hour pressure profiles could be applied.

The annual energy impact of the hybrid control philosophy at Shaft A was then validated. A total annual energy impact of 10.88 GWh was achieved of which 3.96 GWh was contributed by the implementation of the hybrid control philosophy. The actual results were then compared with the theoretical models' predictions, resulting in an error of less than 5%, thus verifying the accuracy of the theoretical model.

CHAPTER 4 - CONCLUSION

In Chapter 4, the dissertation presented is summarised. Chapter 4 begins with a summary of the study in which the details of each chapter are discussed, and the study objectives are identified. Thereafter, the study objectives are analysed to determine if they have been effectively addressed. Lastly, future recommendations are made based off the findings of the study.

4.1 Summary of the study

The purpose of Section 4.1 is to summarise Chapters 1 to 3. Each Chapter is summarised such that the critical information found in each chapter is clearly conveyed. Chapter 1 is summarised first such that the problem statement is clearly highlighted, and the deduction of the study objectives is understood. Thereafter, Chapter 2 is discussed, and the methodology used to address the problem statements identified in Chapter 1 is summarised. Lastly, the case study on which the methodology was implemented is discussed and the results of the implemented methodology, as per Chapter 3, are summarised.

Chapter 1 commenced by investigating the efficiencies of industrial compressed air systems across the globe and in the South African mining industry. The literature analysis revealed that the efficiencies of the compressed air systems in question were as low as 10%. The low operational efficiencies were attributed to high baseload energy consumptions caused by poor compressed air management protocols as well as misappropriation of compressed air.

The low efficiencies, extensive size and complexity of the South African mining industry's compressed air systems highlighted the mining industry as a prime candidate for energy efficiency initiatives. The existing energy efficiency initiatives implemented on the South African mining industry's compressed air networks identified that a 75% energy reduction can be achieved through effective implementation of supply side management and demand side management. However, it was noted that 70% of the total energy reduction could be achieved through demand side management alone. Therefore, the primary focus of the study was to investigate the feasibility of improving existing demand side management initiatives.

In order to understand the workings of the various demand side management initiatives, background was given on the compressed air systems used in the South African mining industry. The background explained the general layout of compressed air networks, the authorised and unauthorised compressed air end-users, the pressure requirements of the authorised end-users and the schedule on which the authorised end-users operate. Further investigations revealed that majority of the compressed air wastage in deep-level mining operations was caused by unauthorised compressed air end-users whose wastage was directly proportional to the pressure supplied to them.

Therefore, demand side management initiatives focused on reducing the negative impact of the unauthorised compressed air end-users by limiting the pressure supplied to them. Investigation of the existing DSM initiatives revealed four commonly used methodologies, namely: Surface control valves, level control valves, crosscut isolation valves and leak management.

In order for the respective DSM initiatives to be successful and sustainable in the South African mining industry, the initiatives had to have a low capital cost, a moderate project lead time, low maintenance requirements, low resource intensities and a high energy impact. The two initiatives which met these requirements were surface control valves and level control valves across all levels.

Analysis of existing literature revealed that surface control valves achieved a moderate energy impact and had low capital costs, shorter project lead times, required less maintenance and had lower resource intensities whilst level control valves achieved a high energy impact but resulted in increased capital costs, longer project lead times, required additional maintenance and had higher resource intensities. Therefore, a hybrid control philosophy was proposed in which a surface control valve is used in conjunction with selected level valves. The goal of the proposed hybrid control philosophy was to increase the energy impact compared to that of a surface control valve alone whilst decreasing the capital cost, project lead time, required maintenance and resource intensities when compared to level control valves across all levels.

Investigation of existing DSM initiatives revealed that a hybrid control philosophy had not been previously implemented on a compressed air system. Thus, the objective of this study was to develop an analysis methodology which could be used to select the optimal hybrid control valve layout. Chapter 1 was concluded by highlighting the selected study objectives as follows:

1. Develop a methodology which can be used to determine the hybrid control philosophy which:
    a. Maximises the energy impact of the DSM initiative
    b. Minimises the capital cost, required maintenance, project lead time and resource intensity.
2. Implement and verify the hybrid control philosophy analysis methodology.

In Chapter 2, an analysis methodology was developed to address the study objectives identified in Chapter 1. The methodology was written such that it was applicable to any deep-level mining compressed air network. The analysis methodology was comprised of multiple sub-methodologies used to: analyse the existing compressed air network, theoretically analyse the various hybrid control valve layouts, select the optimal hybrid control philosophy, implement the selected hybrid control philosophy, validate the achieved energy impact, and verify the accuracy of the theoretical model.

The analysis methodology began by investigating the existing compressed air network of the deep-level mining operation in question. The sub-methodologies used to determine the compressed air network reticulation, existing control valves, available instrumentation, compressed air distribution, baseline development, end-user pressure requirements and shaft schedule were presented.

The initial investigation gathered the information required to conduct the theoretical analysis of each possible hybrid control philosophy. The gathered information was used to develop the theoretical 24-hour pressure profiles for each of the possible control valve installations. The 24-hour pressure profiles were then used to determine the theoretical energy impact of each of the possible control valve installations.

Thereafter, each of the possible control valve installations were assigned a rating according to their cumulative impact on capital cost, required maintenance project lead time and resource intensity. The energy impacts and ratings were then used to develop various hybrid control philosophy combinations. The various hybrid control philosophies were then critically analysed to determine the optimal hybrid control philosophy which maximised the energy impact whilst minimising the capital cost, required maintenance, project lead time and resource intensity.

Once the optimal hybrid control philosophy had been selected, the pressure control methodology used for each of the control valves was highlighted. In order to implement the pressure control philosophy, control valves, actuators and pressure sensors were required. The various control valve, actuator and pressure sensor options were then presented, and the methodology used to select the optimal infrastructure for the mining operation in question was discussed. Once the infrastructural upgrades had been installed and commissioned, the process used to implement the 24-hour theoretical pressure profiles at the mining operation in question was highlighted.

Lastly, the methodology used to validate the impact of the hybrid control philosophy was developed. The achieved energy impact could then be used to verify the accuracy of the model.

In Chapter 3, the analysis methodology developed in Chapter 2 was applied to a case study. The case study in question was a deep-level platinum mine located in the North West province of South Africa, referred to as Shaft A.

During the analysis of the existing compressed air infrastructure at Shaft A, it was noted that a surface control valve was already installed and operational at the shaft. Additionally, 14 active mining levels were identified on which level control valves could be installed. The information required to determine the possibility of implementing a level control valve at each of the identified levels was gathered and a baseload test was performed to determine the compressed air distribution from surface to each of the active mining levels.

Baselines of Shaft A's surface flow and surface pressure profiles for the various modes of operation were then developed, according to the IPMVP standard, prior to the implementation of the hybrid control philosophy. The developed baselines were then extrapolated to generate flow and pressure baselines for each of the active mining levels, using the baseload flow fractions. The developed baselines would later be used for two purposes. The first was to determine the theoretical energy impact of the various hybrid control valve layouts and the second was to validate the impact of the selected hybrid control philosophy upon implementation.

