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Developing a compressed air benchmark approach to be used as a metric to identify ventilation shortfalls

by
Ulrich van Gruting

Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Industrial Engineering) in the Faculty of Engineering at Stellenbosch University

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Declaration

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Date: December 2023

ABSTRACT

Title: Developing a compressed air benchmark approach to be used as a metric to identify ventilation shortfalls

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Keywords: Baseload, deep-level mining, ventilation, benchmark, compressed air, wastage, shortfalls.

Platinum mining contributes significantly to the economy of South Africa. However, deep-level platinum mines in South Africa are facing numerous challenges which is placing strain on the profitability of these mines. One challenge that stood out is the rising electricity cost which is detracting from the price of Platinum Group Metals. This challenge has forced platinum mines to investigate improving the efficiency of electricity consumers. Two utilities that were specifically highlighted are compressed air and ventilation.

Compressed air is a critical component in the mining operation and accounts for a large portion of electricity use. It has been estimated that 75% of produced compressed air is wasted because of mismanagement and misappropriation. The wastage stems from leakages, as a result of poor maintenance, mismanagement and misappropriation. To address the low efficiencies in deep-level mine compressed air systems, previous studies have investigated several demand-side management initiatives to reduce the wastage of compressed air.

Ventilation, the second utility, promotes an optimised mining cycle and is critical to ensuring that the health and safety standards of mine personnel are adhered to. Mining companies prioritise production considerations over ventilation requirements and as a result, ventilation networks are often inadequate. This often causes compressed air to be misappropriated as an interim solution for cooling working areas underground.

Existing studies on underground compressed air wastage and ventilation shortfalls in deep-level mines are limited. Additionally, the effect of ventilation shortfalls on compressed air misappropriation has not been evaluated. Hence, a need exists to determine the relationship between compressed air wastage and ventilation shortfalls.

Current methods for addressing compressed air wastage and ventilation inefficiencies, such as benchmarking models, simulations, leak management, and conventional audits, do not specifically target ventilation shortfalls as a root cause for compressed air wastage. Additionally, these studies make use of complicated and limited methods to address compressed air wastage and ventilation inefficiencies.

To address the problem identified, the main study objective of this thesis was the development of a new methodology, utilising compressed air wastage as a metric, to identify ventilation shortfalls in a less resources and time-intensive way. A new method was developed that benchmarks compressed air systems in deep-level underground mines to identify and prioritise levels based on the highest compressed air wastage. This newly developed method was further tailored towards ventilation shortfalls, utilising a newly developed Baseload Intensity indicator, to identify the level with the highest possibility of a ventilation shortfall. By localising ventilation shortfalls to specific crosscuts using the crosscut baseload method (in conjunction with the Baseload Intensity indicator), the methodology reduces the resources and time required to identify ventilation shortfalls.

The newly developed methodology, with its sub-methods, was applied to two deep-level platinum mines in the North West province of South Africa. The application of the newly developed methodology successfully identified ventilation shortfalls using less resources and time (when compared with conventional audits) on both case studies.

OPSOMMING

Titel: Developing a compressed air benchmark approach to be used as a metric to identify ventilation shortfalls

Skrywer: Ulrich van Gruting

Studieleier: Prof Corne Schutte

Mede-studieleier: Wiehan A. Pelser

Sleutelwoorde: Basislading, diepvlak mynbou, ventilasie, maatstafmodelle, hoë-druk lug, vermorsing, tekortkoming.

Platinum mynbou dra aansienlik by tot die ekonomie van Suid-Afrika. Tog staar die Platinum diepvlak mynbou in Suid-Afrika talle uitdagings in die gesig, wat druk plaas op die winsgewendheid van hierdie myne. Een merkbare uitdaging is die stygende elektrisiteitskoste wat afwyk van die prys van Platinum Groep Metale. Hierdie uitdaging het gelei tot ondersoek deur platinum myne om die doeltreffendheid van elektrisiteitsverbruikers te verbeter. Twee operasionele dienste wat spesifiek uitgelig is, is hoë-druk lug en ventilasie.

Hoë-druk lug is 'n kritiese komponent in die mynbou-operasie en maak 'n groot deel uit van die elektrisiteitsgebruik. Daar is beraam dat 75% van die hoë-druk lug wat geproduseer word, gemors word as gevolg van wanbestuur en wanbesteding. Die morsing spruit voort uit lekke,'n direkte oorsaak van swak onderhoud, wanbestuur en wanbesteding. Om die lae doeltreffendheid van die hoë-druk lugstelsels in diep-vlak myne aan te spreek, het vorige studies verskeie inisiatiewe vir aanvraagkantbestuur ondersoek, om die morsing van hoë-druk lug te verminder.

Ventilasie bevorder 'n geoptimaliseerde mynbousiklus en is van kritieke belang om te verseker dat die gesondheid- en veiligheidstandaard van mynpersoneel nagekom word. In menigde gevalle prioritiseer mynmaatskappye produksie-oorwegings oor ventilasievereistes en as gevolg daarvan is ventilasienetwerke dikwels onvoldoende. Dit lei daartoe dat hoë-druk lug gereeld wanbestee word as 'n tussentydse oplossing vir die verkoeling van ondergrondse werkareas.

Bestaande studies oor die morsing van hoë-druk lug en ventilasietekorte in diep-vlak myne is beperk. Die omvattende effek van ventilasietekorte op die wanbestee van hoë-druk lug is nog nie ten volle geëvalueer nie. Daar is dus 'n behoefte om die verband tussen morsing van saamgedrukte lug (as gevolg van wanbestee) en ventilasietekorte te bepaal. Huidige metodes vir die aanspreek van morsing van saamgedrukte lug en ventilasie-ondoeltreffendheid, soos maatstafmodelle, simulasies, lekkasiebestuur en konvensionele oudite, teiken nie spesifiek ventilasietekorte as 'n kernoorsaak vir morsing van hoë-druk lug nie. Hierdie studies maak ook gebruik van ingewikkelde en beperkte metodes om die morsing van hoë-druk lug en ventilasie-ondoeltreffendheid aan te spreek.

Om die geïdentifiseerde probleem aan te spreek, was die hoof doelwit van hierdie tesis, die ontwikkeling van 'n nuwe metodologie wat die morsing van hoë-druk lug gebruik as 'n maatstaaf om ventilasietekorte op 'n minder tyd- en hulpbronintensiewe wyse te identifiseer. 'n Nuwe metode is ontwikkel om die hoë-druk lugstelsels in diep-vlak ondergrondse myne te maatstaaf en te prioriteer gebaseer op die hoogste morsing van hoë-druk lug per mynvlak. Hierdie nuwe metode is spesifiek verder aangepas om ventilasietekorte te identifiseer deur 'n nuwe “Baseload Intensity indicator” te gebruik, om die mynvlak met die hoogste moontlikheid van 'n ventilasietekort te identifiseer. Deur ventilasietekorte na spesifieke “crosscuts” te lokaliseer deur die “crosscut baseload” metode (saam met die “Baseload Intensity indicator”) te gebruik, verminder dié nuwe metodologie, die hoeveelheid hulpbronne en tyd benodig om ventilasietekorte te identifiseer.

Die nuwe metodologie, met sy sub-metodes, was toegepas op twee diep-vlak platinum myne in die Noordwes-provinsie van Suid-Afrika. Die nuwe metodologie was op twee gevallestudies toegepas, het die ventilasietekorte suksesvol geïdentifiseer en was minder tyd- en hulpbronintensief (in vergelyking met konvensionele oudite).

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NOMENCLATURE

Air amplifier	A low-cost device that produces a highly concentrated air stream to distribute the air throughout a working place.
Baseload	Compressed air consumption of shaft when no authorised compressed air end-users (other than refuge bays) are present.
Baseload test	Operational baseload testing method which is discussed in Section 4.2.1.1.
BI indicator	Baseload intensity indicator – Explained in Section 5.4.1.
Bulk Air Cooler	Air coolers that chill air before it goes underground.
Centre gullies	Excavation in the stope to enable the removal of ore from the mining face. Centre gullies also provide access for mining personnel to the stope mining face.
Digital twin	Creating a duplication of a mine using simulation software.
Half-level	The reef being mined is divided into different working levels. The shaft column usually connects in the middle of the level, thereby splitting the level into two parts. Each part of the level is referred to as a half-level.
Haulage	Underground tunnel found in each half-level where ore is transported via rail from the stoping areas. These tunnels are also where services such as water, compressed air, network cable and electricity as well as personnel are transported.
kPa_g	Gauge pressure measured in kilo pascals.
SCADA	Supervisory Control and Data Acquisition system used by mining companies to monitor all their different utilities in one central environment.
Self-ventilation	The act of using an open-ended compressed air hose to temporarily cool a working place.
Stope	Area where mine personnel extract ore through drilling and blasting.
Virgin rock temperature	Geothermal temperature of rock in deep-level mines.
XC	Crosscut.
Zero-wastage model	Mathematical model developed to compute theoretical compressed air consumption of mining equipment.

ABBREVIATIONS

ADP	Automated Data Processing
ACM	Automated Calculation Model
BAC	Bulk Air Cooler
BI	Baseload Intensity
DSP	Digital Signal Processing
EoD	End of Development
GDP	Gross Domestic Product
GIS	Geographic Information System
KPI	Key Performance Indicator
MHSA	Mine Health and Safety Act
MN	Merensky North reef
MS	Merensky South reef
PGM	Platinum Group Metals
PI	Performance Indicator
RDO	Rock Drill Operator
SAIJE	South African Journal of Industrial Engineering
SCADA	Supervisory Control and Data Acquisition
UG2-N	Upper Group 2 North reef
UG2-S	Upper Group 2 South reef
WB	Wet-Bulb
XC	Crosscut

CHAPTER 1 – INTRODUCTION

1.1 Preamble

The South African mining industry is a vital sector that contributes significantly to the economy of the country [1] [2] [3]. Platinum mining is a critical component of this industry, accounting for a substantial portion of gross domestic product (GDP) and employment [1]. However, platinum mines are facing unique challenges in South Africa, placing strain on the profitability of these mines [2] [4]. Platinum mines are experiencing a decrease in production output due to increased operational costs and lower mineral prices [3] [5] [6]. The increased energy consumption of utilities such as compressed air are hindering the profitability of mines [7]. Additionally, extreme temperatures and working conditions as a result of continuous ventilation shortfalls, are negatively impacting the health and safety of mine personnel [1] [8]. The lack of ventilation adequacy negatively impacts the production output, thereby placing further strain on the profitability of mines [1].

This chapter discusses platinum mining in South Africa and the unique challenges faced within this mining environment. It presents several challenges, including labour costs, high energy consumption, rising operational costs, and efficient energy management concerns [4] [9]. It will present a general overview of the platinum mine utilities, with a focus on compressed air and ventilation. Chapter 1 highlights compressed air as a critical utility in deep-level platinum mining for production. The chapter will also introduce the reader to the importance of ventilation and the management thereof. The chapter concludes with a problem statement and the need for the study, followed by the research objectives and proposed methodology.

Figure 1-1 presents a VENN diagram highlighting the three main topics relevant to this study: platinum mines, compressed air, and ventilation. These topics are covered in this study, along with the overlapping topics relevant to this study, as presented in the figure. The topics covered in Chapter 1 focus on platinum mines, with the relevant topics for discussion listed in the figure. This VENN diagram expands as this thesis continues, showcasing the important topics of discussion in each chapter.

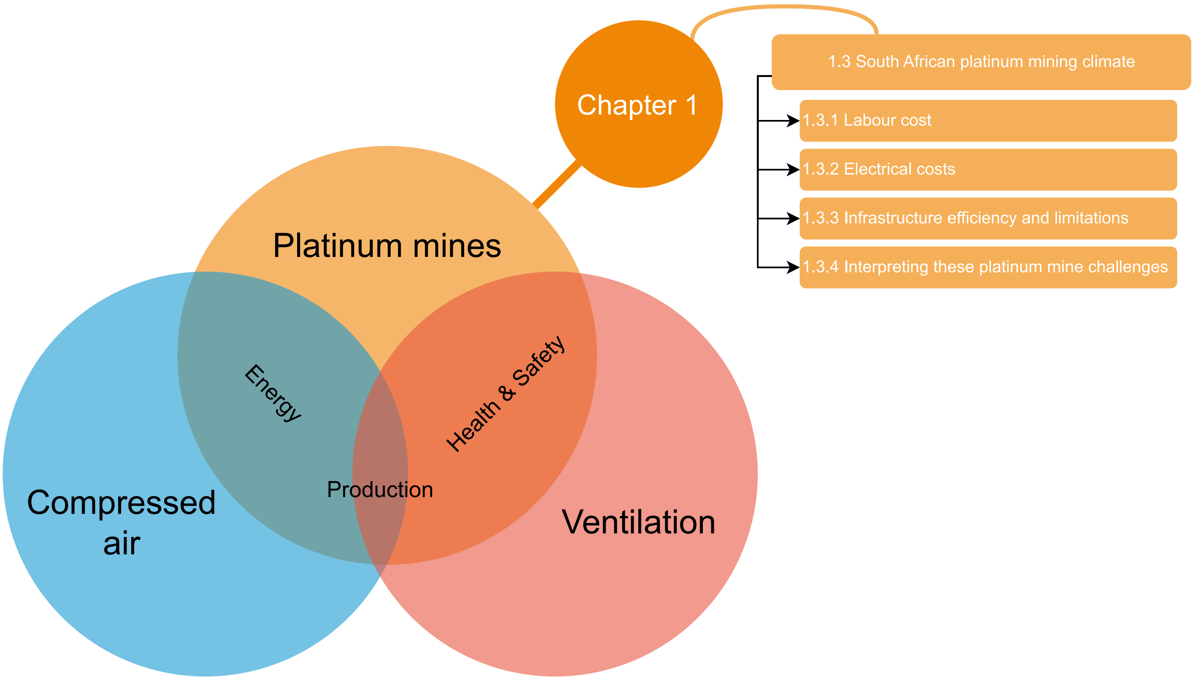

Figure 1-1: Chapter 1 overview and topics to be discussed

1.2 The South African mining industry

The mining industry in South Africa continues to contribute significantly to employment, the gross domestic product, and export earnings [10] [11]. South Africa is one of the leading contributors of Platinum Group Metals (PGM), accounting for one-third of the global reserve [12] [13]. The mining sector contributes roughly R8 for every R100 produced by the national economy [14]. The contribution of gold and platinum to the total South African mining revenue might very soon start to see a decline as input costs are slowly starting to outpace commodity price increases [3] [4] [5] [15].

It is vital to understand that mined minerals, such as PGMs and gold, are supplied at global market related prices [8] [9]. This means it is not possible to adjust the price of PGMs or gold to offset an increase in input costs. Another important aspect to note is that as commodity prices increase, input costs quickly catch up and can easily surpass them [15]. Figure 1-2 illustrates the price-taking tendency of the South Africa mining industry. It is evident that from 2019, the input cost escalation is exceeding the increase in commodity prices.

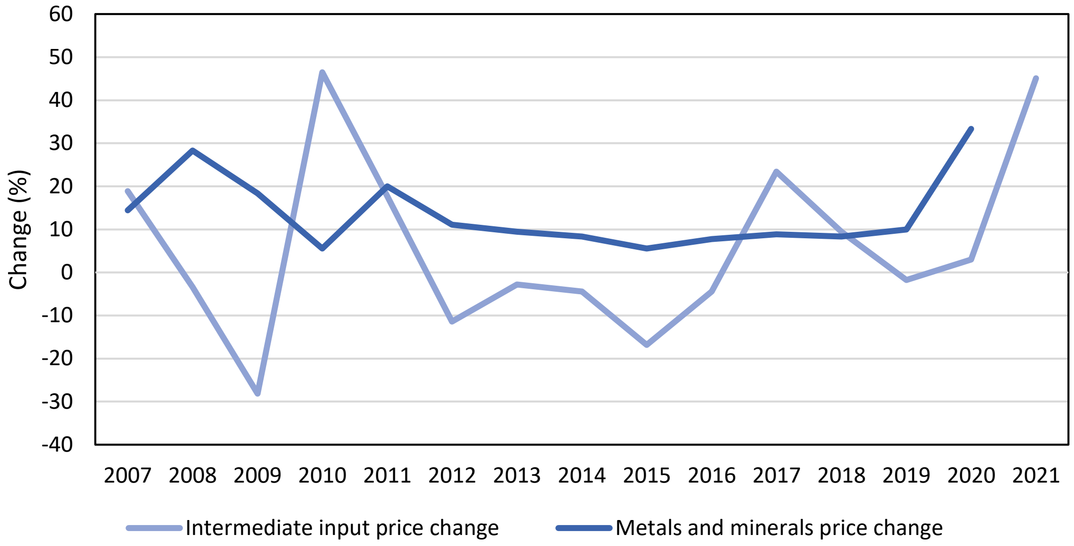

Figure 1-2: Input cost change versus commodity price changes (%) adapted from [15]

To mitigate the effects of market volatility on the livelihood of their mining operations and the drastic increase in expenditures, the mining industry has had to establish a fine balance between labour and capital. The mining industry employs roughly 2.5% of South Africa's total labour force [14]. However, mining companies are closing mines that are not profitable in an effort to decrease their input costs, lower their operational expenses, and as a result to increase profitability [4] . This has caused a 10% decrease in the total number of permanent employees (from 2011 to 2021)[1] .

The above-mentioned factors indicate that multiple challenges are present in the mining sector. This study will specifically focus on combatting the difficulties and unique challenges faced on deep-level platinum mines. The next section will focus on the current platinum mining climate in South Africa and highlight the main challenges that these platinum mining companies face.

1.3 South African platinum mining climate

The platinum mining sector may continue to decrease in size and production because of the increased operational costs [4]. Therefore, the platinum mining industry in South Africa has started to adopt a more aggressive strategy to minimise production/operational cost as an alternative means to maintain maximum profit margins. Persistent challenges that contribute to the operational costs of platinum mines can mainly be divided into the following categories [2] [16]:

[1] StatsSA, "Number of mining employees in South Africa from 2011 to 2021," 2022. Retrieved March 19, 2022, from https://www.statista.com/statistics/1312267/south-africa-mining-employment/#:~:text=In%202021%2C%20a%20total%20of,overall%20mining%20employment%20in%202021.

- Labour costs
- Electrical costs
- Infrastructure efficiency and limitations

These challenges are discussed in more detail below.

1.3.1 Labour costs

In South African platinum mines, conventional underground mining techniques are commonly employed, which are extremely labour-intensive when compared with mechanised mining techniques [7] [16] [17] [18]. Labour and contractors are the most significant operational expenditure on a platinum mine, accounting for up to 40% of their total operational costs [4] [19]. Labour relations and the political drive by unions to promote social and racial equality continue to have a substantial effect on the platinum mining sector in South Africa. Frequent union strikes influence the total productivity and subsequently contribute to the increases in wages [2] [20] [21] [22] [23]. This has caused a stagnant labour productivity that is slowly trending lower, even though mining methods and technology have improved. This is illustrated graphically in Figure 1-3.

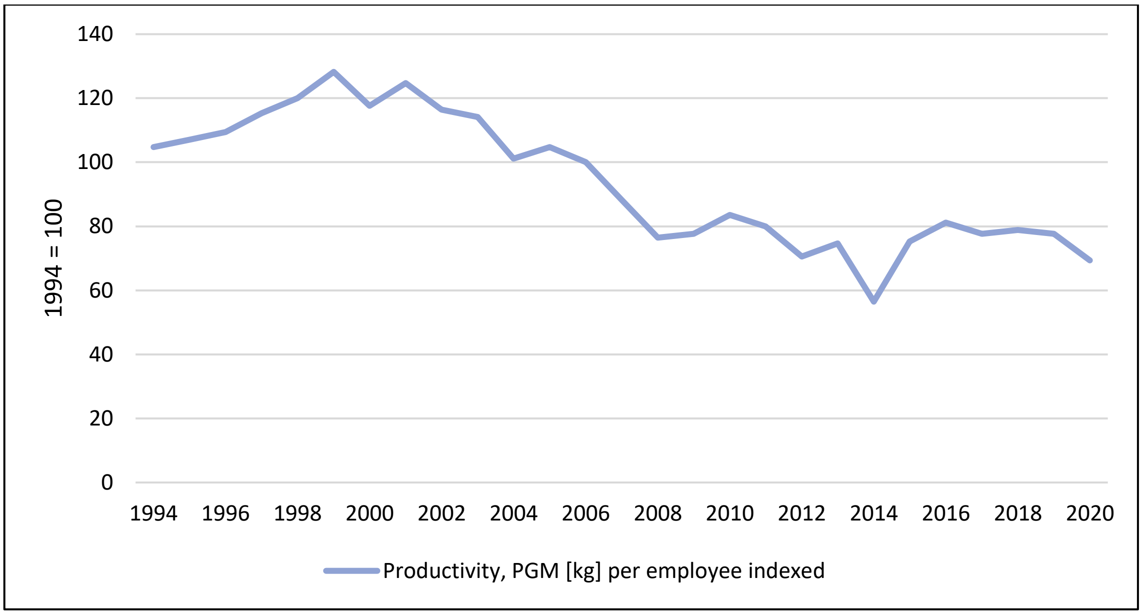

Figure 1-3: Platinum mining sector productivity [15] [24]

As productivity slowly decreases while labour costs increase, more pressure is put on the platinum mines to remain financially profitable. This also has a direct impact the GDP contribution.

1.3.2 Electrical costs

As part of mining development, mines are constantly expanding underground levels and increasing in depth. This dynamic environment causes an exponential increase in operating costs [16] and results in deep underground mines being highly energy-intensive [25]. Highly energy-intensive operations mean that large electricity consumption is typical on a platinum mine [26].

Since 2011, South Africa has seen a dramatic spike in the cost of electricity [7] [27] [28] [29]. The price of electricity has increased by 127%[2] (as of 2022). The comparison of electricity price increase versus average cost per kWh from 2011 to 2022 is presented in Figure 1-4.

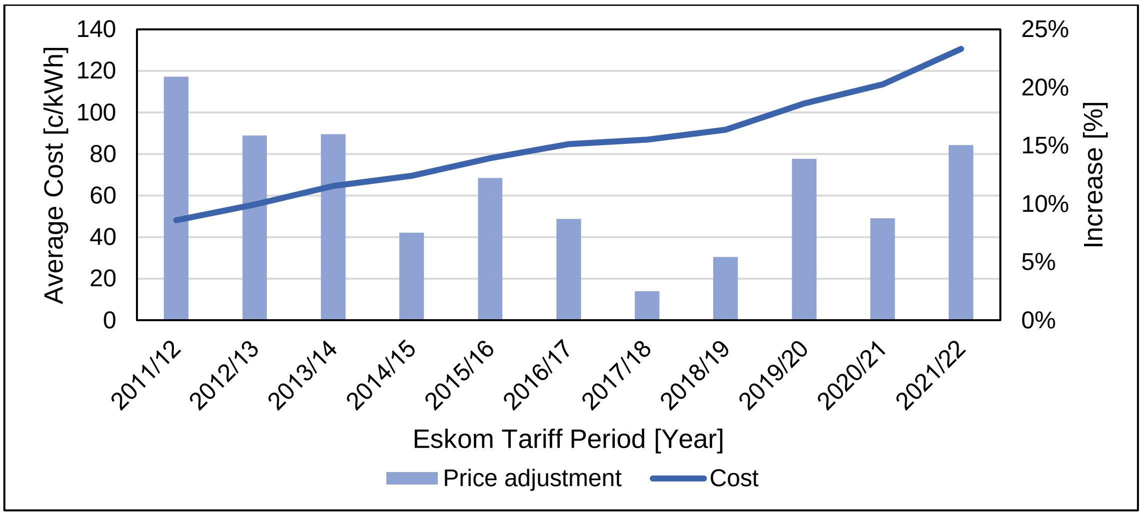

Figure 1-4: South African electricity price increase

Energy-intensive PGM mining groups are sensitive to electricity tariff increases [4] [30] [31]. This higher-than-inflation increase in electricity prices is expected to have a negative impact on the mining industry: it places strain on the South African deep-level platinum mining industry to reduce energy consumption and can render certain operations unprofitable [16] [32].

The increases in electrical costs are exacerbated by a constrained power network that periodically compels major consumers to restrict their demand during specified hours [32]. The reason for this is that South Africa has a peak demand in excess of 51 GW of energy, which is more than the generating capacity of Eskom. This has a negative effect on the production output of mining companies, placing further strain on their profitability [33].

It is evident that because of these tariff increases, electricity usage and costs have become a significant component of operating expenses in South African deep-level platinum mining. There is still an opportunity for maintaining profits by decreasing the usage of electricity in deep-level mines [34] [35]. This is, however, not an easy undertaking as deep-level platinum mines have multiple energy-intensive systems that are essential for operation. These are complex systems that work in unison and operate continuously to achieve production outputs as well as to ensure that ore is

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[2] *StatsSA, "Municipal finances and electricity: 11 years in perspective," 2022*. Retrieved March 20, 2022, from https://www.statssa.gov.za/?p=15612 (accessed Sep. 09, 2022).

extracted safely and effectively [36]. A breakdown of these electricity-consuming systems is illustrated in Figure 1-5.

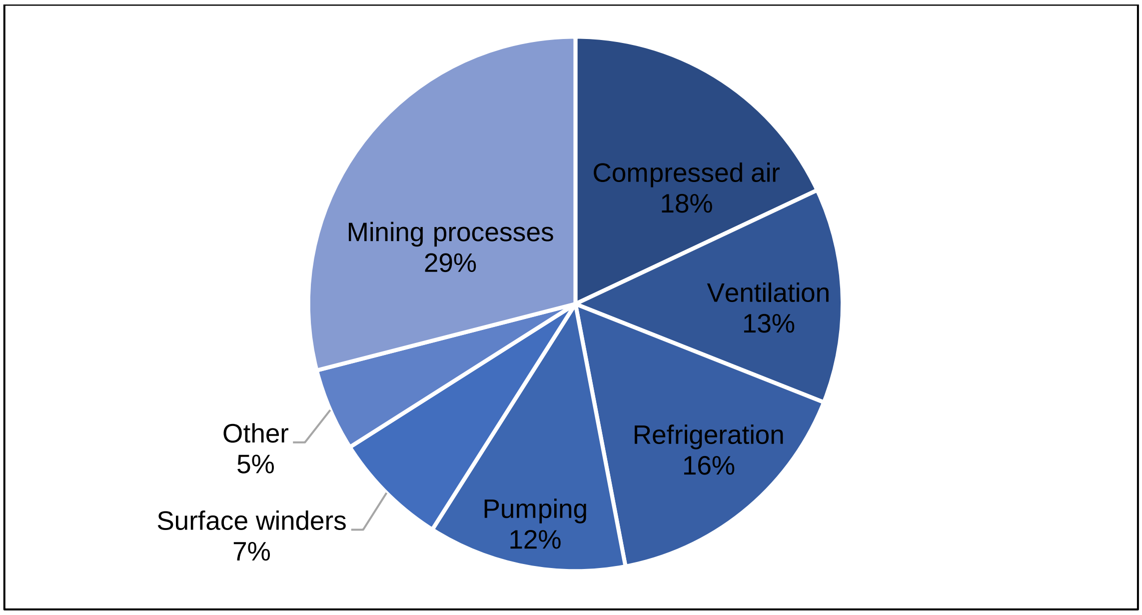

Figure 1-5: Breakdown of electricity-consuming utilities on a typical deep-level platinum mine (adapted from [4])

These electricity-consuming systems, which are further described as utilities, are briefly discussed below. Specific focus is placed on the discussion of compressed air and ventilation, as these utilities form the primary focus of this study.

- **Mining processes:** Mining processes are comprised of multiple components. This includes battery powered locomotives, chairlifts, conveyer belts, hydraulic winches, and mono-rail locomotives. Mining processes are dynamic with multiple, constantly changing variables, which means that they are often not the preferred utility for electricity cost saving initiatives [7].
- **Compressed air:** Majority of machinery used in deep-level mine operations in South Africa require compressed air. Centrifugal compressors, usually situated on the surface, supply compressed air to the equipment and machinery. Figure 1-5 depicts that 18% of the total electricity consumption is attributable to compressed air production. When misappropriation and mismanagement of compressed air are excessive, this percentage can increase to as high as 50% [37] [38] [39].
- **Ventilation:** Surface and underground ventilation systems are critical to maintain a productive and safe working environment underground. The ventilation networks are generally composed of an array of components that work together to ensure airflow throughout the mine. Surface ventilation systems consist of large, energy-intensive surface fans that extract polluted air through a ventilation shaft by creating a suction pressure [40].

The underground ventilation network is composed of a variety of fan types. These fans operate in unison to ensure sufficient distribution and supply of fresh air to sections where mine personnel work. Ventilation fans vary in size and are typically operated on an uninterrupted basis to ensure that air is continuously circulated through the mine [41].

- **Refrigeration:** Deep-level mine refrigeration systems are complex systems used to cool underground working environments. This is accomplished by installing Bulk Air Coolers (BACs) on surface that induce cold air which is fed underground. These refrigeration systems are energy-intensive and can account for a significant portion of a mine's total electricity consumption [42] [43]. Several factors, including the mine's depth, virgin rock temperature, airflow rates, and humidity levels, must be considered when designing and operating these systems. Refrigeration systems rely on ventilation networks to distribute the cooled air efficiently and effectively to the areas where mining personnel are working.
- **Pumping:** Water is utilised by the mines for cooling and production. The underground pumping systems distribute water on demand to different levels underground. After utilisation, the contaminated water is pumped to the surface to prevent underground flooding. Multiple underground pumping stations on various levels are frequent in deep underground mines. Thus, the size of the dewatering pumps is dependent on the mine’s depth. Agitators are often used to optimise the dewatering system.
- **Surface winders:** Surface winders form an integral part in the mining operation [44] and are crucial for the efficient and safe operation of underground mines. A typical winder system consists of a headgear, winder, and a cage. Winder systems are divided into “man” winders and “rock” winders. Man winders are used to transport personnel, equipment and material, while rock winders are used to transport mined ore and waste rock to the surface [45] [7].

The rise in electricity costs is a big motivation for mining companies to focus on the operational efficiency of their utilities. Increasing the operational efficiency will decrease the energy intensity, resulting in lower electrical costs. However, the operational efficiency of each individual utility is directly affected by its corresponding infrastructure. The impact of infrastructure efficiency and limitations is discussed in more detail below.

1.3.3 Infrastructure efficiency and limitations

All utilities in a mine consist of different infrastructure. This ranges from pipe- and ventilation networks, instrumentation, storage equipment, machinery etc. Figure 1-6 illustrates the typical infrastructure of the previously discussed utilities found in an underground platinum mine and the complexity thereof. Effective use and management of the infrastructure will mitigate operational losses and promote an optimised mining cycle.

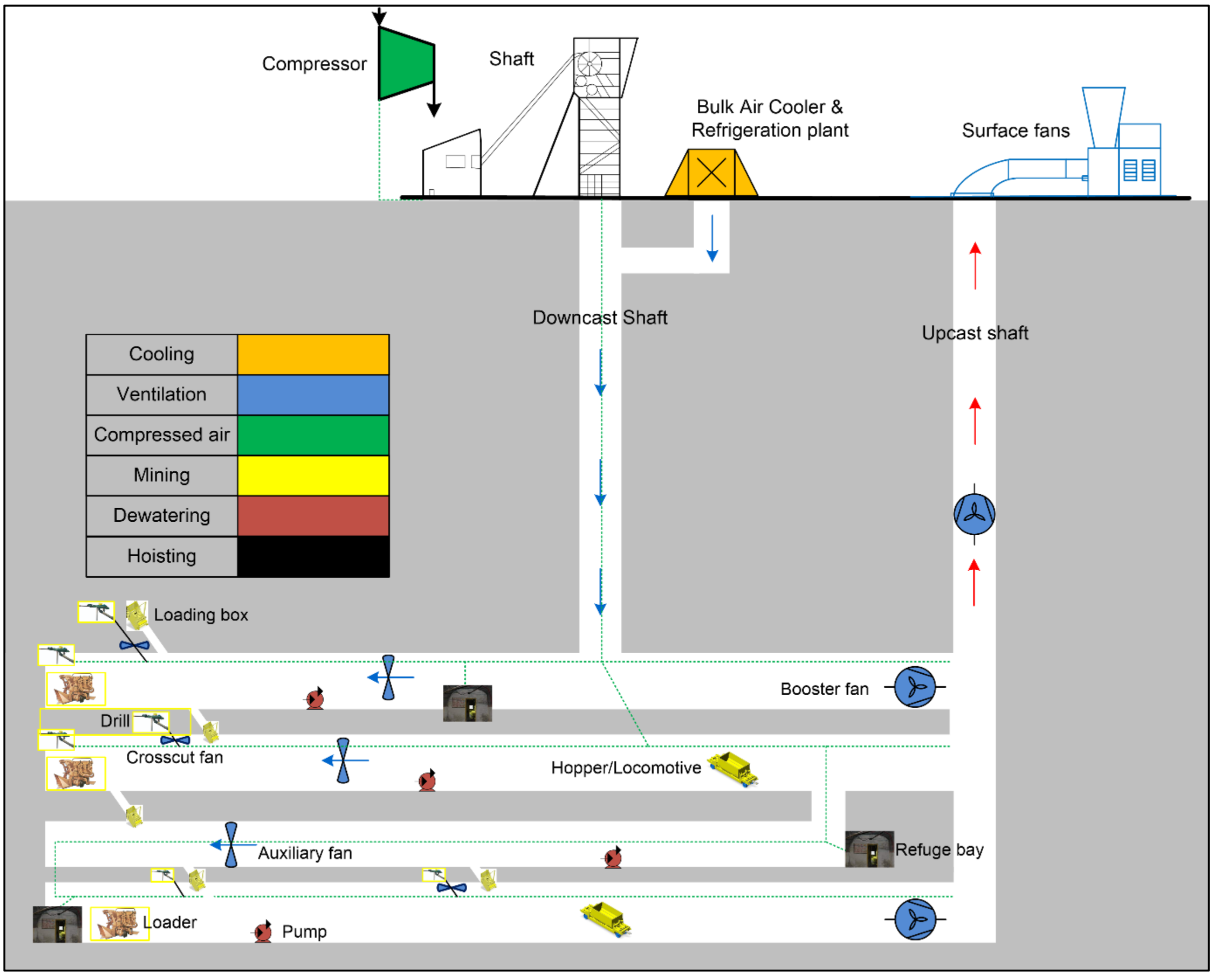

Figure 1-6: Deep-level mine layout with supporting utilities

Figure 1-6 showcases that ventilation and compressed air utilities are critical systems required by the mine for operation. Compressed air is used by multiple machinery for production while ventilation ensures safe working environments. As mining operations advance, these utilities are the most likely to be affected by mismanagement and misappropriation, which hinders the improvement of their operational efficiency [2].

As mines expand to extract ore from greater depths, the ventilation demand increases. To meet the demand, ventilation networks expand rapidly, causing them to become large and complex systems. The complexity of these systems makes it difficult to manage them effectively. This often results in shortfalls in the adequacy of sufficient ventilation which negatively impact the mine's operational efficiency and can place workers at risk. These shortfalls often re-occur as mine planning and design are primarily driven by production considerations rather than ventilation requirements [46].

Moreover, ventilation not only has a direct impact on operational expenses but also typically affects production in two ways:

1. Sufficient ventilation ensures safe and habitable working conditions as per the occupational health and safety mining regulations that are laid out by the Mine Health and Safety Council

of South Africa [47]. If the health and safety standards are not adhered to, the mine is periodically forced to close a specific section until the shortfalls are resolved, which negatively impacts production.

2. Sufficient ventilation aids in regulating the thermal comfort of mine personnel. The thermal comfort of mine personnel greatly influences the production output of the mine [48]. This is because precision, speed, and work force are negatively affected, while errors become more frequent in thermally uncomfortable conditions [49]. Several studies have indicated that if ventilation is insufficient, compressed air is often used as a subsidy for ventilation [4] [5] [29] [50]. This is due to the accessibility and convenience of readily available compressed air throughout the mining operation. This misappropriation of compressed air, because of ventilation mismanagement, results in the increased energy consumption of compressed air.

Thus, if these complex underground ventilation systems are not effectively managed, their efficiency drastically decreases. This will lead to ventilation shortfalls, negatively affecting production output as well as the efficiency of other utilities, specifically compressed air.

As mines expand for further development, the compressed air pipe network is expanded to supply additional air (for production) to the newly developed working areas. As these pipe networks expand, leaks, wastages and losses become more prominent. This causes these extensive networks to become more inefficient. Compressed air networks also deteriorate over time if they are not frequently inspected and maintained. Research showcased that compressed air networks are often inadequately maintained, causing rapid decay [27] [28].

As previously mentioned, compressed air is not only used by the end users for production operations, but also misappropriated for unregulated operations [51]. These unregulated operations refer to “self-ventilation” of underground work environments. Self-ventilation is the unregulated act of opening compressed air pipelines to supply additional ventilation to workers [34] and is regarded as pure wastage. This increases the demand for compressed air, causing substantial pressure drops across compressed air networks. This misappropriation hinders the ability to attain high compressed air network efficiency, whilst also having an adverse effect on the production output of the mining operation [52] [3]. The effect of misappropriation becomes more prevalent over the life of the mine as these compressed air networks expand and decay.

Up to 70% of the total compressed air demand can be attributable to these previously highlighted inefficiencies, found within the compressed air network [5] [53] [54]. Hence, the main reason for rising compressed air consumption is misappropriation and deteriorating network efficiency, to such an extent that self-ventilation, losses, and leaks account for the majority of underground compressed air demand/consumption [5] [27] [37] [54].

The potential impact of proper ventilation and compressed air network management and subsequently efficient energy management can only be exploited if it can be actively monitored from the surface. To enable active monitoring, the majority of mines use Supervisory Control and Data Acquisition (SCADA) systems, which monitor operations and parameters in real time. In certain circumstances, these SCADA systems have the capacity to store for future examination. SCADA systems are usually configured uniquely to each mine, which means SCADA systems can vary substantially between mines [55].