Thereafter, the authorised end-users' pressure requirements and shaft schedule of Shaft A were determined by consulting with the relevant mining and engineering personnel. The gathered information was then combined to generate theoretical 24-hour pressure profiles for each of the possible control valve installation locations.

The theoretical energy impact for each of the identified control valve installation locations was then determined using the baselines and theoretical 24-hour pressure profiles by means of the ideal gas law. The theoretical energy impact analysis at Shaft A was split into two sections. The first section analysed the energy impact of optimising the existing surface control valve's pressure setpoints to match the identified theoretical 24-hour pressure profiles. The second section analysed the additional energy impact that could be achieved for each of the possible level control valve installation locations.

The surface control valve and possible level control valves were then rated in a weighted decision matrix such that the cumulative impact of the capital cost, project lead time, required maintenance and resource intensities per valve could be determined. Thus, rating the surface control valve and possible level control valves on how well they met Shafts A's requirements for each of the above-mentioned factors.

Lastly, the surface control valve and possible level control valves were ranked according to their energy impact and various hybrid control philosophy combinations were generated. The cumulative energy impact and rating of each hybrid control philosophy combination was then critically analysed and the hybrid control philosophy which maximised the cumulative energy impact and minimised the cumulative rating, relative to a surface control valve alone and level valves across all levels, was determined. Upon presenting the theoretical model's proposed hybrid control valve layout to the engineering and mining personnel of Shaft A, it was decided to select a slightly different hybrid control valve layout which would maximise the long-term energy impact and sustainability of the hybrid control philosophy based on plans for future expansion.

Once the optimal hybrid control philosophy for Shaft A had been selected, the required infrastructural upgrades were analysed and the control valves, actuators and pressure sensors were specified. The level control valves were then installed and commissioned at Shaft A and the theoretical 24-hour pressure profiles were implemented on the surface control valve and level control valves accordingly.

Upon implementation of the theoretical 24-hour pressure profiles, the energy impact of the hybrid control philosophy was validated. The process of validation was done in two steps. The first step critically analysed the energy impact of optimising the surface control valve's setpoints alone. Thereafter, the second step critically analysed the additional benefit brought about by the implementation of the hybrid control philosophy.

The actual results of the case study at Shaft A showed that an annual energy impact of 6.92 GWh was achieved by optimising the pressure setpoints of the surface control valve alone and an additional annual energy impact of 3.96 GWh was achieved by implementing the selected hybrid control philosophy, resulting in a total energy impact of 10.88 GWh. Therefore, validating that a hybrid control philosophy can be used to maximise the energy impact whilst minimising capital cost, required maintenance, project lead time and resource intensity.

Lastly, the achieved energy impact of the hybrid control philosophy was then compared with the theoretical model's energy impact predictions to verify the theoretical model. After the necessary adjustments were made to account for the pressure profiles which were in fact implemented, the theoretical model predicted the energy impact of the hybrid control philosophy with an error of less than 5%, therefore, verifying the accuracy of the theoretical model developed in Chapter 2.

4.2 Study objective analysis

Chapter 1 was concluded by determining two study objectives. The purpose of the following section is to determine if the identified study objectives have been adequately satisfied. A critical analysis of each study objective is presented as follows:

1. Develop a methodology which can be used to determine the hybrid control philosophy which maximises the energy impact of the DSM initiative whilst minimising the capital cost, required maintenance, project lead time and resource intensity.

In Chapter 2 the analysis methodology was developed such that the theoretical energy impact of the various hybrid control valve layouts could be determined. Additionally, a decision matrix was developed which rated how well each hybrid control valve layout minimised the capital cost, required maintenance, project lead time and resource intensity. The cumulative energy impact and rating of each hybrid control philosophy could then be compared to determine the optimal hybrid control valve layout.

When the analysis methodology was applied to the case study at Shaft A, the optimal hybrid control valve layout was clearly identified by the theoretical model. Thus, the analysis methodology satisfies the first study objective described in point 1.

2. Implement and verify the hybrid control philosophy analysis methodology.

In Chapter 3, the identified optimal hybrid control philosophy was implemented at Shaft A. An additional annual energy impact of 3.96 GWh was achieved by the hybrid control philosophy. The annual energy impact was then compared to the theoretical annual energy impact and the resulting error was less than 5%, thus verifying the accuracy of the theoretical model's energy impact predictions. This satisfies the requirements of the second study objective described in point 2.

4.3 Future recommendations

Upon completion of the investigation into expanding compressed air DSM initiatives through selective level control, recommendations for future work are made based on the shortfalls noted in the study. The future recommendations are as follows:

- In this study, the analysis methodology developed in Chapter 2 could only be applied to a single case study. It is therefore recommended that additional case studies be evaluated using the methodology described in Chapter 2 such that the analysis methodology can be further validated and verified.

- The case study used to evaluate the hybrid control philosophy was implemented on a Shaft which already had a surface control valve in place. It is recommended that the hybrid control philosophy be implemented on a shaft without a surface control valve such that the full impact of the hybrid control philosophy can be determined.
- The case study used to evaluate the feasibility of a hybrid control philosophy was conducted on a deep-level platinum mine. It is recommended that the hybrid control philosophy be evaluated for alternative mining operations which also make use of compressed air to further confirm the validity of the model.
- A hybrid control philosophy should in fact be applicable to any compressed air system in which variable pressure demands are present. Therefore, it is recommended that the methodology be used to determine the feasibility of a hybrid control valve layout in other industrial compressed air networks.
- For future work, the analysis methodology described in Chapter 2 can be used to prioritise the installation of control valves whether it be surface control valves across multiple shafts, a combination of surface and level control valves, level valves alone or even stope isolation valves, such that the energy impact is maximised.
- For future analysis of hybrid control valve layouts in the deep-level mining industry, it is recommended that the effects of auto compression and dynamic pressure losses from each control valve to the relevant end-users be accounted for.
- Lastly, it is recommended that the feasibility of implementing alternative technologies, which have higher efficiencies than existing compressed air end-users, be investigated such that the use of compressed air can be eliminated from the South African mining industry in turn, increasing the energy efficiency of the existing mining operations.

4.4 Conclusion

The low efficiencies of compressed air networks in the South African mining industry and in the global industry are cause for concern. This study provides an economical and sustainable solution to reduce the negative impact caused by the misappropriation and mismanagement experienced by compressed air systems in the South African mining industry. It is recommended that future studies search for solutions, to the low efficiencies experienced by compressed air systems, which maximise the energy impact whilst also improving the project sustainability by minimising capital cost, required maintenance, project lead times and resource intensities.