Unfortunately, numerous platinum mines in South Africa fail to monitor their infrastructure and utilities adequately through these SCADA systems [2]. This results in the operation of some of these networks without a defined performance metric. In such instances, data must be collected by taking manual measurements. This is often time-consuming and resource-intensive which makes it less appealing to mine operators (who are under tremendous pressure to achieve production targets). As a result, manual data collection and processing is often neglected or even disregarded.

1.3.4 Interpreting platinum mine challenges

It is evident that the operational costs of South African platinum mining operations have been increasing as a direct result of these previously discussed challenges. It is therefore vital that emphasis is placed on optimising the current mining method to prolong the life of mines and maximise profitability. This entails utilising the infrastructure more effectively to optimise production. One method of doing this is through effective energy management of compressed air and ventilation systems. However, effective energy management relies on practical methods to be able to identify ventilation and compressed air inefficiencies.

It was also highlighted that ventilation shortfalls are the main culprit for compressed air being misappropriated for underground “self-ventilation”; the largest contributor to compressed air inefficiencies [34]. This evidence suggests that compressed air network inefficiencies may be a by-product of ventilation mismanagement. Thus, a link between compressed air wastage and ventilation shortfalls could exist. An article that proved this link was published in the South African Journal of Industrial Engineering (SAJIE) – see Appendix A. The author of this dissertation is the leading author of the article. The method, result and conclusion of this article are discussed in Chapter 3.

1.4 Study motivation

1.4.1 Problem statement and need of the study

South African platinum mining operations have historically prioritised production, with limited focus being placed on energy management. However, in recent years, the formidable challenges that exert significant financial pressure on the industry have resulted in mining groups recognising that energy management and efficiency optimisation are vital for sustaining productivity.

Compressed air is a substantial contributor to the total energy cost of deep-level platinum mines in South Africa. A large contributor to this wastage is due to inadequate ventilation networks resulting in “self-ventilation” by misappropriating compressed air. Identifying and localising compressed air misappropriation (because of inadequate ventilation) in large and complex deep-level underground mines are challenging when limited to no instrumentation is available [56].

The identified problem is that current approaches for identifying high compressed air wastage areas and ventilation shortfalls are time-consuming and resource-intensive, and their efficacy is often hindered by limited data availability.

Existing literature suggested that there might be a correlation between compressed air wastage and ventilation shortfalls. Hypothesis testing was applied as part of the research of this study, and in a published article by van Gruting et. al. [57], a link is proved between compressed air wastage and ventilation shortfalls.

Following the above discussion, it is evident that a need exists to develop a simplified benchmarking method that can be utilised by the mine to identify high compressed air wastage areas effectively. The benchmarking method will also need to utilise the link between compressed air wastage and ventilation shortfalls to simplify the process of identifying ventilation shortfalls (the root cause for compressed air misappropriation) in deep-level platinum mines.

1.4.2 Study objectives

The foundation of this study is rooted in the dual facets of the problem statement – compressed air and ventilation. Given the potential interdependence between compressed air wastage and ventilation shortfalls, a comprehensive solution must address the complexities of both aspects. Consequently, it becomes imperative to prove the link between compressed air wastage and ventilation shortfalls as a foundational step, prior to addressing the need to identify compressed air wastage and ventilation shortfalls effectively. Hence, the following objectives have been defined to address the identified need:

<u>Study objective 1</u>

Prove the link between compressed air wastage and ventilation shortfalls[3].

[3] This link was proved in a published article by van Gruting et. al. [57] as part of the research completed for this study and is presented in Chapter 3 of this thesis.

Study objective 2

Develop a versatile, simplified and less resource-intensive benchmarking method to identify areas with high compressed air wastage.

Study objective 3

Develop a method (leveraging the link between compressed air wastage and ventilation shortfalls) to simplify identification and prioritisation of ventilation shortfalls in a shorter time period than existing identification methods.

The chronological sequence and structured progression through these study objectives ensures a comprehensive and effective approach to solving the identified problem.

1.4.3 Research methodology

To ensure that these study objectives are addressed, it is important to implement a methodical and logically structured research methodology. For this study, the waterfall research methodology is applied. The waterfall methodology uses a linear approach, where the development of the solution is broken into a sequence of objectives and detail tasks. It aids in a complete understanding of the deliverables and requirements to meet those deliverables [58]. Figure 1-7 elaborates on the methodology applied in this study, which will aid in the development of the solution.

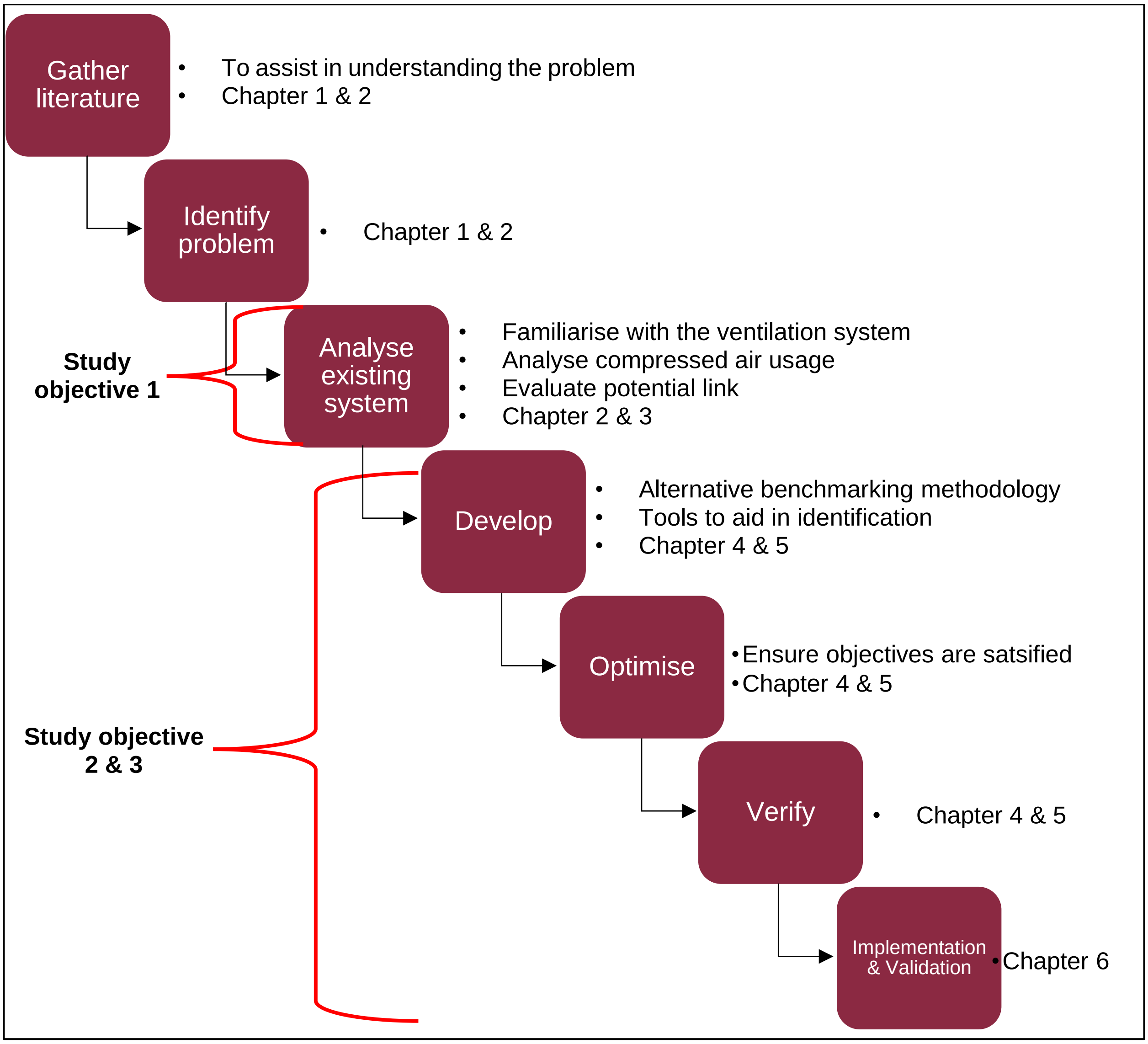

Figure 1-7: Waterfall Research methodology

The relevant steps in the methodology links with the indicated chapters, as elaborated on in the next section.

1.5 Document structure

This section provides an overview of the thesis, presenting a VENN diagram, as per Figure 1-8, that visually illustrates the main discussion points and focal areas covered in each chapter. The diagram serves as a concise representation of the interplay between the different chapters, highlighting the interconnectedness of the research. The diagram provides a roadmap of the thesis, allowing the navigation through the different sections and understanding the progression of research findings. Chapter 7, which provides a comprehensive summary of the entire thesis, is not included in the VENN diagram as it encompasses the entire scope of the diagram. Following the VENN diagram, a more detailed breakdown and discussion of each chapter are presented.

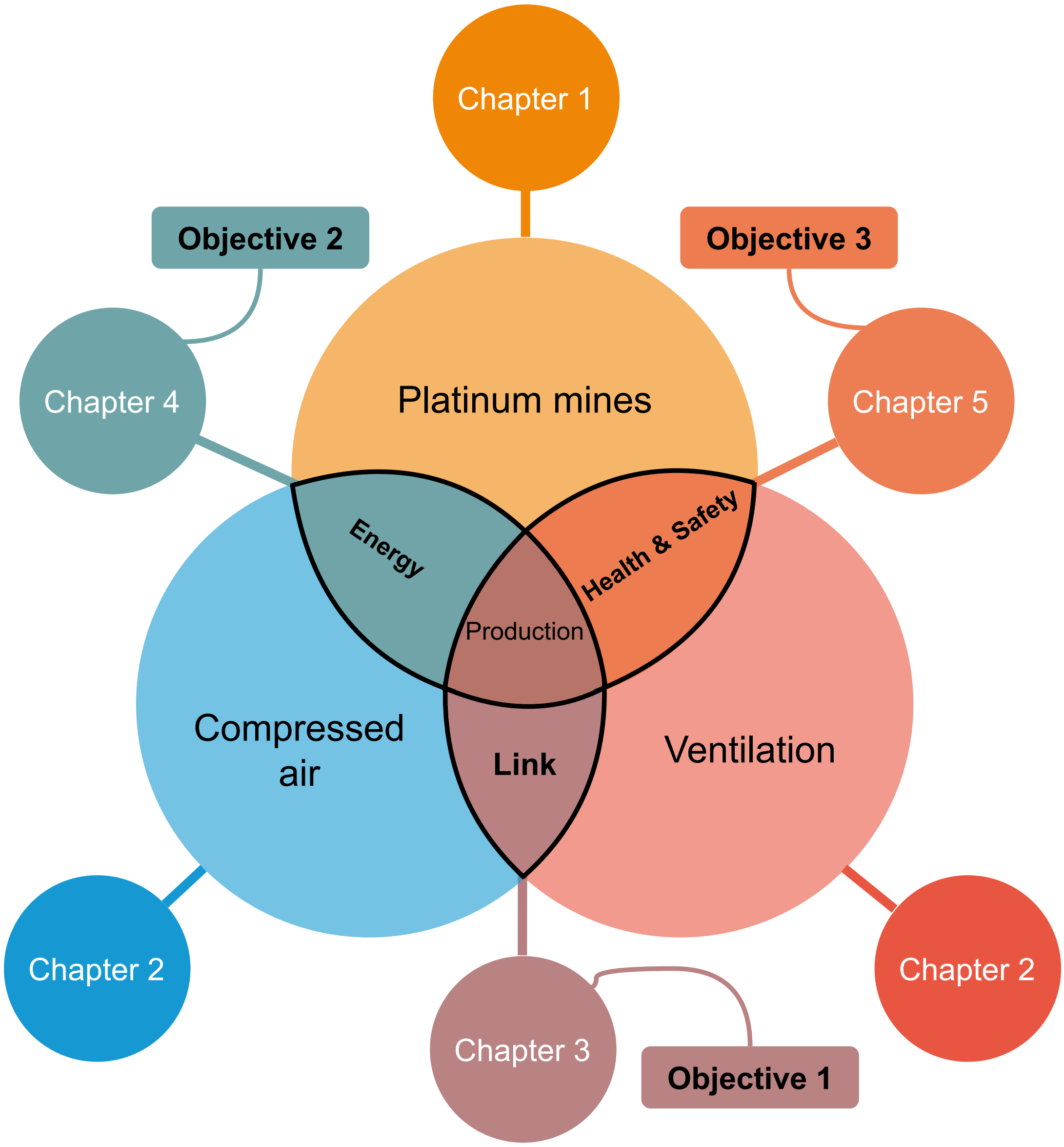

Figure 1-8: Dissertation overview

Chapter 1: A brief background of the industry to assist in the understanding of the problem. It depicts the problem this study aims to address and specifies the research objectives. The research methodology was also established as the Waterfall Research methodology, and an overview of the dissertation is provided.

Chapter 2: Provides a comprehensive overview of current technology and research to emphasise the need for the study, and to assess what research exists that could potentially aid with addressing the identified problem.

Chapter 3: Investigates the misappropriation of compressed air due to ventilation shortfalls to verify if a link exists between compressed air wastage and ventilation shortfalls. Verification of this link is critical for the development of a new benchmark approach using compressed air as a metric to identify ventilation shortfalls in Chapter 4. The main focus of Chapter 3 is the published article by van Gruting et. al. [57] as part of the research completed for this study.

Chapter 4: Describes the two new compressed air benchmark methods developed to address objective 2 of the study. This chapter will also provide verification of the two benchmark methods, used to identify compressed air wastage.

Chapter 5: Describes the methodology and sub-methods developed to address the problem identified in Chapter 1. This includes the development of a versatile methodology to identify and prioritise ventilation shortfalls. The proposed methodology addresses the identified need, highlighted in Chapter 1. This chapter will also provide verification of the methods within the newly developed methodology.

Chapter 6: Depicts the results obtained by implementing the new methodology on deep-level platinum mines in South Africa. These results serve as the validation of the solution developed in this study.

Chapter 7: The final chapter summarises the study and assesses the outcomes of the research with reference to the research objectives stated in Chapter 1. It is confirmed that the developed solution addresses the identified problem. Recommendations for future work based on this research are identified to further address the problem and gap identified in the research.

A summary of the dissertation overview is depicted in a VENN diagram, Figure 1-8, to illustrate each chapter discussion (and focus) and to indicate in which chapter each objective is satisfied. Chapter 7 is not included in the VENN diagram as it is a summary entailing the entire VENN diagram.

CHAPTER 2: VENTILATION AND COMPRESSED AIR IN DEEP-LEVEL MINES

2.1 Preamble

In Chapter 1 it was highlighted that deep-level platinum mines are experiencing persistent challenges that increase their operational costs. Labour costs are rising, putting pressure on deep-level mines to remain financially profitable. It was also highlighted that the thermal comfort of mine personnel is affected by the efficiency of the ventilation networks. If mine personnel are thermally uncomfortable due to ventilation shortfalls, their productivity, and consequently production output is hindered. This leads to an increased labour cost per kilogram of ore produced.

Due to the accessibility and convenience of readily available compressed air, it is misappropriated by mine personnel as an interim solution to combat the ventilation shortfalls. Hence, ventilation infrastructure efficiency and limitations affect the electrical cost required to produce compressed air. If shortfalls in a deep-level mine ventilation network can be effectively identified, it is expected that this will promote an optimised mining cycle, by reducing the occurrence of compressed air misappropriation, and improving the thermal comfort of underground personnel. A link between compressed air wastage and ventilation shortfalls was identified and proven in a published article van Gruting et. al. [57].

It is evident from Chapter 1 that ventilation shortfalls are one of the root causes for the increase in the electrical cost of compressed air and rising labour cost (per kilogram of ore produced). Thus, a need was identified to improve on the existing methods used to identify ventilation shortfalls, seeing that existing methods are resource- and time-intensive. Chapter 1 highlighted that there is a possible link between compressed air wastage and ventilation shortfalls. Therefore, compressed air and ventilation in deep-level mines need to be considered in more detail to develop a comprehensive understanding of these two intricate systems. This will aid in developing a method to identify ventilation shortfalls by utilising its link with compressed air wastage.

This chapter discusses and provides the background of deep-level mine ventilation networks as well as the various strategies utilised to monitor and optimise these networks. Additionally, it provides a comprehensive overview of compressed air, followed by an in-depth investigation into current strategies to identify and reduce compressed air wastage. The information presented in this chapter provides a foundational knowledge base which is essential for the development of a new method to identify ventilation shortfalls. Figure 2-1 provides an overview of Chapter 2 and highlights the important topics discussed.

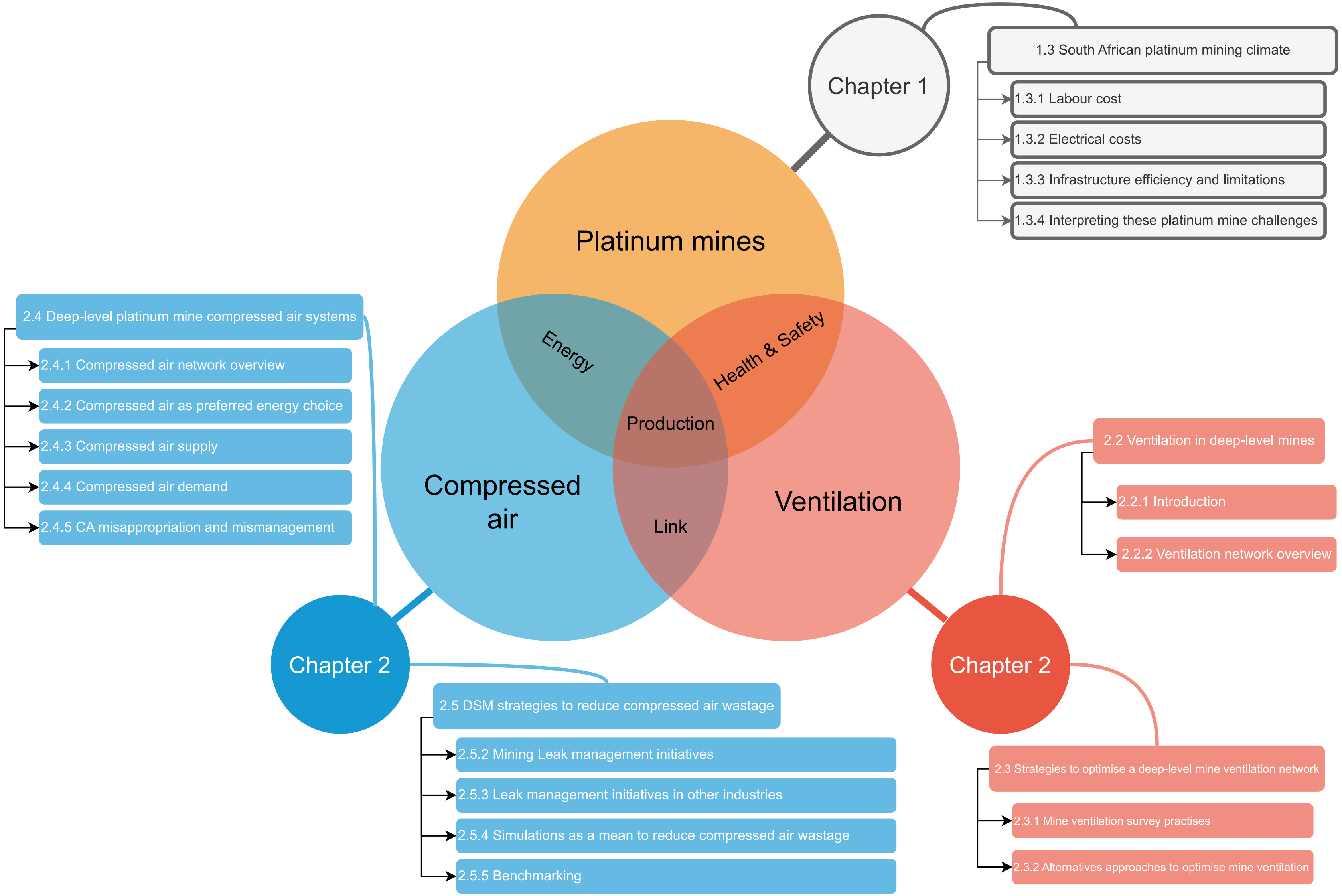

Figure 2-1: Overview of Chapter 2 and important topics to be discussed

2.2 Ventilation in deep-level mines

2.2.1 Introduction

The purpose of a ventilation system is to ensure that the health and safety of mining personnel are maintained. Ventilation systems must provide adequate quality and quantity of airflow to dilute contaminants and ventilate underground working environments [59] [60] [61] [62]. This should also be done in the most cost-effective manner. Mine ventilation is a very dynamic and intricate system, consisting of several interconnected sections and branches [1] [60] [63]. These systems are typically comprised of complex networks of airways, each with a multitude of ventilation components [63]. Ventilation forms an integral part of the mining cycle and without an appropriately designed and maintained ventilation network, the mining cycle would collapse [1]. This stresses the importance of an adequately designed and efficiently maintained ventilation system.

Optimising and identifying inefficiencies in these complicated networks, to ensure adequate ventilation requirements, is challenging [60] [63]. Shortfalls in ventilation adequacy are common and often recurring as mine planning and design are primarily driven by production considerations rather than ventilation requirements [46]. This results in compressed air being misappropriated for underground "self-ventilation", which is the largest contributor to compressed air wastage [46]. Thus, a further investigation into ventilation systems is needed to fully understand the possible causes for shortfalls in deep-level underground mines.

2.2.2 Ventilation network overview in deep-level mines

The primary focus of ventilation systems in deep-level underground mines is on the health and safety of mining personnel. Ventilation is defined as the process of regulating the supply of fresh air to underground working environments and the removal of heat as virgin rock temperatures can reach up to 70°C [64]. Thus, ventilation has three main objectives:

- To ensure working area temperatures are within the legal limit through adequate fresh air supply and cooling to personnel in the specific working areas. This is done by displacing the hot air from virgin rock radiation and reducing the humidity.
- To dilute the concentration of potentially hazardous gases emitted from mining the rock face [65].
- To eliminate dangerous dust particles that have been released while mining the rock face or after blasting has been completed [1].

If any one of the above-mentioned objectives is not met, it is regarded as a ventilation shortfall. The most common ventilation shortfall is inadequate ventilation and cooling to mine personnel in specific working areas. Inadequate ventilation increases the dry- and wet-bulb temperatures of the ambient air, which creates uncomfortable working environments. This has a direct impact on the thermal comfort of mine personnel as well as their health and safety (due to heat exhaustion and, in extreme cases, death).

Dry-bulb temperature refers to the true ambient temperature that is usually measured by a regular thermometer [66]. Wet-bulb is the temperature of the adiabatic saturation and is the lowest temperature at which water evaporates into the air [67]. Thermal comfort has the greatest influence on the comfort and productivity of occupants [68] [69]. Literature indicated that a wet-bulb temperature exceeding 27.4 °C in South African deep-level mines is deemed hot and uncomfortable and requires the implementation of safety measures to protect underground mining personnel [70] [71].

Ventilation not only promotes the health and safety of mine personnel but typically affects production in two ways:

1. Sufficient ventilation ensures safe and habitable working conditions, as per the occupational safety and health mining regulations that are laid out by the Mine Health and Safety Council of South Africa [47]. If the health and safety standards are not adhered to, the mine is forced to close a specific section, which will negatively impact production.

2. The thermal comfort of mine personnel greatly influences the production output of the mine [48]. This is because precision, speed, and work force is negatively affected, while errors become more frequent in these thermally uncomfortable conditions [49]. Overheated working environments will thus lead to unproductive mine personnel.

Thus, the quality of a ventilation network directly impacts production output.

Ventilation networks are vast and complex and are composed of numerous components and machines that operate in unison to manipulate the fresh air to underground working areas. These components and machines include auxiliary fans, booster fans, extraction fans, ventilation branches, air coolers, and regulators [72].

Suction pressure is created on the surface by large extraction fans, located on the surface. This pressure differential causes a flow down the downcast shaft, then through the mine ventilation network, allowing for the ventilation of various areas, and ultimately back up the upcast shaft. Booster fans are used to compensate for the increased airflow demand by overcoming the growing airflow resistance, while air coolers and regulators are used to regulate the air temperature. Auxiliary fans are usually installed in areas where additional ventilation is required [73].

Figure 2-2 reiterates the ventilation process described above and depicts a simplified representation of the complicated configuration of an underground ventilation network.

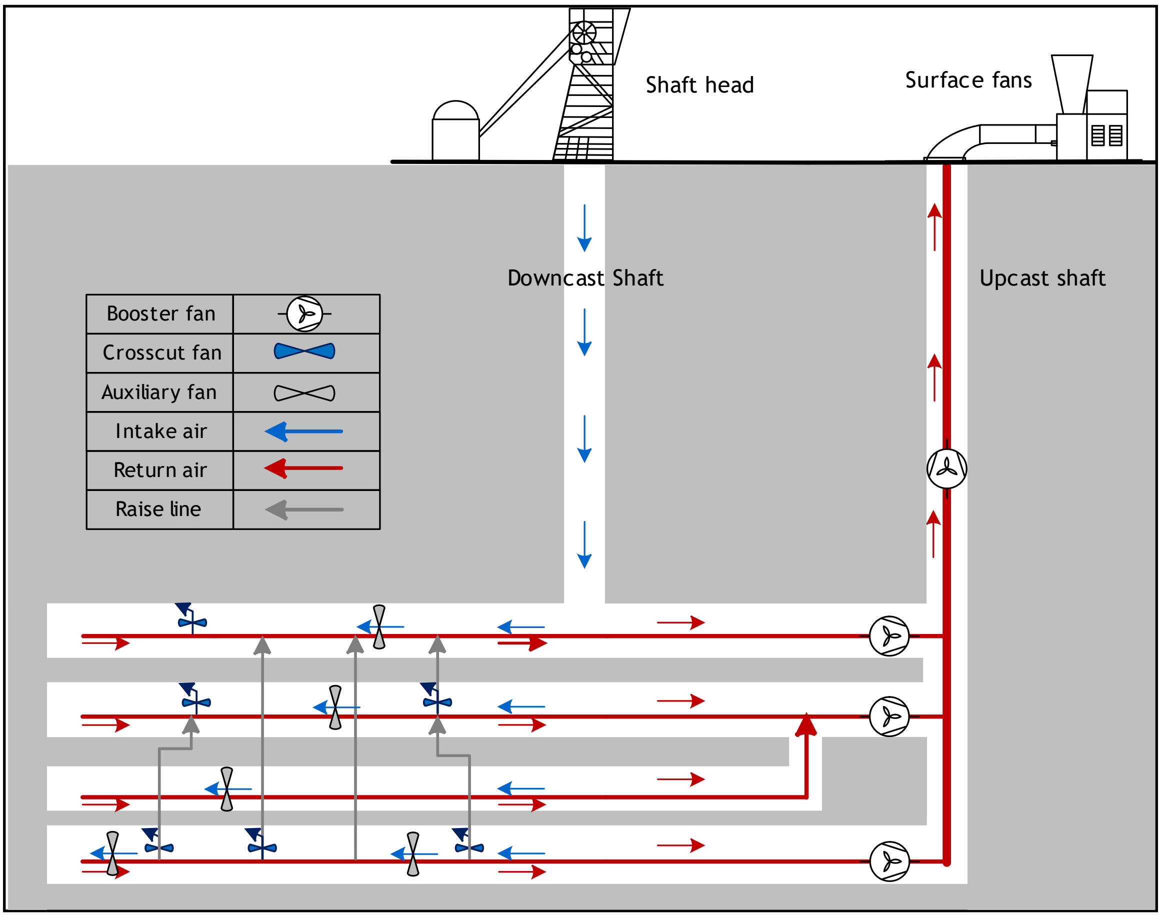

Figure 2-2: Typical configuration of an underground ventilation network

As a mine expands, the airflow demand increases, which yields a significant increase in ventilation requirements for the mine [48]. This can cause the size and complexity of a ventilation system to increase quickly, which increases the difficulty of managing the ventilation network [46] and to identify possible shortfalls. While the primary fan assembly is designed and installed with great care, less attention is paid to the ongoing optimisation and management of auxiliary ventilation systems [1]. This includes shaft collar design, fan isolation selection, and ductwork configurations [74]. Previous research has demonstrated that poorly designed and maintained auxiliary systems lead to significant inefficiencies [21]. This can cause ventilation shortfalls and impact production. De Villiers *et al.* (2019:938) found that fan and ducting inefficiencies were the largest contributors to total system inefficiency, suggesting that more attention should be given to subsurface ventilation practices.

It is essential that the ventilation network operates at optimal efficiency with minimal shortfalls as production of a mine is directly impacted by the quality of a ventilation network. Previous studies have shown that, to minimise shortfalls, ventilation networks must be monitored and assessed continuously [73] [75]. Existing methods to actively manage and assess ventilation networks for possible ventilation shortfalls include:

- **Simulation:** Simulation has become a critical part of the planning and development of ventilation networks [46]. It has proved to be a useful optimisation tool to manage a dynamic underground environment effectively. However, these simulation models are highly dependent on the accuracy, reliability, and continuity of the multivariable data sets as inputs [76]. Collecting the data required for the simulation models is challenging due to the dynamic nature and harsh conditions of deep-level mines [77]. The use of simulation packages is also often time-consuming and requires skilled workers [34].

- **Equipment and instrumentation:** Instrumentation forms a critical part of ventilation management and identifying shortfalls, as well as ensuring that health and safety standards are adhered to. Health and safety criteria, such as gas emissions, air pressure, air flow, and temperature, are actively monitored by equipment and instrumentation. These are all critical elements by which the efficacy of a ventilation network is evaluated. However, instrumentation is often limited and expensive and the installation time and resource costs are demanding, which often constrains the full potential of the ventilation network efficacy.

- **Physical examinations, inspections, and surveys:** This typically depends on the primary aim, but usually entails the collection of data on the air mass flow rate, pressure, and air thermal quality throughout the ventilation system [76]. Additionally, information about the infrastructure of the ventilation network is required [78]. The information collected varies depending on the purpose thereof, and may also include the location, status, and performance of fans, doors, regulators, underground coolers, and ducting infrastructure.

As platinum mines often have limited infrastructure to collect data (i.e. equipment and instrumentation), most mines rely on the latter (physical examinations, inspections, and surveys) as a means to investigate, survey, and manage a ventilation system. The strategies to investigate and survey a ventilation system are considered in more detail in the section below.

2.3 Strategies to identify ventilation shortfalls on deep-level mines

2.3.1 Mine ventilation survey practices

A ventilation survey is the structured process of collecting data from underground to assess the airflow, air quality, and pressure within the ventilation system [1] [79]. One of the primary goals of ventilation surveys is to measure the airflows and corresponding pressure drops throughout the network branches and to verify thermal conditions where mine personnel work [1] [48] [79].

To manage ventilation appropriately in accordance with safety regulations, the following ventilation control parameters should be measured and monitored [76] [80] [81]:

- Airflow quantity and thermal quality
- Presence of toxic gases
- Concentration of dust particles

Ensuring an adequate air quantity is essential for maintaining safe underground working conditions. It ensures the underground working area is ventilated and free from dust and hazardous gases, thereby enhancing overall workforce productivity [1] [79]. Thermal air quality pertains to the thermal comfort of mining personnel [82] and is affected by the temperature and humidity of the underground working area. Literature has emphasised that inadequate airflow quality directly impacts health and safety and has a detrimental effect on employee productivity. As the temperature and humidity increase, thermal comfort declines, negatively affecting the productivity of mining personnel.

The presence of hazardous gases underground presents significant health and safety risks for mining personnel [46] [83]. Common hazardous gases found underground include carbon dioxide, carbon monoxide, methane produced by diesel machinery, sulphide gases, and nitrogen oxide [46] [83]. Elevated dust concentrations are particularly linked to silicosis, lung disease, and tuberculosis, with silica dust being the primary culprit [1]. Hence, ventilation is utilised to transport dust to the surface using auxiliary ventilation systems.

Before any ventilation strategies can be realised, all micro-ventilation areas (including stopes) should be assessed. These ventilation assessments, with a high regard to safety, are mandated by law. Each underground working area must be visited regularly, and routine measurements taken at least once a month [1]. Hancock *et al.* (2018) [1] indicated that the objective of these routine measurements is to achieve the following:

- Ensure that work areas are ventilated and receive adequate airflow efficiently [79],
- Maintain up-to-date ventilation records [1] [79], and
- Confirm that distributions, quantities, and ventilation infrastructure are satisfactory, up to standard, and appropriately maintained [79].

Previous studies have provided suggested procedures to follow when conducting ventilation surveys, as presented in Figure 2-3 [76] [84].

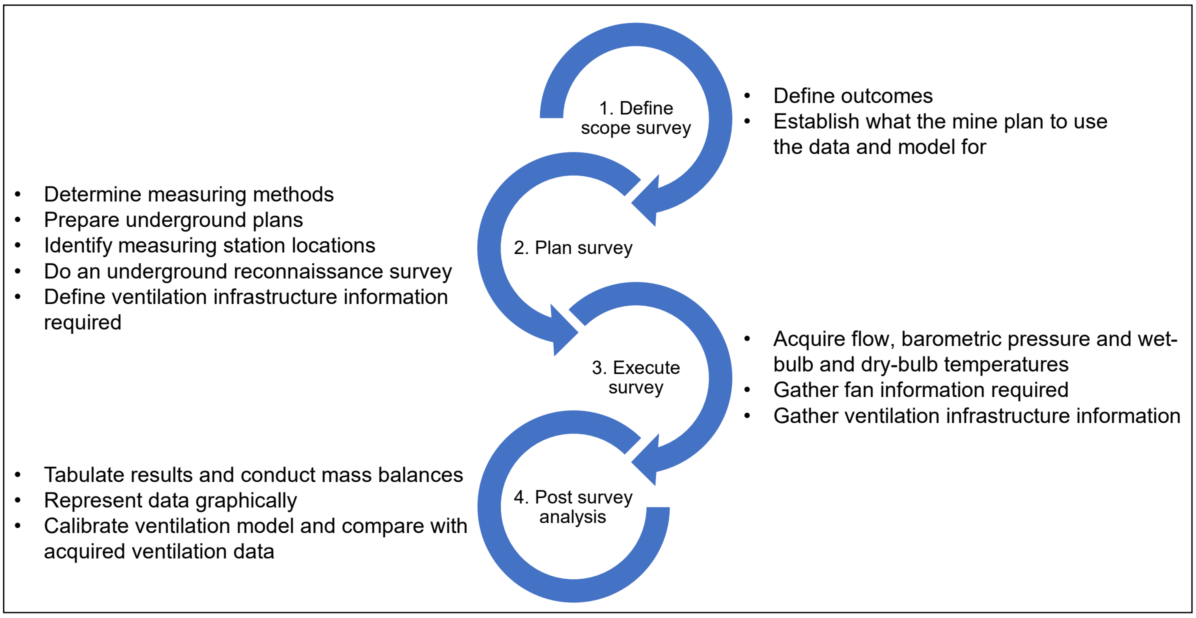

Figure 2-3: Proposed mine ventilation survey procedure [76]

Once the multivariable data from these detailed ventilation surveys are collected, parameters to evaluate the ventilation network can be calculated. These parameters are then used to make incremental adjustments to the ventilation controls. This is crucial to ensure that ventilation improvement is continuous as mines expand and develop further.

It is evident that ventilation surveys and processing multivariable data to do a system performance analysis are tedious processes which requires time, effort and skilled personnel [76]. However, as previously mentioned, mines tend to place more emphasis on production considerations rather than ventilation concerns. Hence, ventilation system performance analysis is often neglected.

The result is a reactive ventilation network instead of a proactive ventilation network. Simply put, ventilation networks deteriorate to the point where an underground workplace (or multiple workplaces) becomes inadequate and non-compliant with health and safety regulations. This is then only later identified when the surveys are done (once a month at a specific workplace).

2.3.2 Alternative approaches to optimise mine ventilation

There are limited studies that focus on identifying ventilation shortfalls in deep-level underground mines. However, to optimise a deep-level mine ventilation network, the inefficiencies within the ventilation network must be identified. Hence, this study will consider optimisation studies with specific focus on how the ventilation inefficiency was identified. Most of the studies on deep-level mine ventilation networks focus on:

- Improving ventilation efficiency through
    - Simulations [60] [85]
    - Theoretical models
- Use of algorithms to optimise the infrastructure of ventilation network [86], or
- Optimising auxiliary ventilation networks underground, often using simulations, for cost saving [87].

With recent advances in technology, simulations have become a dominant solution used in literature to evaluate ventilation networks [88]. When implemented correctly, simulations can be a proactive solution to mitigate prospective ventilation shortfalls before they even occur. However, most simulation models do not directly identify ventilation shortfalls. Moreover, simulation models require an abundance of data, skilled personnel, and are resource- and time-intensive [88]. Hence a need still exists for an alternative method to identify existing ventilation shortfalls.

Studies that have focussed on identifying ventilation shortfalls are listed and individually evaluated in Table 2-1. These studies are evaluated based on the following criteria:

A – Ventilation shortfall identification

B – Resource intensity (Low, Medium, High)

C – Time intensity (Low, Medium, High)

Table 2-1: Previous studies done on ventilation shortfall identification

Ref	A	B	C	**Title:** Shortfall
[89]	☑	Medium	Medium	**Temperature Prediction Model in the Main Ventilation System of an Underground Mine** The study requires the collection of multiple data points across the ventilation network (using temperature sensors) before a mathematical model can be created.
[90]	☑	High	Low	**Heat stress management in underground mines** The study uses continuous monitoring of strategic locations in a ventilation network to monitor the ventilation network. Continuous monitoring requires extensive amounts of instrumentation which is capital-intensive.
[91]	☑	High	Low	**Monitoring and assessment of underground climatic conditions using sensors and GIS tools**

Ref	A	B	C	**Title:** Shortfall
				This paper evaluates the concept of continuous monitoring of climatic conditions in an underground mine using geographic information system (GIS) tools and sensors. Continuous monitoring requires extensive amounts of instrumentation which is capital-intensive.
[92]	☑	High	High	**Application of ventilation management programs for improved mine safety** The study developed a ventilation management programme, and still resorts to comprehensive audits to identify ventilation shortfalls.
[76]	Limited	High	Medium	**Evaluating sub surface ventilation practices** The study developed a practical method to measure airflow underground. This will aid to reduce the time taken to do a ventilation survey. However, the study still made use of conventional audits which are time-consuming.
[1]	☑	High	Medium	**Improving the operational efficiency of deep-level mine ventilation systems** The study developed an improved ventilation survey practice using key performance indicators (KPIs) and made use of a simulation model to further identify ventilation inefficiencies. The survey still required personnel to do an extensive audit of the entire ventilation network to identify ventilation shortfalls. The simulation model also required an extensive amount of data which is labour- and resource-intensive.