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ANNEXURES

ANNEXURE A – SURFACE CONROL ON A RING-FED NETWORK

Figure 62 is an example of the use of surface control valves on a ring-fed compressed air network. Each control valve is installed on the compressed air line at the breakaway point which supplies the underground compressed air end-users. The loading box supply line usually ties off prior to the control valve as the loading box operates throughout the 24-hour mining cycle to hoist ore from underground to surface.

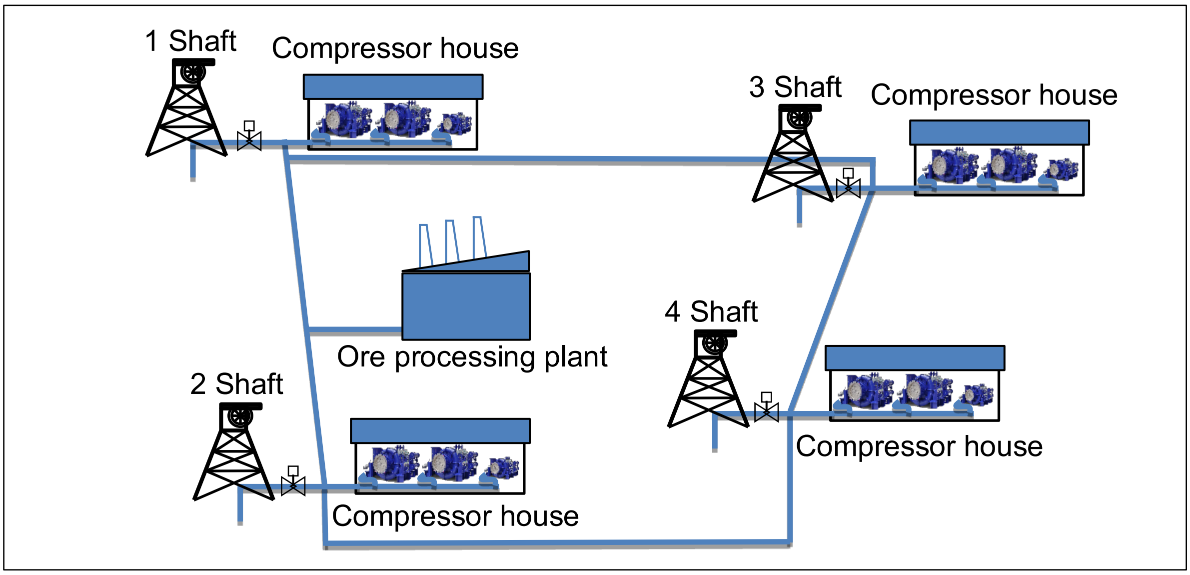


Figure 62 - Example of the use of surface control valves on a ring-fed compressed air network.

Surface control valves are beneficial on a ring-fed system as there are surface users such as the ore processing plant and loading boxes which require a constant supply of 600 kPa to operate effectively, whilst the underground end-users of the shafts follow a typical 24-hour mining cycle.

Each shafts 24-hour mining cycle may differ slightly due to the difference in shift cycles, cage capacity, shaft size and travelling time to the working place. In the instance where two shafts share the same 24-hour pressure demand profile, installation of surface control valves is still beneficial. This is due to the difference in pressure demand requirements between the shaft profiles and the surface user's profile.

By installing the control valves, each shaft can operate on its' own 24-hour mining profile. Thus, further refining the pressure control capabilities of the compressed air network. An example of the difference in pressure profiles for the different users listed above is highlighted in Figure 63.

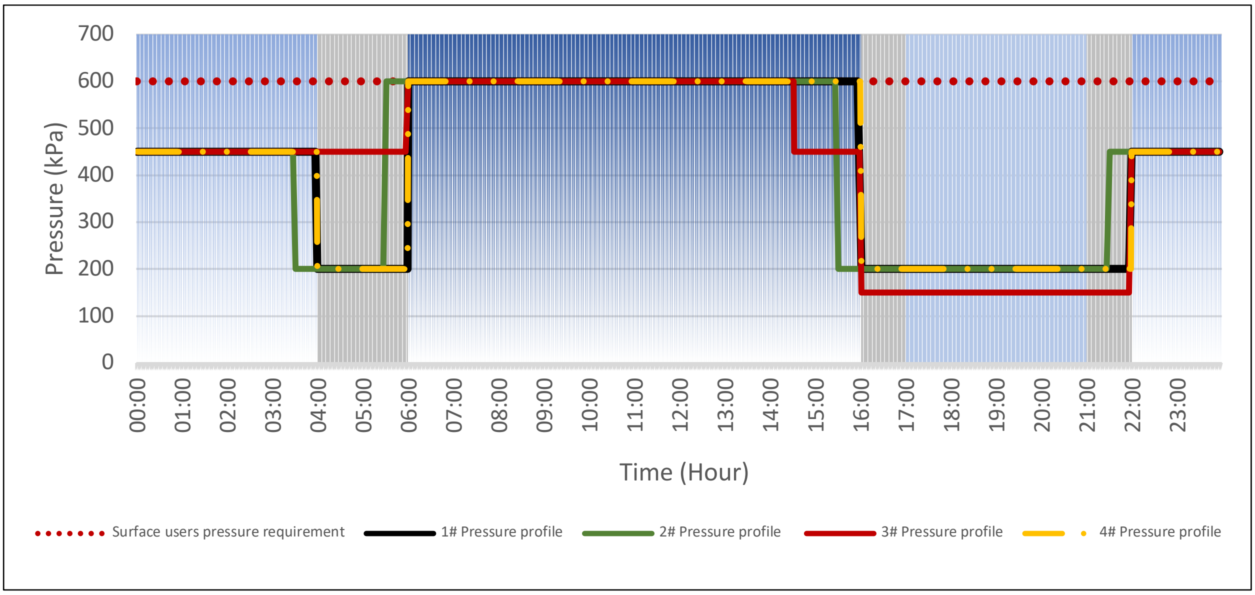


Figure 63 - The difference in pressure demand profiles of the different shafts on the ring-fed network compared to the surface users pressure demand profile.

ANNEXURE B – BASELOAD PROOF

When performing a baseload test the flow per level is determined by measuring the flow rate prior to isolating a level and re-measuring the flow rate after isolating the level. The difference in surface flow rate is equal to the flow of the level that was isolated.

The core principle of this process is to perform a mass balance when the system is at a steady state and to draw your control volume as shown by the dotted green line in Figure 64.

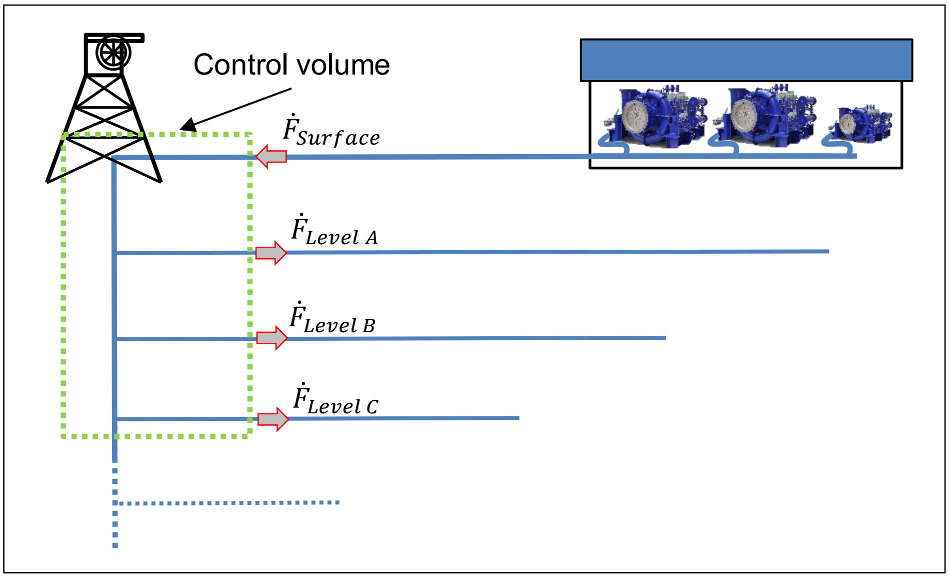


Figure 64 - Example of a control volume drawn over a compressed ait network to perform a mass balance.

Following the determination of the control volume, the law of the conservation of mass can be implemented on the control volume. Therefore, the mass entering the control volume must equal the mass exiting the control volume, when at steady state for compressible fluids, as shown in Equation 9.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{9}$$

Applying the conservation of mass to the control volume drawn in Figure 64, Equation 9 leads to Equation 10. Where the surface flow rate is equal to the sum of the flow rates of all the non-isolated levels.

$$\dot{F}_{Surface} = \sum_{i=1}^{n} \dot{F}_{Level\ i} \tag{10}$$

Where F = compressed air flow rate, i = the first non-isolated level and n = the last non-isolated level. The primary step in the baseload methodology is to determine the total baseload flow with all levels open. This will be referred to as time step 1. Applying Equation 10 during time step 1 leads to Equation 11:

$$\dot{F}_{Surface_{t1}} = \dot{F}_{Level\ A} + \dot{F}_{Level\ B} + \dot{F}_{Level\ C} \tag{11}$$

The next step in the baseload methodology is to isolate the level A and wait until the surface flow rate and pressure have reached a steady state. This will be referred to as time step 2. Applying Equation 10 during time step 2 leads to Equation 12:

$$\dot{F}_{Surface_{t2}} = \dot{F}_{Level\ B} + \dot{F}_{Level\ C} \tag{12}$$

Next Equation 11 is combined with Equation 12 to give us Equation 13:

$$\dot{F}_{Surface_{t1}} = \dot{F}_{Level\ A} + \dot{F}_{Surface_{t2}} \tag{13}$$

Rearranging Equation 13 leads to Equation 14:

$$\dot{F}_{Level\ A} = \dot{F}_{Surface_{t1}} - \dot{F}_{Surface_{t2}} \tag{14}$$

Therefore, the flow into level A can be determined. This process can be repeated for each level to determine its flow. Thus, allowing us to determine the flow per level by means of a baseload test.

ANNEXURE C – POWER DENSITY OF COMPRESSED AIR

In order to determine the power savings, as a result of a reduction of flow, the power density must be calculated. The power density approximates the compressor power required to provide a unit of compressed air flow. The formula to calculate power density is highlighted in Equation 15.

$$\omega = \frac{P_C}{F_{CD}} \tag{15}$$

Where, ω = power impact, P_C = Compressor power and F_{CD} = Compressor discharge flow.

ANNEXURE D – PRESSURE PROFILES FOR VARIOUS MODES OF OPERATION

Annexure D presents and examples of the theoretical 24-hour pressure profiles deducted from the minim end-users pressure requirements combined with the various shifts throughout the different modes of production. Figure 65, Figure 66, and Figure 67 present examples of theoretical 24-hour pressure profiles and the shifts associated with each pressure profile for weekdays, Saturdays and Sundays.

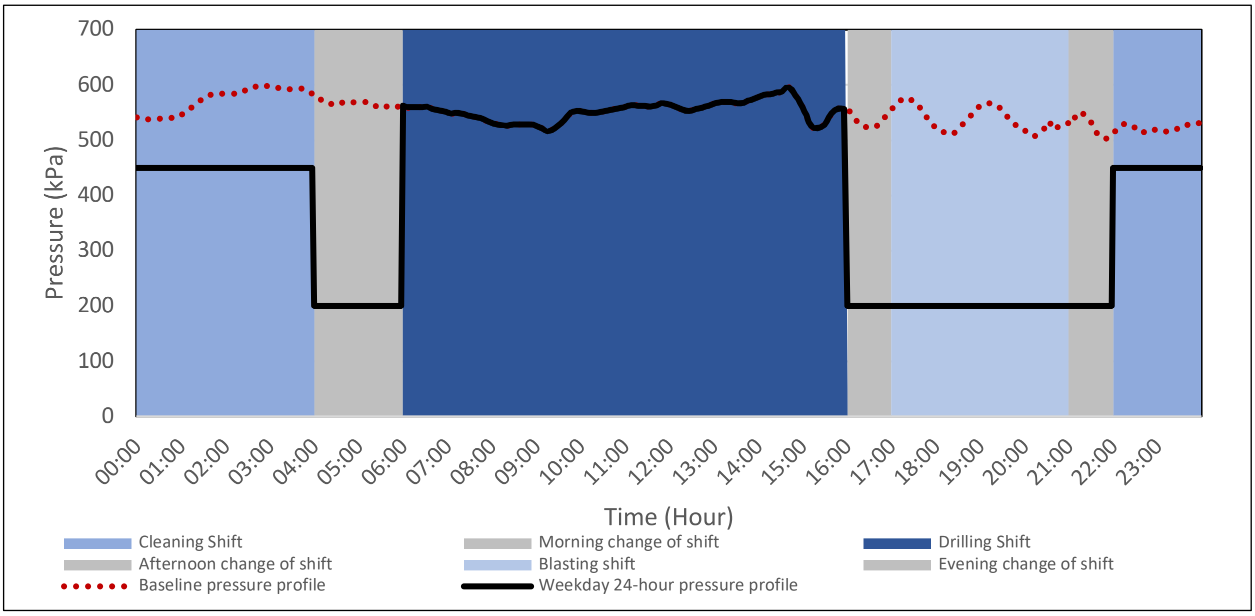


Figure 65 - Example of a weekday 24-hour pressure profile.