From Table 2-1 it is concluded that the majority of existing research relies on simulations and/or digital twins, mathematical models, or improved conventional survey methods to identify ventilation shortfalls. These studies highlight the need for an alternative method that is less resource-intensive, time efficient, and does not entail auditing the entire ventilation network to identify ventilation shortfalls.

2.4 Deep-level platinum mine compressed air systems

2.4.1 Compressed air network overview in deep-level platinum mines

Before any strategies can be released to reduce compressed air consumption, the purpose and use of compressed air in deep-level platinum mines must first be thoroughly investigated. Deep-level platinum mining consists of a vast underground tunnel network to access mineral deposits, with compressed air serving as the primarily utilised energy source required to achieve production outputs [50] [55]. This is due to its adaptability and upgradability, as well as the simplicity of use and consistency [93]. Compressed air branching into these difference tunnels forms a compressed air network. The management of these compressed air networks is classified into two main sections: demand (Section 2.4.4) and supply (Section 2.4.3) [4] [34].

The supply side is further divided into the following two key components:

Compressed air production: This involves multi-stage compressors that produce compressed air at a certain flow and pressure demand. The compressed air feeds directly into a compressed air network. These compressors can either feed into a compressed air ring, supplying multiple shafts, or work as stand-alone compressors supplying only a single shaft.

Compressed air distribution: Pipe networks of different sizes distribute the compressed air from the compressors (supply) to the end-users (demand). This can either be to direct end-users or to various shafts. These shafts are often interconnected by these pipe networks and are regarded as a compressed air ring.

The demand side is composed of numerous end-users that convert the compressed air energy to mechanical energy. Figure 2-4 provides an overview of a simplified compressed air network and illustrates the supply-and-demand split which is discussed in more detail in Sections 2.4.3 and 2.4.4.

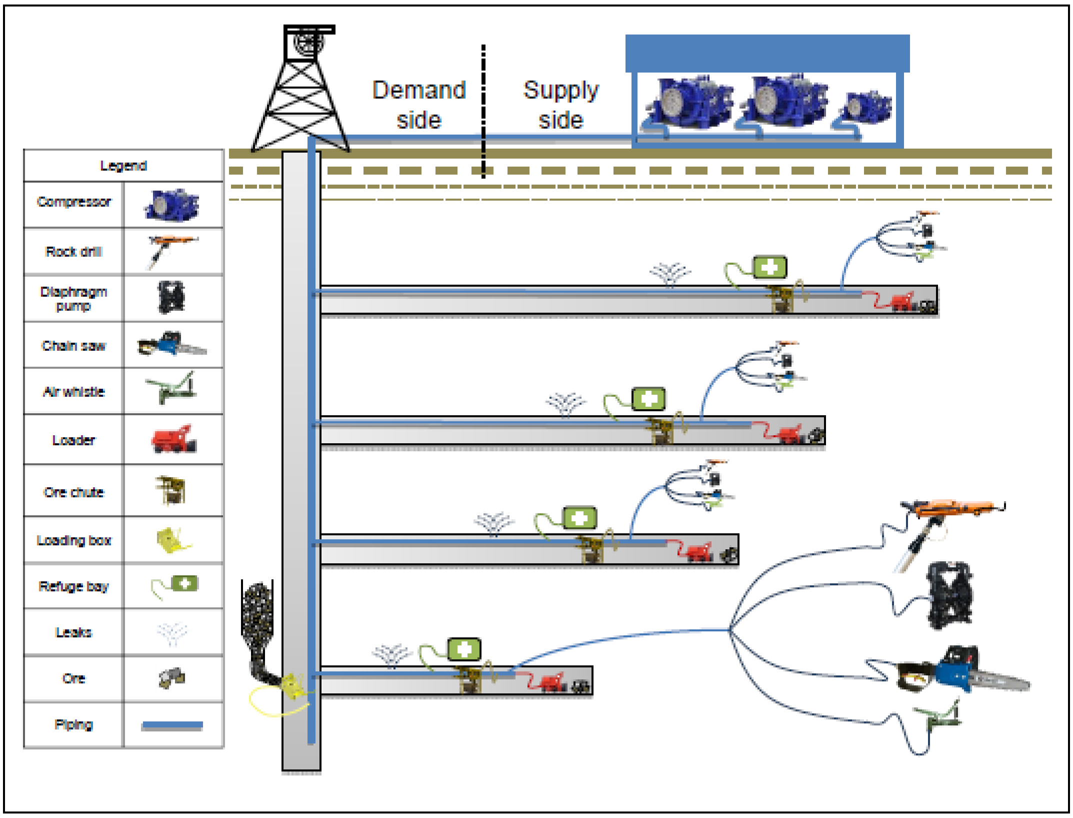

Figure 2-4: Simplified illustration of a deep-level compressed air network, end users and supply-demand split [50]**.**

2.4.2 Compressed air as preferred energy choice

The compressed air system is a vital component of all operations in a deep-level mine. The majority of deep-level platinum mining operations (in South Africa) use compressed air as their primary form of mechanical power [50]. Chapter 1 highlighted that compressed air accounts for 18% of the total electricity consumption on a mine. In extreme cases, this number can jump to 50% [37] [38]. Compressed air is also characterised as a very inefficient resource with efficiencies as low as 10%-15% [34] [94] [95]. There are several alternative technologies to compressed air, but the adoption of these new technologies has been slow, with only a few mines in South Africa that have replaced compressed air as their primary source of mechanical power [50].

Literature has indicated that mining companies are reluctant to adopt new technologies due the extensive nature and complexity of existing compressed air networks, large capital requirements to convert the whole system, and insufficient infrastructure to accommodate the additional electrical and water requirements [50]. Pertaining to these previous challenges, mining companies are more likely to extend their current compressed air network and improve their energy efficiency rather than to convert to new technologies. Therefore, it is crucial to pursue compressed air optimisation strategies for current systems, as far as possible [37].

2.4.3 Compressed air supply

Although demand side management is the focus of this study, it is beneficial to understand the supply side to realise the energy savings potential created by demand side management initiatives. Therefore, a summary of compressed air production is provided, followed by a more detailed description of compressed air distribution. This will help to strengthen the argument that compressed air networks are extensive systems, making it difficult to identify inefficiencies.

2.4.3.1 Compressed air production

A high volume of compressed air (at pressures of between 400 and 600 kPa) is often required for deep-level mines. Centrifugal compressors, ranging from 1MW to 15MW, are typically used to produce the high volume of compressed air [4] [94] [96] [97]. Centrifugal compressors can regulate the compressed air flow by means of mechanisms such as blow-off valves and inlet guide vanes [2] [97] [98]. These compressors can be operated simultaneously, in several different configurations, to accommodate the pressure and flow demand of different shafts [99]. Therefore, these compressors are the preferred choice for energy production, due to their mechanical simplicity, ease of use, and dynamic operational capabilities [4].

2.4.3.2 Compressed air distribution

A compressed air distribution network is comprised of a network of steel pipes that stretch across vast distances above ground and underground to various end users [29]. The length of the pipes range from 6 m to 9 m, often connected over several kilometres, while the size of these pipes ranges from 150 mm to as large as 700 mm [34]. The compressors and the different shafts are connected by this network of pipes, to aid in matching the supply and demand on various shafts [4] [7] [29]. Figure 2-5 depicts a simple diagram of a compressed air ring (on surface), commonly used by large platinum deep-level mines.

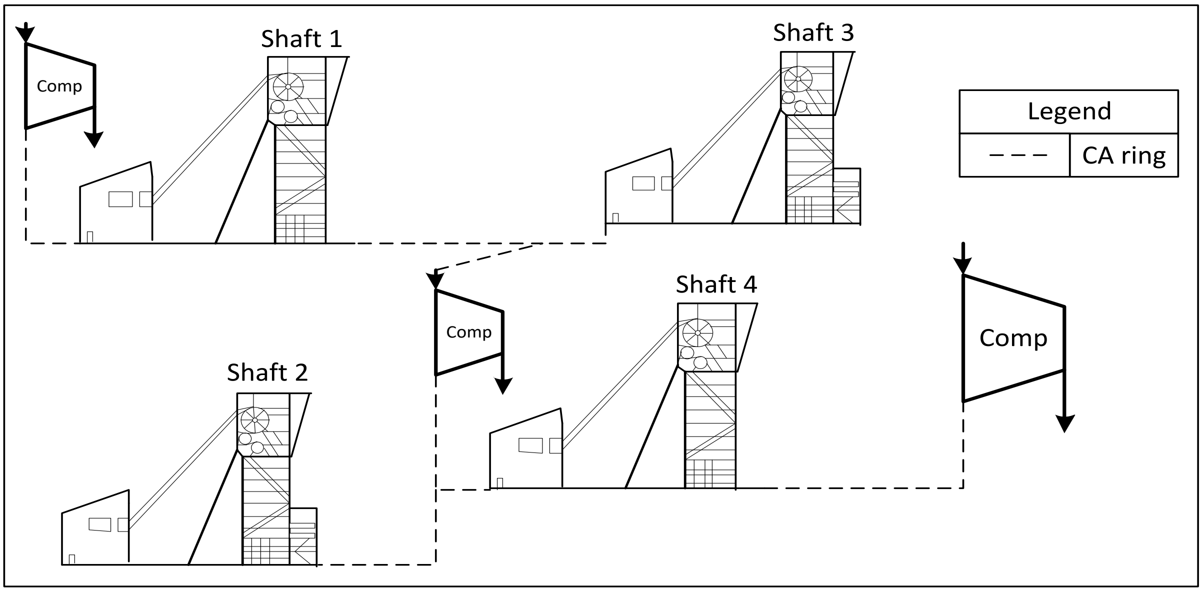

Figure 2-5: Compressed air ring found on surface of a deep-level platinum mine

This compressed air network extends into underground levels. From there the network expands into half-levels, commonly referred to as half-level main haulages. These haulages provide passage for the mining personnel, rock transport, and operational infrastructure (i.e. compressed air network, ventilation infrastructure, electricity, and water) [4]. The haulages branch off into small passageways, commonly known as crosscuts.

Crosscuts provide a travelling way into the working area (where the ore is mined), known as a stope [4]. The steel compressed air pipes are replaced by rubber or plastic pipes when they branch off from the main haulage, into the stopes, as these stopes continuously change and advance[4]. A simplified layout of a typical Platinum mine stope is shown in Figure 2-6.

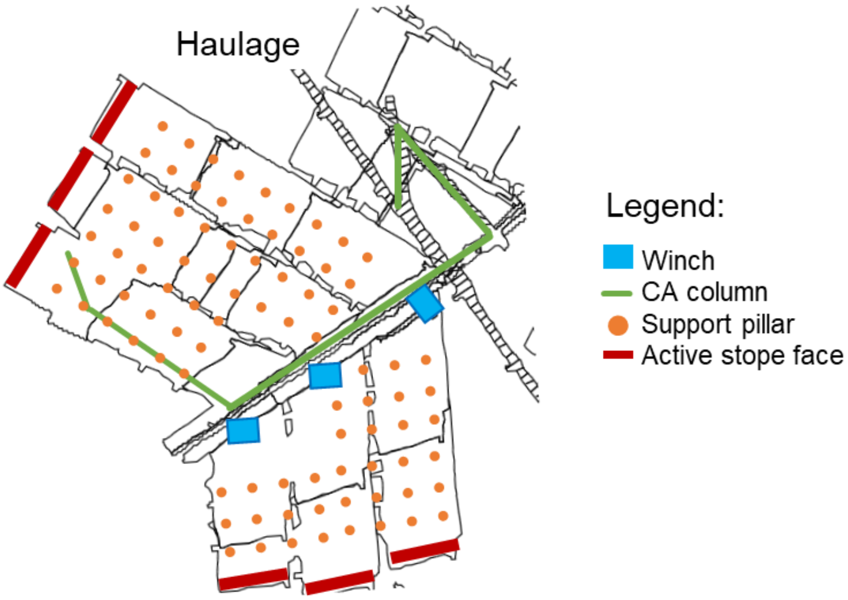

Figure 2-6: Simplified top view of a typical platinum mine stope layout [4]

It is essential to remember that compressed air, water, and electricity infrastructure must all continue along the main haulage, cross cuts and travelling ways until it reaches the stopes [4]. This compressed air network must also be continuously pressurised, so that any pneumatic machinery (within the main haulages and/or stopes) can be directly connected to the compressed air network at any time [50]. The supply side thus consists of compressors that produce air at a desired pressure and flow and a pipe network that distributes it all the way to the stopes.

2.4.4 Compressed air demand

Compressed air is used extensively in deep-level mining operations because of its versatility, ease of use, and safety (compared with alternative technologies that can be used for the same purposes). In order to realise the significance of demand side management initiatives in deep-level mining operations, it is imperative to have a comprehensive understanding of processes used in deep-level mining operations that utilise compressed air. The demand side is made up of several end-users that convert compressed air (pressure and flow energy) to mechanical energy [55]. When discussing these compressed air end users, it is crucial to understand the time periods, further referred to as shifts, in which these end-users are present in the mining cycle.

2.4.4.1 Overview of different operational periods in a mining cycle

Deep-level mines typically operate on a 24-hour schedule with three governing shifts [3] [4], each having different compressed air end-users [34] [100]. These shifts are:

1. The drilling shift: Rock drill operators (RDO's) use pneumatic drills to drill blastholes into the face of the stope (which is where most of the ore is extracted). Additionally, during drilling shift, rock drills and/or drill rigs are also used to drill centre gullies.

2. The blasting shift[4]: Explosives are placed in the blastholes that were drilled during the drilling shift. The explosive is a blasting agent usually consisting of ammonium nitrate and fuel oil[5]. Before the explosives are detonated, all mining personnel are cleared from underground as no personnel are permitted underground during blasting shifts [3] [4] [101]. Hence, the compressed air consumption is at its lowest during the blasting shift as no compressed air end-users are present during this period.

3. The cleaning and auxiliary shift: Three hours after blasting, the blasting area is considered safe. The blasted ore is transported from the face of the stope, usually with multiple winches, to ore pass (chutes) and loading boxes [2]. This is then gravity fed into ore locomotives (hoppers) that deposit the ore into station ore passes (tippers). The cleaning shift is regarded

[4] Blasting period (official terminology) is referred to as blasting shift in the remainder of this thesis.
[5] *Hustrulid, W. Andrew, Clark, George B. and Mero, John Lawrence. "Mining." Encyclopaedia Britannica, April 25, 2017. https://www.britannica.com/technology/mining.*

as a low compressed air consumption period as only refuge bays, loading boxes and pneumatic loaders consume compressed air. Refuge bays must remain open (as per the Mine Health and Safety Act) [102] and continuously consume compressed air, while loading boxes and pneumatic loaders periodically consume compressed air during the cleaning shift.

A typical 24-hour mining cycle on a deep-level platinum mine is depicted in Figure 2-7.

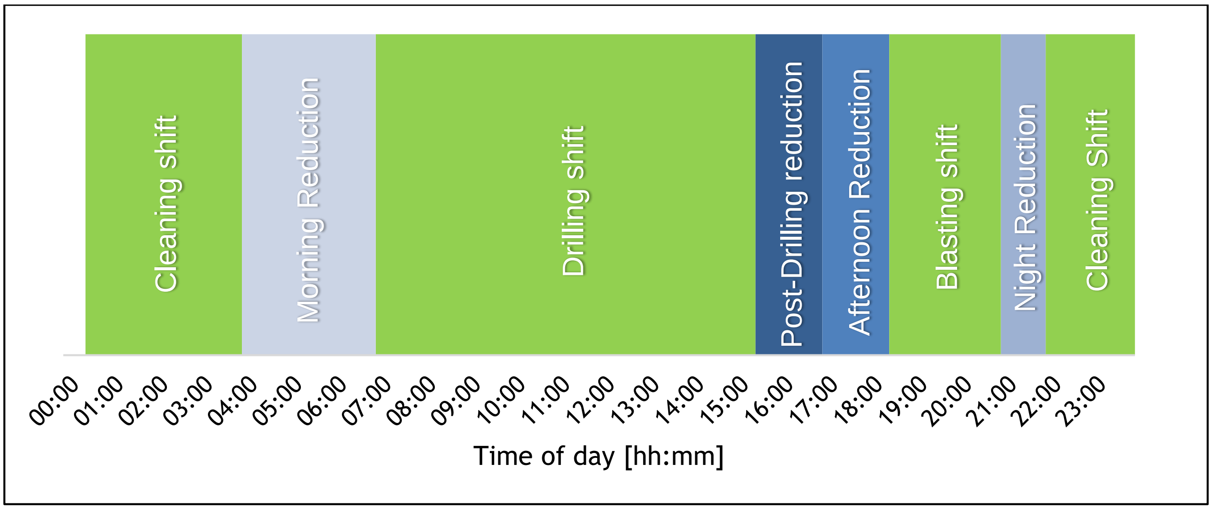

Figure 2-7: Typical 24-hour cycle on a deep-level platinum mine with three governing shifts

Figure 2-7 depicts the governing shifts (highlighted in green) as well as additional time periods, best described as changeover or reduction shifts. During these periods, a changeover happens between the different shifts. The personnel of the next shift are transported from surface, with a cage, to the specific levels. From there, personnel must travel by foot (up to 10 km) to reach their working area [3] [16] [103]. The personnel from the previous shift are transported to the surface. It is important to note that there are usually few to no end-users present during these changeover shifts. Having an in-depth knowledge of the shift schedules and individual shift demands is crucial to optimise the energy efficiency of compressed air [50]. The next section elaborates on the typical end-users present in a 24-hour mining cycle, the equipment used and their operational requirements.

2.4.4.2 Overview of critical end-users, equipment, and operational requirements

Compressed air is required by a variety of equipment utilised for mining. Various pieces of equipment are used in each shift, which are specific to the operation that needs to be performed during that mining shift [28] [96] [29]. For this study specific focus is placed on the pneumatic machinery (and their demand) used in these different shifts. All the equipment and end-users are usually connected to one compressed air network. Thus, to ensure uninterrupted production, the pressure demand of the end-user component with the highest pressure requirements at any given time must be satisfied [29] [96] [97].

Below are specifics on some typical compressed air end-users, divided into two distinct categories:

1. Authorised compressed air end-users
2. Prohibited compressed air end-user

Table 2-2 provides a summary of the typical category 1 - authorised compressed air end-users (that are essential to production), their flow, and pressure demand, as well as the shift within which the equipment is normally found. The equipment with the highest pressure requirement for each shift is also highlighted as follow: green – drilling shift, red – blasting shift, and blue – cleaning shift.