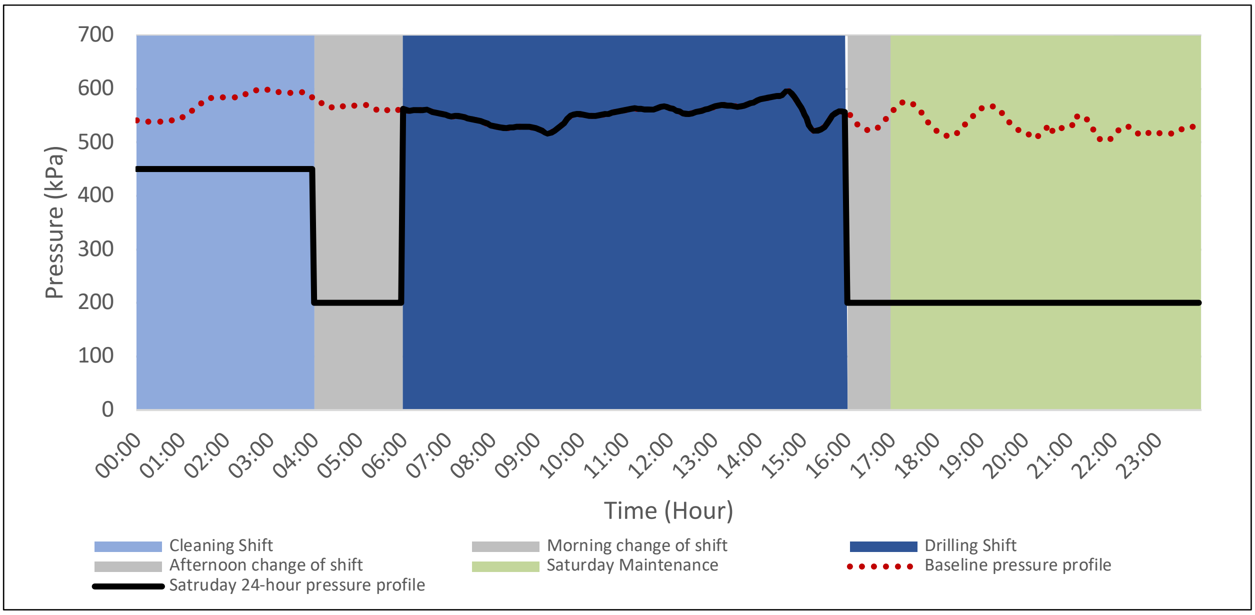


Figure 66 - Example of a Saturday 24-hour pressure profile.

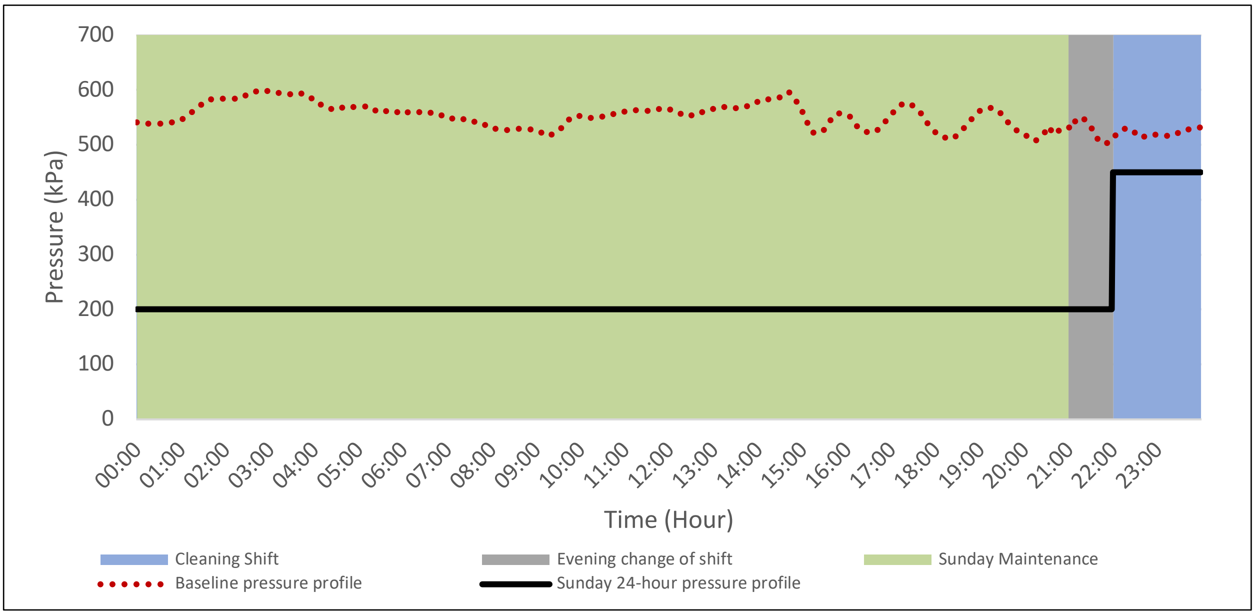


Figure 67 - Example of a Sunday 24-hour pressure profile.

ANNEXURE E – IDEAL GAS LAW

To determine the flow rate of a fixed demand at various supply pressures, the ideal gas law can be used. The derivation of Equation 3 from first principles is performed as follows.

The primary step is to begin with the ideal gas law as shown in Equation 16:

$$\frac{p}{n} = \frac{RT}{V} \tag{16}$$

Where p = pressure, n = number of moles in the gas at present, R = gas constant, T = temperature and V = volume. Equation 16 can then be applied to two scenarios in which we have the same system at two different pressures to get Equation 17 and Equation 18:

$$\frac{p_1}{n_1} = \frac{R_1 T_1}{V_1} \tag{17}$$

Where p_1 = pressure at time 1, n_1 = number of moles of gas at time 1, R_1 = gas constant at time 1, T_1 = temperature at time 1 and V_1 = volume at time 1.

$$\frac{p_2}{n_2} = \frac{R_2 T_2}{V_2} \tag{18}$$

Where p_2 = pressure at time 2, n_2 = number of moles of gas at time 2, R_2 = gas constant at time 2, T_2 = temperature at time 2 and V_2 = volume at time 2. However, for a given quantity of gas n and R are constant. Thus, leading to Equation 19:

$$\frac{p_1}{n_1} = \frac{p_2}{n_2} \tag{19}$$

Thus, the molar flow of compressed air at desired pressure can be determined by modifying Equation 19 which leads to Equation 20:

$$n_2 = n_1 \frac{p_2}{p_1} \tag{20}$$

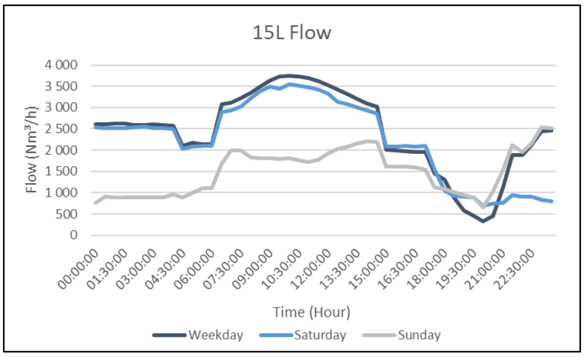
The molar flow is equivalent to the Nominal flow in which compressed air is measured as the flow is normalised to a constant pressure and temperature therefore leading to Equation 21:

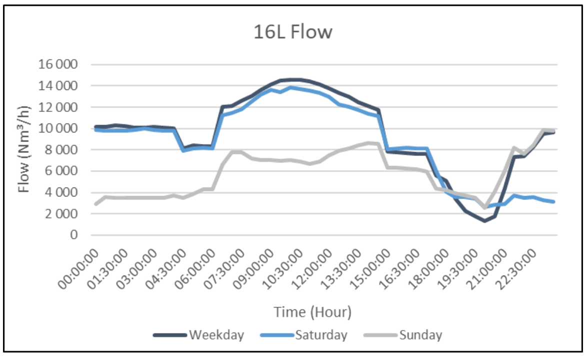
$$\dot{F}_2 = \dot{F}_1 \frac{p_2}{p_1} \tag{21}$$

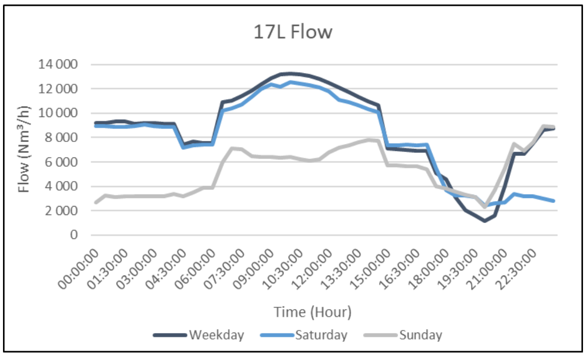
Where $\dot{F}$ = Nominal flow rate and p = pressure.

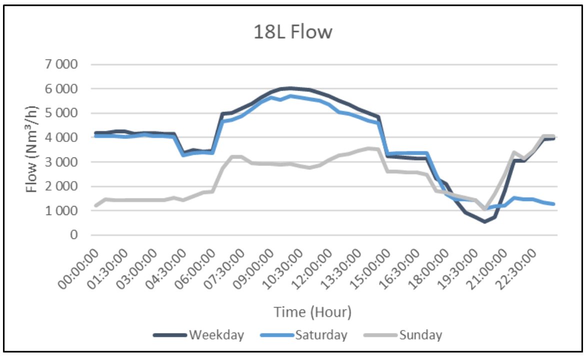
ANNEXURE F – FLOW BASELINES PER LEVEL

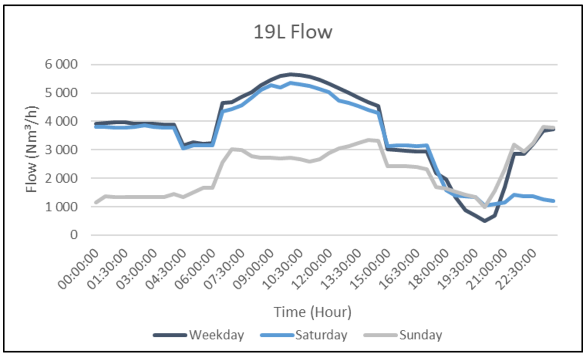
Annexure F shows the baselines per level in Figure 68, as developed in Section 3.2.3.