Table 2-2: Overview of compressed air equipment and their operational requirements [4] [28] [29] [56] [104]

End-user	Description	Flow demand [kg/s]	Pressure demand [kPa]	Shift
Pneumatic rock drill	Drills utilising compressed air to drill holes into the rock face[4].	0.12	450 – 620	Drilling
Loading box (ore chute)	The blasted ore is placed into the loading box. A pneumatic piston opens the loading box, allowing the ore to fall into a track-bound hopper. In contrast to pneumatic drills, which operate almost continuously, loading boxes are only utilised for brief periods when ore handling is necessary. Additionally, there are substantially fewer loading boxes, than drills, in operation.	0.004-0.1	400-500	Cleaning
Pneumatic loader	These loaders are track-bound and utilise compressed air to transfer the waste rock from haulage development ends into the hopper cars. The loader also uses compressed air to move forward and backwards on the train track. Typically, there is just one pneumatic loader per half-level.	0.8 [104]	350-450	Cleaning

End-user	Description	Flow demand [kg/s]	Pressure demand [kPa]	Shift
Rock breakers	After the ore and waste rock release from rock faces, large pneumatic breakers are used to reduce the rock and ore to manageable sizes.	0.8	450	Drilling
Refuge bays	Refuge bays are a legal requirement in the mine. They provide a place of safety for mine personnel in emergency events. Refuge bays must be constantly supplied with air [102]. Compressed air is usually utilised to ventilate a refuge bay because it is non-toxic and breathable. The constant flow of compressed air creates a positive pressure boundary in the refuge bay, meaning the pressure is higher than its surroundings [46]. This ensures that hazardous gases cannot enter the refuge bay.	< 0.06	150-200	All

Unfortunately, compressed air is not only used by the end-users for production operations, but also misappropriated for unregulated operations [51]. These unregulated operations, which form part of category 2 – Prohibited Compressed air end-users – include "self-ventilation" of underground work environments and other leaks. These unregulated operations result in erratic and unwanted compressed air demand. Consequently, additional energy is required to maintain the flow and pressure requirement [100] [6] [105] [34]. Misappropriation and mismanagement of compressed air is discussed in more detail in the section that follows.

2.4.5 Compressed air misappropriation and mismanagement

Multiple studies have highlighted the negative impact of misappropriation and mismanagement, which form part of prohibited compressed air end-users, to the total consumption of compressed air in deep-level mines [4] [5] [37] [50] [106]. The presence of prohibited end-users increases the constant baseload flow required to meet the operational requirements of end-users [5] [34] [107], which hinders operational efficiencies and negatively impacts production [3] [5] [50].

2.4.5.1 Compressed air misappropriation

Compressed air is misappropriated when it is utilised for operations that are outside of the defined scope of operation, i.e. prohibited operations. Compressed air is often misappropriated in deep-level platinum mines due to the culture that condones this wastage or because mining personnel are unaware of the cost of compressed air [4] [50] [93].

The most prevalent forms of compressed air misappropriation are ventilating with compressed air and negligent personnel leaving inactive equipment running or not isolating inactive areas [29] [50] [108]. Direct ventilation in the stoping area, with a hose or piercing the rubber piping with a nail, and ventilation by means of an air amplifier are the two most significant forms of compressed air misappropriation in deep-level mining operations [96] [107] [108]. This misappropriation causes excessive compressed air usage, which thus has a detrimental impact on the compressed air network efficiency.

2.4.5.2 Compressed air mismanagement

Mismanagement of compressed air systems in the deep-level mining industry is also a significant contributor to large baseload consumptions. Mismanagement refers to inadequate maintenance and repair of existing compressed air systems. Repairing system leaks and blanking off inactive working areas, specifically crosscuts, are two key issues associated with compressed air mismanagement. Leaks in the compressed air system are a direct result of the harsh underground environments which cause the compressed air network infrastructure to deteriorate [93] [103].

Compressed air mismanagement often recurs due to poor maintenance awareness, and because of the size and complexity of compressed air networks underground, few people are familiar with the underground distribution network. Since production is the primary objective of mining operations, misappropriation and mismanagement are often disregarded by mining personnel. However, the impact of the above-mentioned factors on production are significant and become more prominent as compressed air networks expand. The effect of compressed air misappropriation and mismanagement on the system efficiency is discussed in more detail below.

2.4.5.3 Extent of misappropriation and mismanagement

The effect of prohibited end-users is significant, and some studies suggest that it can account for up to 75% of the total compressed air consumption [4] [50]. Prohibited end-users contribute to the baseload consumption of compressed air because they are a constant consumer throughout the 24-hour mining cycle. They do not contribute to production; therefore, their consumption directly reduces the efficiency of the compressed air system.

It is important to understand that because prohibited end-users are continuous throughout the 24-hour mining cycle, their impact on the compressed air system varies with the supply pressure. Their consumption is also dependent on the orifice size, thus highlighting why self-ventilation has a much more detrimental effect on the compressed air efficiency, when compared with smaller flange leaks and holes in the rubber piping. Figure 2-8 illustrates the effect of a leak, based on different supply pressures and orifice diameters.

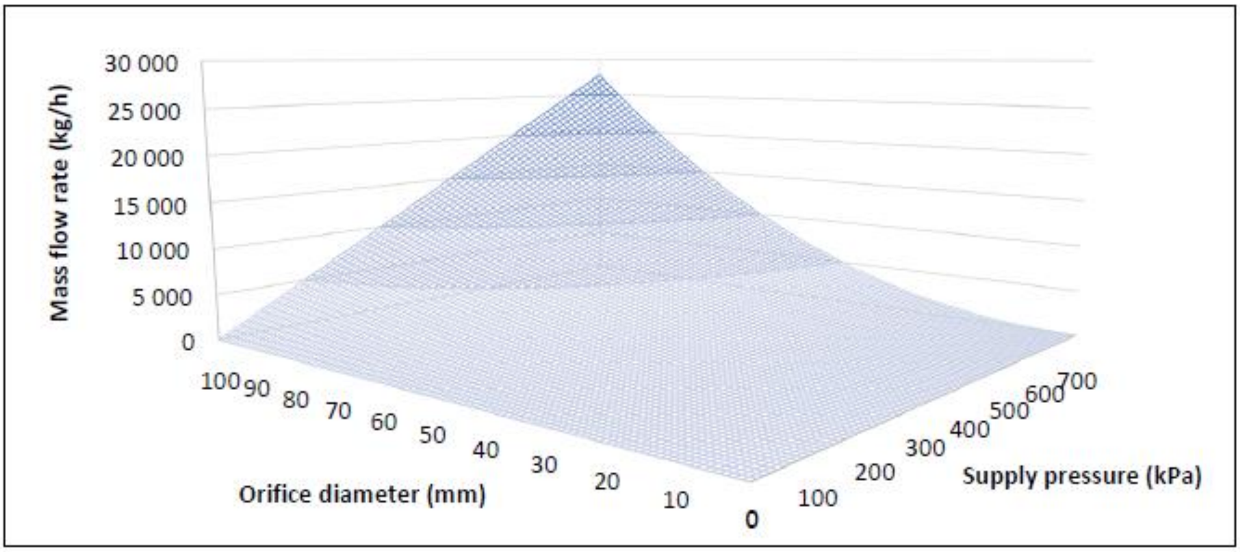

Figure 2-8: Illustration of relationship between orifice diameter, supply pressure and mass flow rate of a leak (adapted from [50]**)**

Figure 2-8 highlights that prohibited end-users have a linear relationship between the consumption and the supply pressure as well as an exponential relationship between the consumption and orifice diameter. This highlights the importance of identifying compressed air wastage. Additionally, it showcases that self-ventilation (with open-ended pipes that have a large orifice diameter) creates a substantial amount of compressed air wastage. This strengthens the argument that compressed air wastage could potentially be used as a leading indicator for ventilation shortfalls.

A study by Zietsman [4] also showcased the effect of prohibited compressed air end-users on the compressed air consumption during a typical 24-hour mining profile. Zietsman [4] made use of a simulation model to compare the theoretical consumption of authorised compressed air users against the actual consumption of a deep-level mine. The difference between the two consumption profiles highlighted the consumption of the prohibited compressed air end-users. This is shown in Figure 2-9.

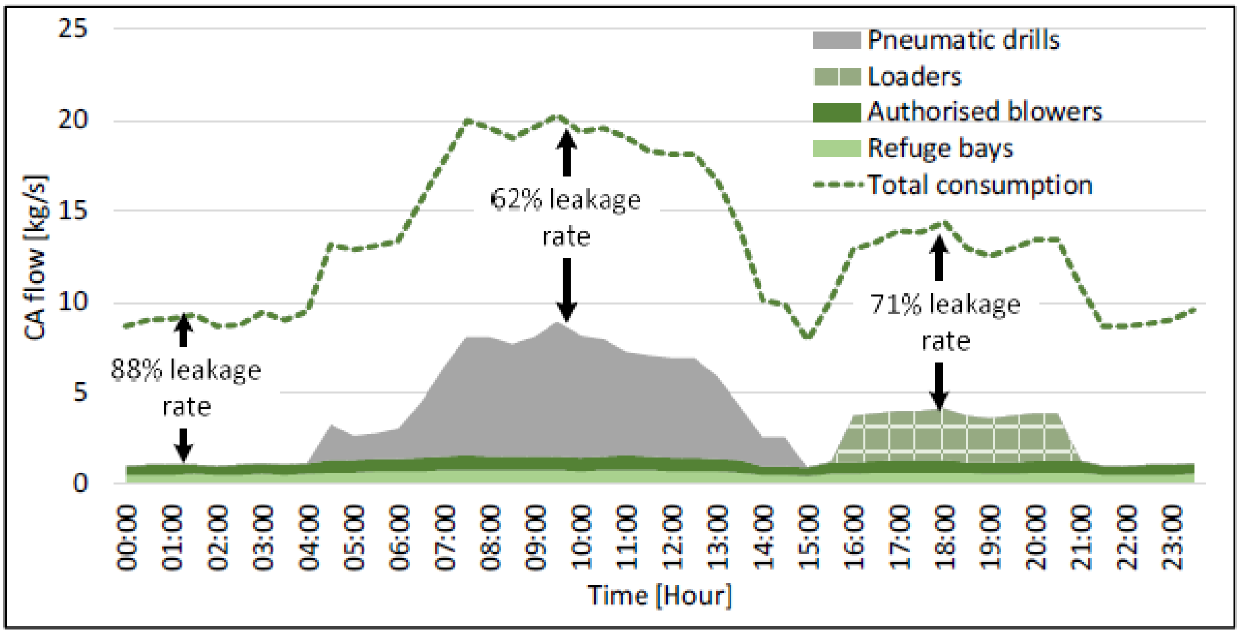

Figure 2-9: Compressed air consumption of authorised compressed air end-users vs actual consumption (adapted from [4])

From the data in Figure 2-9, there is an average difference of approximately 75% between theoretical consumption and actual consumption. Zietsman [4] noted that the difference is attributed to prohibited compressed air end-users. The study by Zietsman [4] highlights two important aspects which link back to the need for this study:

- The extensive and continuous difference between theoretical consumption and actual consumption over the 24-hour profile showcases that there is a high probability of ‘self- ventilation’. Since there is a link between compressed air wastage and ventilation shortfalls[6], this difference is likely due to ventilation shortfalls in numerous areas underground.

- The importance of identifying compressed air wastage areas. Having a reliable and less resource-intensive method to identify compressed air wastage of prohibited end-users will help reduce the total compressed consumption, thus reducing the compressed air baseload consumption.

It is evident that the primary cause of compressed air network inefficiencies in deep-level mining operations stems from misappropriation and mismanagement of compressed air. The compressed air wastage caused by prohibited end-users will only get worse as these compressed air networks continue to expand [4] [50]. To combat the effect of prohibited compressed air end-users, multiple

[6] Discussed in Chapter 3 – published article.

studies have turned to engineering solutions. These solutions include supply- and demand-side management initiatives.

Supply-side management initiatives include methods such as compressor control and guide vane control. These initiatives control the supply of compressed air and reduce the total compressed air consumption by limiting the consumption of both authorised and prohibited compressed air end-users.

However, the ratio of consumption between these two consumers tends to remain constant [50]. Hence, while these supply-side management initiatives can help mitigate the effects of prohibited end-users, they only treat the symptoms of prohibited end-users (i.e. leaks, pierced piping, and open-ended hoses used for self-ventilation). Therefore, supply side management solutions will not be investigated as they artificially reduce the wastage and do not address the root cause.

A breakdown of existing demand-side management strategies is discussed in more detail in the section to follow. This includes initiatives and solutions to minimise and identify compressed air wastage.

2.5 Demand-side management strategies to reduce compressed air wastage

2.5.1 Preamble

Section 2.4 highlighted that compressed air systems in deep-level mines are large and complex systems, operating at low efficiencies due to misappropriation and mismanagement of compressed air. The root cause of low inefficiencies is due to prohibited end-users within the compressed air network. This section evaluates available techniques and technologies that aim to combat low system efficiencies through demand-side management initiatives.

2.5.2 Mining leak management initiatives

2.5.2.1 Conventional visual audits

Prohibited end-users in a compressed air system increase the constant baseload flow and can contribute up to 75% of the total compressed air consumption [4] [5] [50]. Identifying these prohibited end-users and rectifying them is one of the most effective methods to improve the compressed air network efficiency [3]. However, identifying and rectifying prohibited compressed air-end users is no easy task. Compressed air networks are large and complex, and some parts are often inaccessible due to safety risks, making it challenging to improve the efficiency of compressed air networks [56]. Additionally, compared with other fluids such as steam and water, compressed air leaks are harder to identify through visual methods [56] [107].

The most common method utilised by mines to identify these prohibited compressed air end-users is through comprehensive visual audits of the entire compressed air network [3] [34] [56] [93] [107] [109]. Once the audit is completed, the audit results are documented in a report. The report prioritises leakages based on their leakage rate. The leakage rate is determined through graphs of experimental data (such as Figure 2-8) [110] or by substituting the hole diameter and supply pressure into an empirical equation, such as Equation ***(1)*** [109] [111]:

$$\dot{m}_{air} = C_{discharge}(\frac{2}{k+1})^{1/(k-1)} \frac{P_{line}}{RT_{line}} AT_{line} \sqrt{kR\left(\frac{2}{k+1}\right)T_{line}} \qquad \textbf{(1)}$$

Where:

$\dot{m}_{air}$	-	Mass flow rate of air [kg/s]
$C_{discharge}$	-	Specific heat ratio
k	-	Air specific heat ratio [Assumed value for air = 1.4]
P_{line}	-	Pressure in the compressed air column [kPag]
A	-	Minimum cross-sectional area [m²]
R	-	Gas constant for air [0.287 kJ/kg·K]
T_{line}	-	Temperature in the compressed air line [K]

Larger leaks are prioritised as their impact on the network efficiency is often the most severe [38] [27]. It is important to note that open-ended hoses and punctured holes form part of the leakages. Once these leakages have been fixed, a follow-up audit must be conducted to ensure that all the prioritised repairs have been completed. A cycle diagram, illustrating the procedure for a conventional leak management initiative is depicted in Figure 2-10.

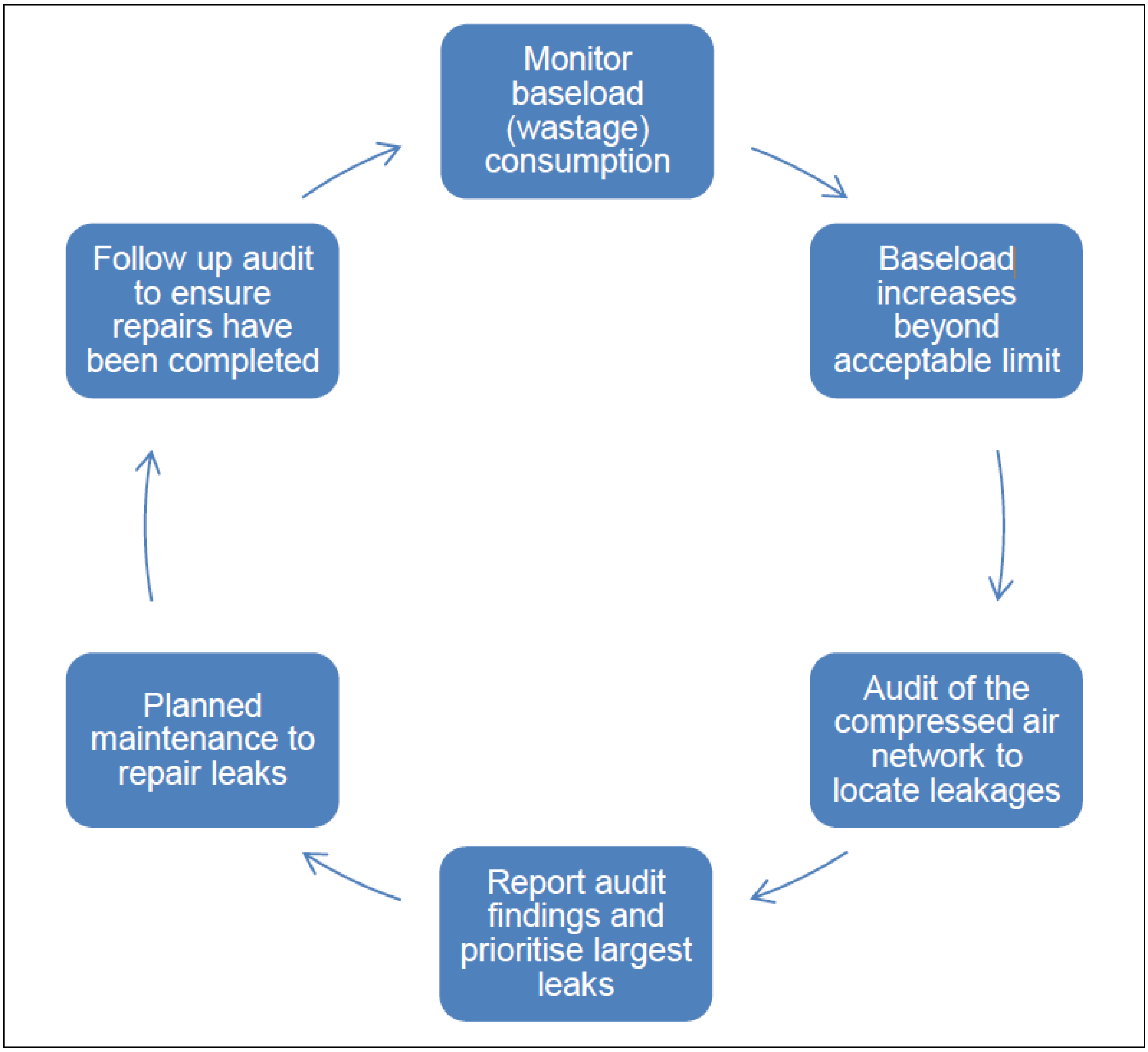

Figure 2-10: Schematic representation of a common procedure for leak management [50]

Despite its apparent simplicity, as depicted in Figure 2-10, this leak management, i.e. auditing of underground compressed air networks, can become time-consuming, resource-intensive and impractical due the size and complexity of compressed air networks on deep-level mines [4] [56] [112] [113].