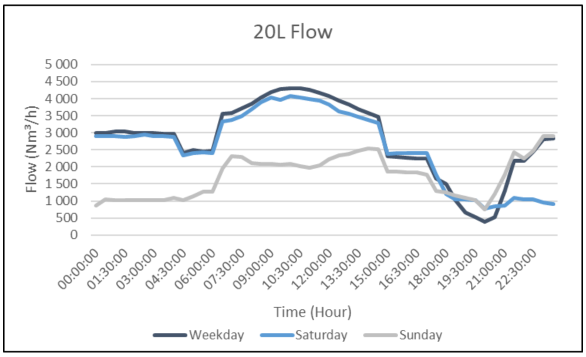


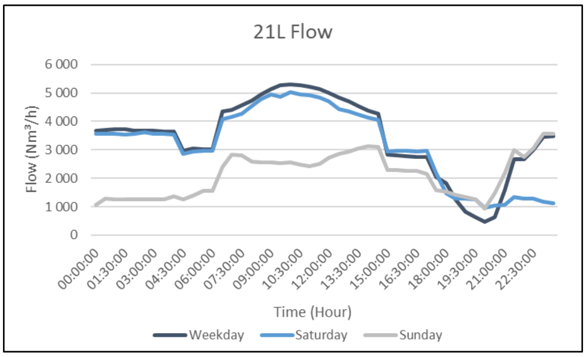


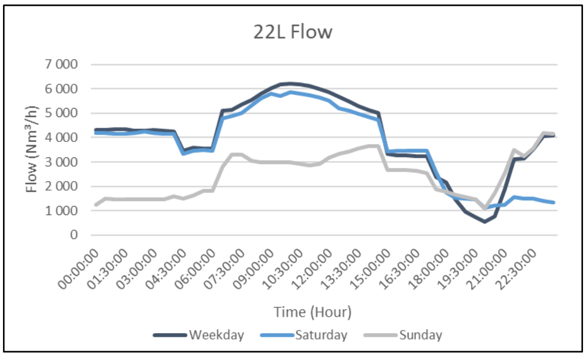












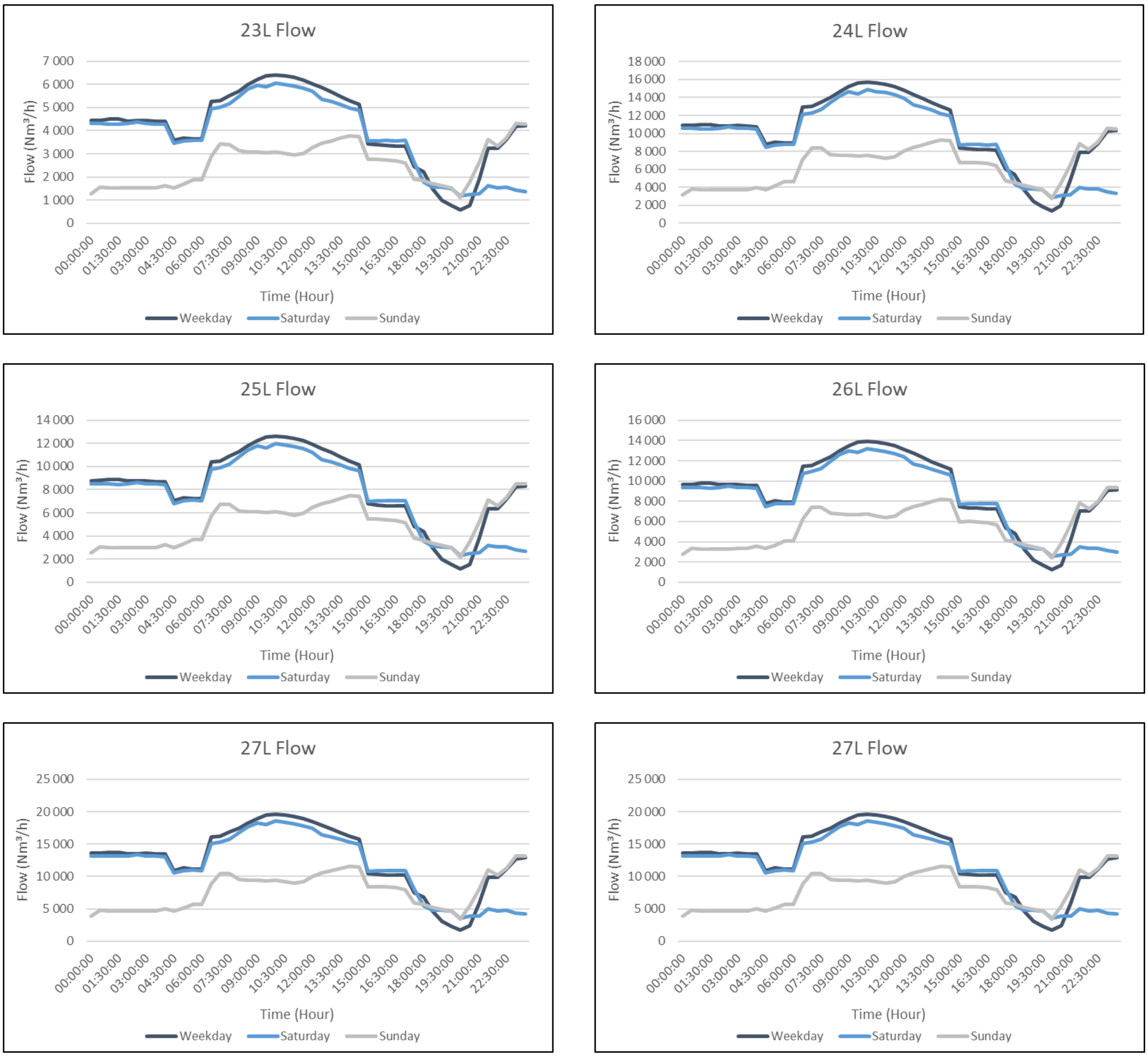


Figure 68 - Flow baselines for each of the levels at Shaft A.

ANNEXURE G - 24-HOUR PRESSURE PROFILES FOR SHAFT A

Annexure G highlights the 24-hour pressure schedules for each possible valve installation location for On-Saturdays, Off-Saturdays and Sundays.

Table 35 – On-Saturday 24-hour pressure profile for each valve installation location.

Time	Surface	15L	16L	17L	18L	19L	20L	21L	22L	23L	24L	25L	26L	27L	28L
00:00	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
00:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
01:00	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
01:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
02:00	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
02:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370
03:00	370	200	200	200	370	370	370	370	370	370	370	370	200	200	200
03:30	370	200	200	200	200	200	200	370	200	370	200	200	200	200	200
04:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
04:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
06:00	443	200	200	200	200	200	200	200	200	200	200	200	200	443	443
06:30	464	464	200	464	200	200	200	200	200	200	200	200	200	464	464
07:00	471	471	471	471	471	200	200	200	200	200	200	200	200	471	471
07:30	476	476	476	476	476	476	476	200	476	200	200	476	476	476	476
08:00	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482
08:30	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482
09:00	497	497	497	497	497	497	497	497	497	497	497	497	497	497	497
09:30	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478
10:00	480	480	480	480	480	480	480	480	480	480	480	480	480	480	480
10:30	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488
11:00	499	499	499	499	499	499	499	499	499	499	499	499	499	499	499
11:30	511	200	511	511	511	511	511	511	511	511	511	511	511	511	511
12:00	505	200	200	505	505	505	505	505	505	505	505	505	505	200	505
12:30	510	200	200	200	510	200	200	510	200	510	510	510	510	200	340
13:00	513	200	200	200	200	200	200	200	200	200	513	513	513	200	340
13:30	510	200	200	200	200	200	200	200	200	200	510	510	510	200	340
14:00	501	200	200	200	200	200	200	200	200	200	200	200	200	200	340
14:30	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
15:00	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
15:30	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
16:00	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
16:30	340	200	200	200	200	200	200	200	200	200	200	200	200	200	340
17:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
17:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
23:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
23:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

Table 36 – Off-Saturday 24-hour pressure profile for each valve installation location.

Time	Surface	15L	16L	17L	18L	19L	20L	21L	22L	23L	24L	25L	26L	27L	28L
00:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
00:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
01:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
01:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
02:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
02:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
03:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
03:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
04:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
04:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
06:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
06:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
07:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
07:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
08:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
08:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
09:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
09:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
10:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
10:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
11:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
11:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
12:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
12:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
13:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
13:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
14:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
14:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
15:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
15:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
16:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
16:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
17:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
17:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
23:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
23:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

Table 37 – Sunday 24-hour pressure profile for each valve installation location.

Time	Surface	15L	16L	17L	18L	19L	20L	21L	22L	23L	24L	25L	26L	27L	28L
00:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
00:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
01:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
01:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
02:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
02:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
03:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
03:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
04:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
04:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
05:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
06:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
06:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
07:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
07:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
08:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
08:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
09:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
09:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
10:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
10:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
11:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
11:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
12:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
12:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
13:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
13:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
14:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
14:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
15:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
15:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
16:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
16:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
17:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
17:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
18:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
19:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
20:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
21:30	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:00	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
22:30	370	370	370	370	370	200	200	200	200	200	200	370	370	370	370
23:00	370	370	370	370	370	370	370	200	370	200	370	370	370	370	370
23:30	370	370	370	370	370	370	370	370	370	370	370	370	370	370	370

ANNEXURE H - SURFACE CONTROL VALVE THEORETICAL FLOW REDUCTION

Annexure H highlights the theoretical flow reduction and power impact for the surface control valve upon implementation of the theoretical pressure profiles for On-Saturdays, Off-Saturdays, and Sundays as presented by Figure 69, Figure 70, and Figure 71.

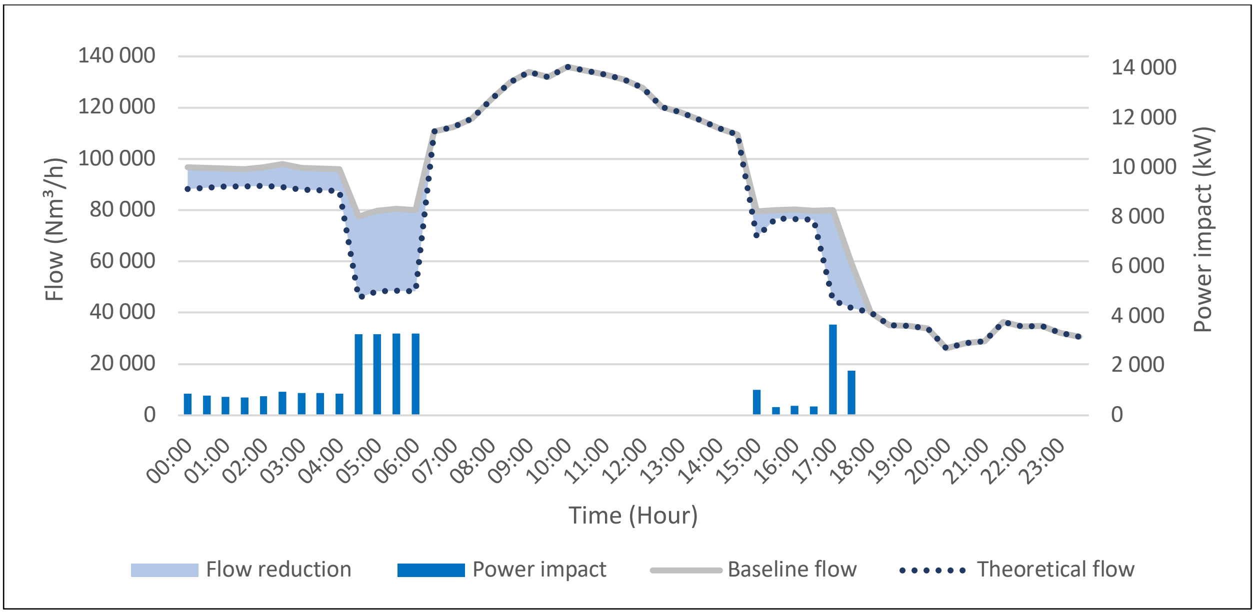


Figure 69 - The theoretical change in flow and resultant power impact upon implementation of the theoretical pressure profile at Shaft A for On-Saturdays only.

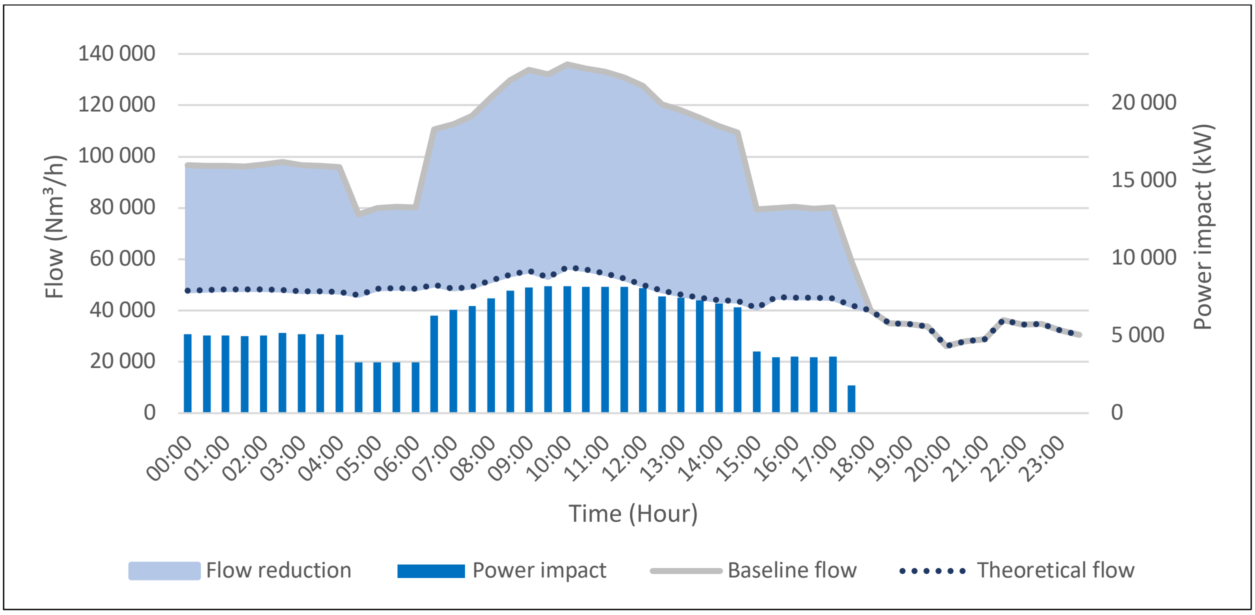


Figure 70 - The theoretical change in flow and resultant power impact upon implementation of the theoretical pressure profile at Shaft A for Off-Saturdays only.

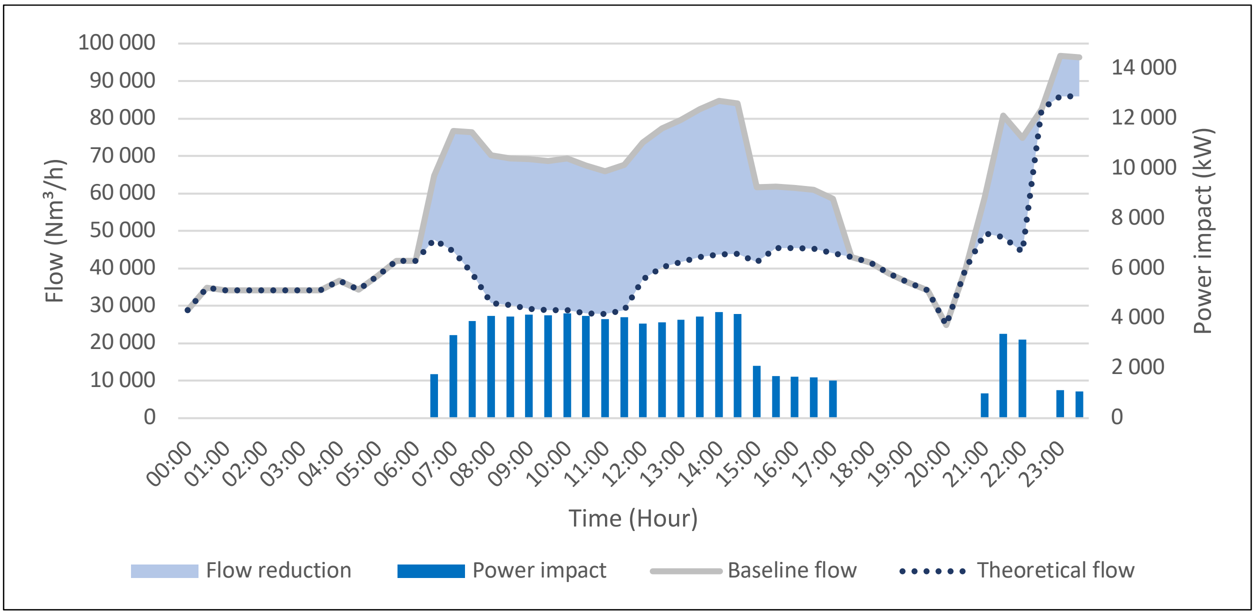


Figure 71 - The theoretical change in flow and resultant power impact upon implementation of the theoretical pressure profile at Shaft A for Sundays only.