One study highlighted that it took a total of three months for four auditors to conduct a detailed audit of an entire compressed air network in a deep-level underground mine [112]. Literature has also indicated that a significant proportion of wastage due to these leaks frequently occurs in inactive stopes/crosscuts, which are typically avoided during audits owing to safety concerns and inaccessibility [28] [56]. Hence a considerable number of leaks (including open-ended hoses) remain unreported and unrepaired.

Addressing identified leaks in compressed air systems is a challenging and time-consuming task, often requiring the isolation of the entire network during maintenance downtime [114]. However, in deep-level mines where mining activities are continuous, the availability of maintenance downtime is often limited, thereby reducing the effectiveness of leak management efforts [50].

One study indicated that leak repairs have yielded less than 25% of the expected benefits [50], highlighting the need for more effective approaches. To improve the efficiency of leak control, it is crucial to develop a more effective method for identifying areas with the most severe wastage. This will enable targeted leak control and maintenance interventions, leading to a more practical and efficient demand-side management strategy with improved outcomes [4]. By focusing on identifying and addressing the areas with the most wastage, the overall effectiveness of leak control initiatives can be greatly improved.

2.5.2.2 Compressed air pressure drop test [2]

Compressed air network drop tests are done to monitor the condition of the network and to assess the status of wastages. These drop tests can be done on multiple levels in an underground mine [2]. The drop test procedure is broken into the steps listed below:

Step 1: Pressurise the compressed air system to drilling shift pressure (it is important to pressurise to the maximum pressure as this will yield the biggest losses from leaks).

Step 2: Determine the total volume of compressed air through calculations using the total compressed air network length and pipe sizes as parameters.

Step 3: Convert the pressurised volume to free air volume at standard atmospheric pressure using Equation ***(2)*** [2] [115]:

$$V_a = \frac{P_c V_c}{P_a} \tag{2}$$

Where:

V_a	-	Volume of free air [m³]
P_c	-	Compressed air pressure [kPa]
V_c		Volume of compressed air [m³]
P_a		Atmospheric pressure [kPa]

Step 4: Isolate the pressurised network (or certain sections), by closing the manual or automatic supply-side isolation valve(s). It is important to close all refuge bays as well (as they do not form part of leakages and will skew the results).

Step 5: Measure the time taken for the compressed air network (or section of the compressed air network) pressure to reach atmospheric pressure (0 kPa gauge pressure).

Step 6: Use the Briggs formula [115], Equation ***(3)***, to calculate the compressed air wastage

$$Q_{wastage} = \frac{5V}{2t} \qquad \textbf{(3)}$$

Where:

$Q_{wastage}$	-	Compressed air wastage through leakages [m³/s]
V	-	Volume of free air lost in the network [m³]
t	-	Time taken to reach atmospheric pressure [kPa]

Step 7 (Optional): Determine the mass flow rate through the leakages (using Equation ***(1)***). This step is often skipped as there are usually multiple leaks present in the compressed air network or section. Hence, the mass flow rate of each leak cannot be calculated as the diameter of each leak is often unknown.

Step 8: Compare the results of step 6 and 7 to previous step tests to determine the condition of the compressed air network and the status of wastages.

This method is effective in identifying whether a compressed air network has deteriorated from its original/previous condition. However, it has several challenges that are listed below.

- Compressed air pressure drop tests must be conducted when there are no mining personnel underground as no compressed air must be used for production activities. As mines are under tremendous pressure to meet production targets [3], there are often few opportunities to perform these pressure drop tests.
- Compressed air pressure drop tests impose a safety risk – closing off refuge bays poses a significant safety risk for the personnel underground and legal requirements need to be considered when conducting the test.
- The accuracy of pressure transducers used during the test can produce less accurate results. If the pressure transducers are damaged, they may read inaccurate data.
- If the compressed air network has changed (which is often the case for underground mines [4]), the results of the pressure drop test cannot be compared with previous tests.
- The pressure drop test can only be compared with the same section; it cannot be compared with different sections because each section has varied conditions (length of pipe network, size of pipes, number of leaks, severity of leaks, etc.) [3]. Hence, it is not possible to

determine which section of the compressed air network is the most inefficient using pressure drop tests.

To overcome the challenges associated with conventional leak management initiatives aimed at reducing compressed air wastage, various studies have been conducted to explore alternative approaches. Relevant previous studies that focussed on initiatives to reduce compressed air wastage due to leaks are summarised in Table 2-3. Studies focussed on benchmarking have not been included as they are discussed in more detail in Section 2.5.5.

Table 2-3: Summary of relevant previous studies done on compressed air wastage due to leaks

Ref.	**Title:** Discussion and shortcoming(s)
[3]	**Development of a local benchmarking strategy to identify inefficient compressed air usage in deep-level mines** An innovative solution to identify leaks using pressure loggers was developed. The method was able to narrow down leaks on different levels and crosscuts. However, this method required a substantial number of pressure transducers. Using pressure transducers with a 10 kPa sampling interval were found to be less accurate [4].
[116]	**Optimization of the compressed air-usage in South African mines** The study achieved compressed air savings through valve and compressor control. Valve control is an artificial method of reducing compressed air wastage. Even though valves can potentially be used to identify areas with high compressed air wastage, this study did not focus on identifying or reducing compressed air wastage due to leakages.
[50]	**Expanding compressed air demand side management through selective level control** The study highlighted the importance of reducing compressed air wastage because of compressed air mismanagement and misappropriation. Focus was placed on developing a method to determine the effect of installing automated control valves on surface, levels, and/or crosscuts on a compressed air network. Although it realised potential savings by reducing leakages, it did not focus on identifying leakages. Additionally, it is artificial demand-side management by limiting the supply pressure to leakages.
[37]	**Reducing compressed air wastage by installing new technology in underground mines** The study focussed on developing an automatic air closing valve for crosscuts. When the demand surpasses a certain threshold, it will automatically close. The shortcoming is that there is no means for locating the areas of wastage.

Ref.	Title: Discussion and shortcoming(s)
[56]	**Sustaining compressed air DSM project savings using an air leakage management system** This study focussed on the impact of leak management on deep-level mine compressed air networks. This study developed a compressed air leak documentation system. However, it still included a comprehensive audit of the entire compressed air network which is time-consuming and resource intensive.
[29]	**An integrated approach to optimise energy consumption of mine compressed air systems** This study focussed on developing a new approach to analyse the compressed air network for surface and underground operations. It involved simplifying the deep-level mine compressed air system to identify savings opportunities. However, the leak auditing methodology involved a detailed audit of the entire compressed air system which is time-consuming and resource intensive.

It is evident from Table 2-3 that none of the above discussed studies are adequate to solve the problems identified in Chapter 1. Hence further investigations into other relevant literature are required. This is discussed in more detail below.

2.5.3 Leak management initiatives in other industries

Compressed air is not only used in the mining industry but also widely utilised in a variety of other industries across the world. Leakages are not only present in compressed air systems but also fluid distribution systems, including oil, water and natural gas industries which can have devastating financial and environmental repercussions [4] [117] [118] [119] [120]. Monitoring for leaks in these systems may be considerably more important than in compressed air systems. Hence the strategies employed on the aforementioned systems are likely more advanced and may offer solutions for improved leak detection and identification on compressed air systems in deep-level underground mines.

When networks, such as those found in the gas and oil industry, become larger and more complex, industry often relies on software-based methods to determine leaks. These software-based methods make use of different parameters to continuously monitor the status of the distribution networks at various points to detect any leakages. The most common parameters used by non-mining industries to detect leakages are flow, pressure, and temperature [3]. To monitor these parameters, multiple instrumentation is required, which is often capital-intensive [4]. A few examples of typical software-based methods used in non-mining industries are summarised below. The method is listed, followed by a short description and discussion.

Mass/Volume balance [121]**:**

Description: Pressure and/or flow instrumentation is installed at the inlet and outlet of a pipe network. A mass/volume balance is done to determine if there are any leakages.

Discussion: This method is often used in the oil and gas industry. The risk associated with this method is that it can become capital-intensive to locate the leak accurately. If instrumentation is not installed at small intervals across the network, it cannot accurately locate a leak. This method is also not ideal for usage in transient conditions as regular alterations to the network will result in an ever-changing mass/volume balance. Compressed air networks in underground mines regularly change [4] and this method will thus be less efficient and reliable.

Inverse resonance method [122]

Description: This method involves inducing a pressure pulse in the pipeline and measuring the response of the system (based on the analysis of resonance frequencies).

Discussion: This method is typically used in small distribution systems. By analysing the frequencies at which resonance occurs, it is possible to pinpoint the location of the leak with relatively good accuracy. Unfortunately, this approach is constrained by the complexity of the pipe network and the necessity for precise frequency response measurements. It is thus not an ideal method to be used in deep-level underground mines as the compressed air networks are large, complex, and often inaccessible.

Pressure residual vector method [122]**:**

Description: It is a leak detection method that uses pressure measurements and a mathematical algorithm (vector analysis) to pinpoint leakages.

Discussion: The method involves collecting pressure data at multiple points in the network and calculating the pressure residuals, which are the differences between the measured pressures and the predicted pressures based on a model of the network. The pressure residuals are then used to identify the location of leaks in the network. One advantage of this method is that it does not require the network to be shut down. This method has been shown to be effective for detecting leaks in small, simple pipelines. However, it is less suitable for larger, more complex systems like those found in deep-level mines, as extensive instrumentation is required to collect sufficient data. Additionally, this method is limited by the need for accurate pressure measurements and is sensitive to changes in system conditions and noisy data.

Negative pressure wave method [122]**:**

Description: Pressure transducers are installed at strategic locations across the network and detect disturbances (negative pressure waves) induced by leakages in the pipeline.

Discussion: When there is a leak on a pipeline, such as a water pipeline, it creates pressure waves which spread throughout the network. The pressure transducers pick up these waves and, using advanced algorithms, the severity and location of the leak can be approximated. This method is sensitive to noisy data and may not be practical in large complex pipe networks where pressure waves (from multiple leaks) can reflect and interfere with each other. Additionally, pressure waves dissipate over long distances, which means that leaks may not be detected in these large underground compressed air networks.

Digital signal processing (DSP) [123]**:**

Description: DSP is the manipulation and analysis of digital signals using mathematical algorithms. For leak detection, DSP is used to process flow and pressure readings continuously to detect changes in the system that indicate the presence of a leak.

Discussion: One advantage of using DSP for leak detection is that it can provide real-time monitoring of the network, allowing for early detection and intervention before the leak causes significant damage or loss. It can also be used in conjunction with other leak detection methods to improve the accuracy of leak detection. However, installation and maintenance of DSP equipment is often capital-intensive as extensive instrumentation is required to collect multivariable data.

Step-testing [4] [124]**:**

Description: A flowmeter is installed at the inlet of the network and valves downstream of the flowmeter are closed to identify sections with leakages.

Discussion: This method is a manual testing method which requires multiple resources to close the valves. Hence, it can become time-consuming. It is, however, an effective method to pinpoint the location of high consuming sections and requires little instrumentation. This method is a viable solution that can be adapted to mine compressed air networks as there are multiple valves across a compressed air network (which means the compressed air network can be divided into smaller, manageable sections) and flowmeter instrumentation is also available (on surface) to measure the change in flow. Section 5.5 will elaborate on the step-testing method and how it will be utilised in the mining industry.

To further realise the reduction in compressed air wastage and operational costs, mines often use computational software to simulate the underground mining environment. This is discussed in more detail below.

2.5.4 Simulations as a means to reduce compressed air wastage

To optimise compressed air system performance, multiple simulation software has emerged as a valuable tool for evaluating potential energy savings initiatives and identifying inefficiencies. Simulation software is a tool that combines multiple complex mathematical formulas to solve a mathematical model which is then incorporated into one user-friendly platform. Although simulation models require basic skills and knowledge from the user, it is still a powerful tool to calculate the probable effect of various scenarios. Using a computer model rather than testing a scenario on a compressed air network allows for more effective planning and execution. Hence, simulations are widely used in the mining industry to evaluate the potential impact of configuration changes on deep-level mine operations [3] [4] [34].

To create a simulation model, a “digital twin” is built to incorporate all the components of a compressed air network, which is then calibrated to recreate operations as closely as possible. This is a time-consuming process, even for a proficient and skilled simulation expert [3] [34]. Another major drawback when building a digital twin is the significant amount of multivariable data that is required to model and calibrate the system accurately. This includes flow rate, pressure, power, and temperature data from several locations across the compressed air system. Although effective, creating an accurate digital twin of a deep-level mine with a large underground compressed air network is thus challenging, time-consuming, and resource-intensive [3] [34].

The mining industry also uses simulations to evaluate the impact of energy savings initiatives before they are implemented [53] [125]. This is an effective method as the different initiatives to reduce compressed air wastage can be compared with each other to evaluate the impact before capital is invested in the initiatives.

Simulation serves as a valuable tool to be used in combatting compressed air wastage by means of identification and desktop testing of the impact of interventions. However, it is important to consider that simulation software is expensive, requires skilled workers and multivariable data to simulate underground compressed air networks. As a result, several studies have developed alternative methods to avoid using simulations [29] [113] [126] [127]. Additionally, simulations focus on reducing compressed air consumption through optimisation of networks and not on identification of compressed air wastage. Thus, a need still exists for an alternative method to identify compressed air wastage.

2.5.5 Benchmarking

Benchmarking is regarded as an effective approach for evaluating energy efficiency of systems and is widely utilised as an energy management strategy across multiple industries [128] [129] [130] [131] [132]. The practice of benchmarking entails comparing the actual performance of an entity to a reference performance [133], to identify areas for improvement in energy usage or management. Benchmarking in mining typically involves the development of quantifiable indicators known as KPIs for different mines or systems. These KPIs vary depending on the application of the benchmarking (i.e. energy usage, mine depth, consumption temperatures, etc.).

One advantage of benchmarking compressed air networks over traditional energy audits is that it requires fewer resources to identify compressor energy reduction potential. This has been demonstrated in a study by Oosthuizen [127], where benchmarking models were found to be more efficient at identifying high-potential areas for energy savings than conventional energy audits [27]. Once these areas have been narrowed down, conventional audits can be conducted with the goal of identifying potential compressed air improvements. Hence, benchmarking can be adapted as an identification strategy to narrow the scope of conventional audits.

Overall, energy benchmarking is an effective tool for identifying energy savings opportunities in the mining industry, particularly in the context of compressed air systems. By comparing KPIs and identifying areas for improvement, benchmarking can help mines to use their resources more efficiently and reduce energy consumption [3].

Various benchmarking studies have been done on compressed air networks of deep-level mines: the associated challenges and the strategies employed to mitigate them are discussed in detail below. Investigating these benchmarking methods and their respective KPIs will help to decide which KPIs to consider relevant to the development of a new method to identify compressed air wastage.

It is important to choose the right benchmarking approach when identifying inefficiencies in a system, to ensure that the results obtained are accurate and useful. Applying the wrong benchmarking method can lead to obsolete or incorrect results, making the entire process futile [3]. Hence careful consideration on which benchmarking approach to use, based on the specific requirements and characteristics of the system being evaluated, is crucial. Understanding the challenges associated with benchmarking strategies will aid in selecting the appropriate benchmarking strategy that will yield the most effective results [3]. Ke et al. [46]conducted a study on current energy benchmarking strategies utilised in industry and identified three key challenges associated with benchmarking:

1. The accuracy of benchmarking is affected by energy governing factors, such as infrastructure, mining methods, and mine depth, that vary between systems. To mitigate these variable energy governing factors and ensure accurate comparisons are made, benchmarking relies heavily on mathematical manipulation and logical assumptions [7] [38] [130] [134] [135].

2. The complexity of individual sub-processes in a system presents a challenge for benchmarking. It is difficult to establish a cause-and-effect link between system input (energy usage) and output (production) [128] [132] [136]. This cause-and-effect relationship is particularly important when choosing a suitable KPI for underground compressed air networks.
3. Obtaining reliable data for benchmarking is challenging, especially when there is limited infrastructure [3].

Hence, these aforementioned challenges should be considered when developing a new benchmark method to identify compressed air wastage. Previous benchmarking studies that present strategies for addressing the previously discussed challenges are evaluated below.

There are limited benchmarking studies that have been done on deep-level mines, but most benchmarking models use KPIs based on:

- Tonnes mined,
- Mining depth and energy consumption, or
- Energy consumption as a single variable.

Most of the previous deep-level mine benchmarking methods compared energy usage with production output (tonnes mined). Even though production data is usually available for longer periods of time, it is not always readily available in smaller increments [7] [34]. Vermeulen [34] also noted that accessing sensitive production data is difficult, with mines often denying access to production data [137]. Several relevant studies are considered below.

Cilliers (2016) [7]

A study conducted by Cilliers [7] in 2016 benchmarked multiple energy utilities on a deep-level mine one of which was compressed air. Cilliers [7] included production, mine depth, and the seasons as variables for his benchmarking approach. A multivariable regression analysis (based on data of ten gold mines) was done by Cilliers [7] to determine the effect of summer and winter on the relationship between ore produced and compressed air energy. The results from his study are presented in Figure 2-11 and Figure 2-12:

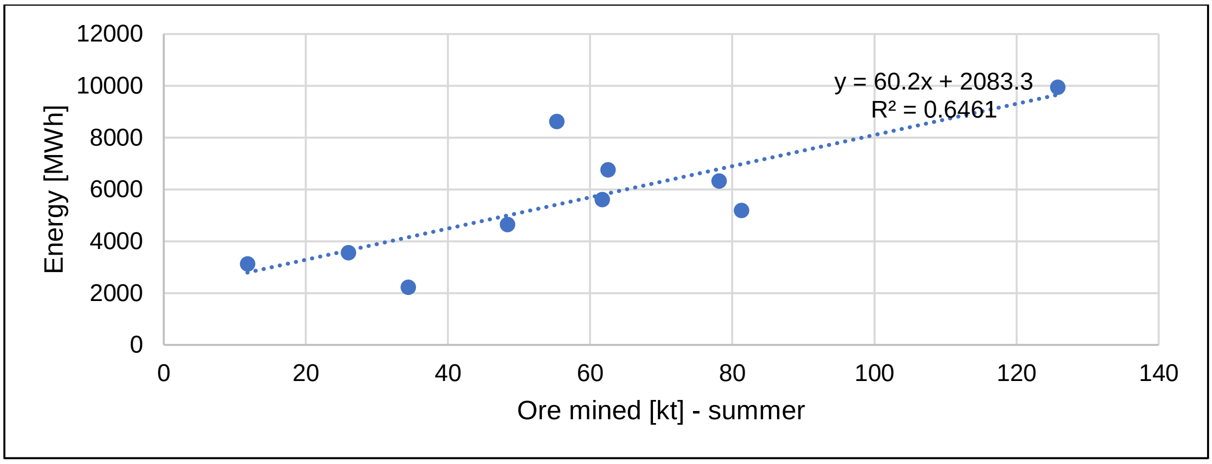

Figure 2-11: Compressed air energy use vs ore mined – summer (adapted from [7])

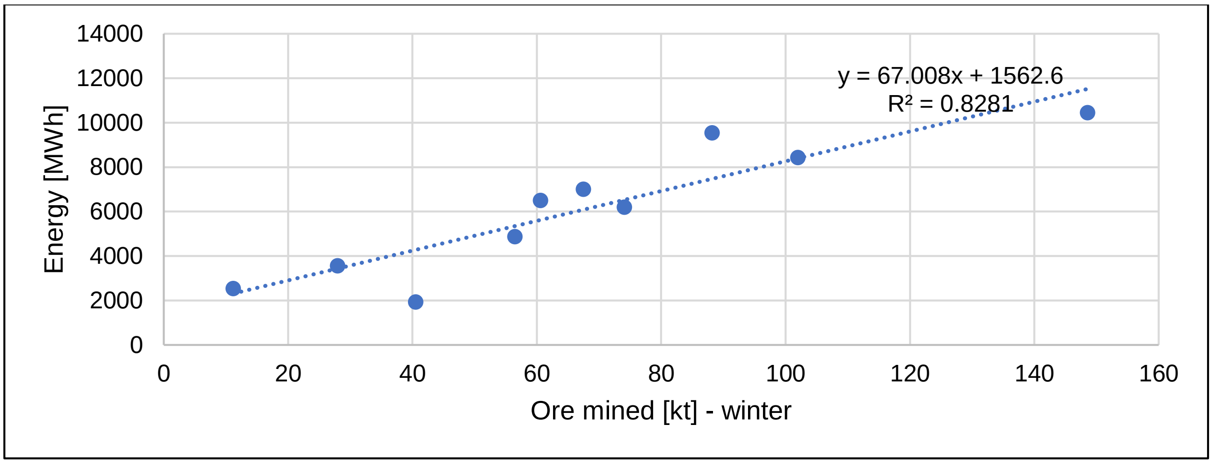

Figure 2-12: Compressed air energy use vs ore mined - winter (adapted from [7])

The results yielded a coefficient of correlation (R^2) value of 0.6459 and 0.8272 for summer and winter respectively. This high R^2 suggest that there is a strong linear correlation between compressed air consumption and ore produced. However, a study by Barnard and Grobler [138] contradicts Cilliers [7] as they found a weak correlation between ore produced and compressed air energy use [138]. Although the study only examined the monthly data correlations of one mine for a period of 18 months it must still be considered when developing a new benchmark method to identify compressed air wastage.

Additionally, Vermeulen noted that mines often have incidents which lead to all production being halted due to a Section 54 [34]. Section 54 of the Mine Health and Safety Act (MHSA) is a legal provision in South Africa that empowers government inspectors to order the suspension of mining operations or specific areas of a mine if they believe there is a risk to the health and safety of workers. Although production operations are halted, compressed air cannot be shut off due to safety reasons. Some mine personnel still work underground to rectify the issues that caused a Section 54. During this time, no ore is produced, and mines rely on ore stockpiled on surface to make up for production halts. Hence, production halts due to a Section 54 can skew the relationship between ore mined and compressed air energy consumption.

The benchmarking method of Cilliers [7] did not distinguish between different sections within an underground compressed air network. This highlights the need to develop a benchmarking method that can be implemented across a whole network of a utility, but also on certain (underground) sections of a utility network.

Du Plooy (2019) [3]

Du Plooy conducted a study to develop a local benchmark method to identify high compressed air wastage areas. His benchmark method was applied to a platinum mine. Du Plooy stated that flowmeters used to measure compressed air consumption were expensive and instead used pressure transducers to measure pressure at various points across the compressed air network on a single level. He used the Darcy-Weisbach equation [139], equation ***(4)***, to depict the relationship between pressure drop and flow rate

$$DP = f\left(\frac{L}{D}\right)\left(\frac{pV^2}{2}\right) \tag{4}$$

Where:

DP	-	Pressure drop [kPa]
f	-	Friction factor
L	-	Pipe length [m]
L	-	Hydraulic diameter [m]
p	-	Fluid density [kg/m3]
V	-	Average velocity [m/s]

Using this equation, he computed a quadratic power relationship between pressure drop and flow rate. Once the flow was calculated, Du Plooy [3] used an intensity indicator (flow consumption divided by ore produced) to identify inefficiencies in the compressed air network. A key assumption that Du Plooy [3] made is that the friction factor is constant throughout the compressed air network. Studies have indicated that compressed air networks deteriorate over time [4], which suggests that the friction factor is not constant across the compressed air network and also differ from mine to mine.

Measuring compressed air using a pressure logger is also an invasive measuring technique which requires measuring points to be installed. Installing a measuring point requires compressed air to be shut off. As mentioned in Section 2.5.2, mines are under tremendous pressure to meet production targets, which means they are likely not going to shut off the compressed air to install multiple measuring points. Additionally, measuring the pressure across several points on a large compressed air network becomes time-consuming.

Van der Zee (2014) [38]

Van der Zee [38] developed a cost-efficient and simplified benchmark method for refrigeration, compressed air, and water. To benchmark the compressed air, van der Zee [38] used multivariable data to combine the compressed air intensity (compressed air energy divided by ore produced) and shaft depth to identify the mine with the highest potential for energy efficiency improvement. Results from van der Zee's study are depicted in Figure 2-13 [38].

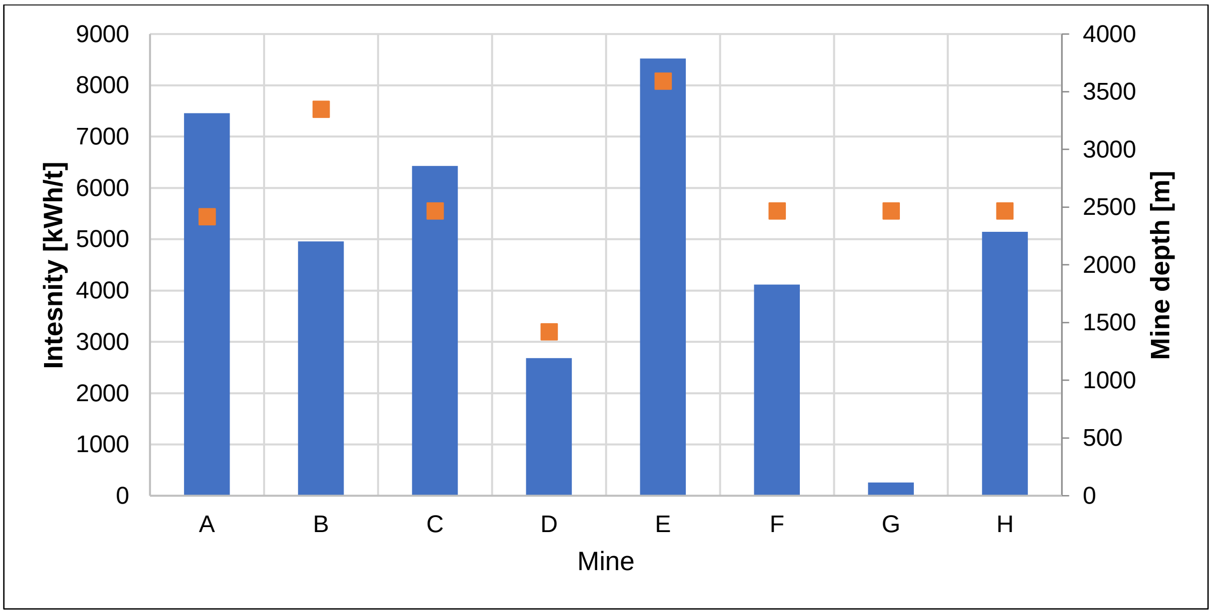

Figure 2-13: Compressed air benchmarking results of van der Zee [38]

Collecting multivariable data sets that are not readily available can prove to be challenging and should be considered when developing a new benchmark method. Platinum mines were not considered in this study. Hence the assumption is made that the benchmarking method of van der Zee [38] was specifically developed for gold mines. The layout and compressed air network of gold and platinum mines differ significantly [4] [104]. Therefore, the energy consumption, specifically compressed air consumption, and efficiency will vary. Van der Zee's [38] benchmarking approach also did not consider different sections of compressed air within the underground network. Hence compressed air could not be benchmarked on a local level. This should be considered when developing a new benchmark method.

Zietsman (2020) [4]

Zietsman [4] proposed novel solutions for compressed air demand management on deep-level mines. The objective of his study was to investigate and implement demand-side management strategies to reduce the consumption of compressed air on deep-level mines. He conducted an extensive literature review and investigated the current compressed air demand management strategies used in the mining industry.

Zietsman's [4] study focussed on two main areas: the reduction of compressed air demand through the optimisation of the compressed air system and the implementation of advanced control strategies for the management of the compressed air system. He proposed a novel method to optimise the compressed air system, which included a benchmarking method to identify scope for underground waste management. Zietsman [4] used the compressed air network length underground and compressed air consumption to create a demand reduction indicator. This indicator was used to determine which shafts had the biggest potential for compressed air demand reduction.

Zietsman [4] did not include the compressed air network length in crosscuts and the compressed air network length was approximated using the mine layout. However, assuming that the compressed air network length is equal to the haulage length is less accurate than measuring the actual network length. This assumption can lead to inaccuracies because the compressed air network may not extend across the entire haulage and may include inactive sections. As a result, the indicator may be skewed, which can have significant implications for the accuracy of the benchmarking results. To overcome this challenge, one would have to measure the compressed air network manually, which is time-consuming and resource-intensive.

2.6 Summary

Literature and existing studies relevant to two main aspects relevant to this study were considered as part of this chapter – ventilation (focussed on shortfalls) and compressed air (focussed on wastage). Ventilation in deep-level platinum mines was discussed to provide insight into the complexity of a ventilation network. It provided background on the different infrastructure found in a ventilation network and the importance of an efficient ventilation network. This chapter also highlighted that instrumentation infrastructure limitations to accurately monitor a ventilation network has caused mines to employ alternative methods to monitor a ventilation network and identify shortfalls. Comprehensive ventilation audits are commonly employed but require extensive resources and time.

To optimise ventilation networks and identify shortfalls, alternative solutions have been developed in literature. This chapter reviewed the literature which revealed that majority of studies focussed on ventilation optimisation, lacking focus on identifying ventilation shortfalls. This emphasises the need for an alternative method to identify ventilation shortfalls.

Compressed air as the preferred energy choice in mining operations was discussed. Despite compressed air being the most inefficient energy source, it remains the most practical choice for mining operations because of its versatility, safety, and widespread availability. An in-depth overview of the compressed air mining cycle, from compressed air production (supply) to end-user (demand) was discussed. This provided a foundational knowledge base to highlight the complexity of a compressed air network and the potential of demand-side management.

Previous studies that developed innovative solutions to identify and address compressed air wastage were considered. The first focus area was on leak management strategies utilised outside of mining, followed by simulations as a means to reduce compressed air demand. From this survey of existing solutions, none was found that would adequately address the identified problem. The last focus area of the chapter was therefore placed on benchmarking, which is fundamental to the development of the solution. The difficulties associated with benchmarking were discussed, followed by an in-depth discussion of previous studies and the shortcomings of each study.

Final literature, which is a critical aspect required for the understanding of the approach with developing the solution, is addressed in the next chapter. It highlights a key finding, the link between compressed air wastage and ventilation shortfalls, that guides the development of the proposed solution, as per the VENN diagram.

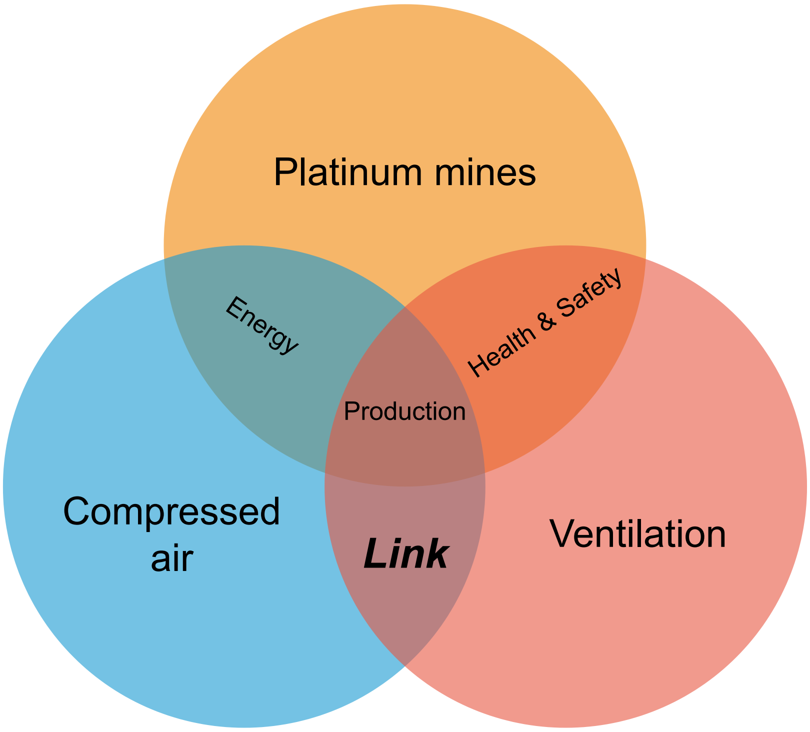

Figure 2-14: Overview of literature that guides the development of the proposed solution

The comprehensive review of existing literature provides a valuable opportunity to leverage effective strategies previously employed to address the identified problem (in Chapter 1). These proven methodologies can serve as essential building blocks, to establish criteria guiding the development of a new solution to address the challenges highlighted in Chapter 1.

The development of solution mirrors the structured progression of the Waterfall Research methodology, as discussed in Section 1.4.3. By breaking down existing strategies and evaluating its successes and limitations, a coherent and systematic approach to address the identified problem emerges. Existing literature will serve as criteria for the development of a new methodology, tailored to address the problem identified in Chapter 1. The criteria that govern the development of a new methodology (as developed in Chapter 5) are summarised in Table 2-4. The section(s) where examples or references from literature can be found to support each criterion is also summarised in the table.

Table 2-4: Criteria used to guide development of solution (new methodology)

Criteria	Reason for criteria	Section
Obtaining accurate data for model	Chapter 2 highlighted the significance of acquiring accurate data and verifying it. This process not only guarantees the reliability and precision of the ensuing results but also reduces the need for redundant data collection.	Sections 2.3.1, 2.3.2 and 2.5
Simple, time- and resource-efficient approach (to identify compressed air wastage)	Gap was identified within existing literature – shortcoming of a simple, time- and resource-efficient approach to identify compressed air wastage (where infrastructure and monitoring capabilities are limited).	Sections 2.5.2, 2.5.3, 2.5.4 and 2.5.5
Tailor results using an appropriate KPI	Chapter 2 emphasised the significance of normalising results to a defined reference standard or criterion to facilitate meaningful comparison and subsequent analysis.	Section 2.5.5
Ventilation shortfall identification	Literature has highlighted that there is a gap to effectively identify ventilation shortfalls requiring less resources and time when limited to no ventilation instrumentation is available.	Sections 2.2.2 and 2.3

CHAPTER 3: INVESTIGATING THE LINK BETWEEN COMPRESSED AIR WASTAGE AND VENTILATION SHORTFALLS

3.1 Preamble

The aim of this study is to address the challenge of identifying ventilation shortfalls using an alternative method that requires fewer resources and less time. Chapter 2 highlighted that there seems to be a cause and effect between ventilation shortfalls and compressed air wastage. It was identified that compressed air is misappropriated as a temporary solution for inadequate ventilation. Compressed air is used to ventilate working areas as it is easily accessible and readily available in all active working areas.

To develop a unique and alternative method, using compressed air as a potential metric to identify ventilation shortfalls, the link between compressed air wastage and ventilation shortfalls must first be evaluated. This link forms a critical part of the study and must be investigated before any further investigation into the development of a new method to identify ventilation shortfalls is pursued.

With no clear link presented from the literature, a need was identified to evaluate the potential link between compressed air wastage and ventilation shortfalls (objective 1 of this study). It is essential to note that the literature review (Chapter 2) served as the foundation, leading to the subsequent publication of an article. A peer-reviewed journal article, proving the link between compressed air wastage and ventilation shortfalls was published in the South African Journal of Industrial Engineering (SAIJE), volume 33, Issue 3, 2022. The article was compiled and submitted to SAIJE for publication and underwent a double-blind peer-review process. The author of this thesis is also the main author of the article and permission has been obtained from the co-authors to allow the use of the article.

The full article that was published in SAIJE is presented in Appendix A [57]. The highlights of the article are discussed in this chapter. A figure illustrating the mind map and highlighting the importance of this article in verifying the link is depicted in Figure 3-1 . It provides an overview of Chapter 3 and important topics to be discussed.

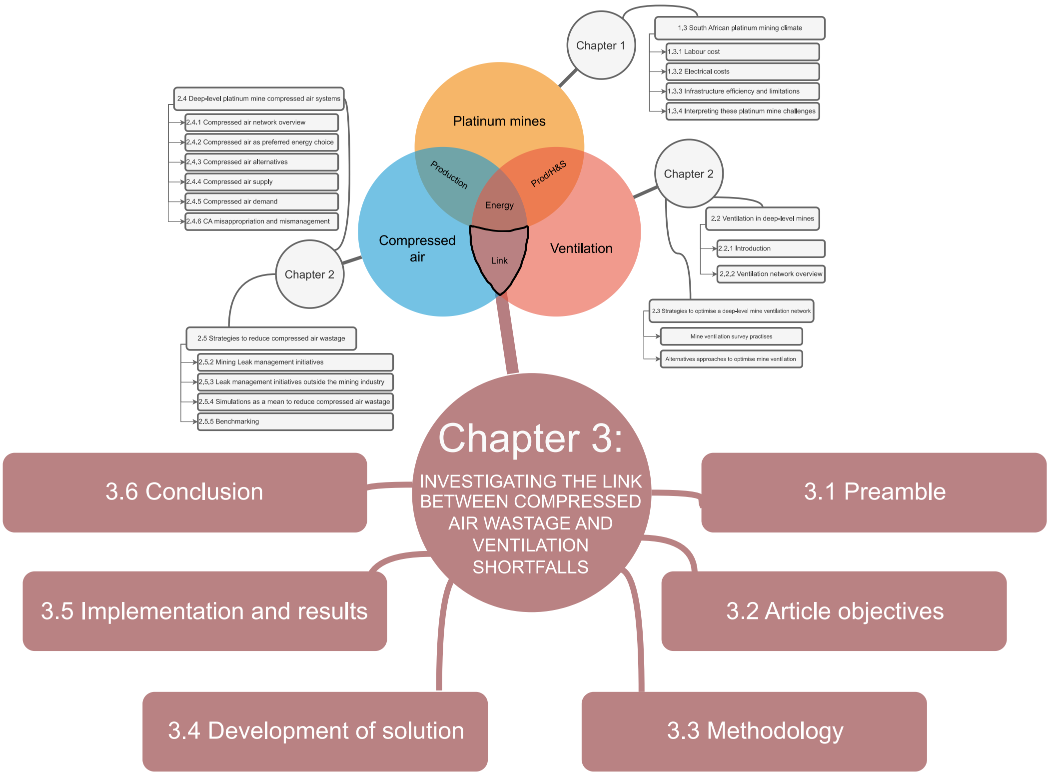

Figure 3-1: Overview of Chapter 3 and important topics to be discussed[7]

Hypothesis testing [140] was applied to a case study conducted on different mines to evaluate the possible link between compressed air wastage and ventilation shortfalls.

3.2 Article objectives

This article aimed to prove the link between compressed air wastage and ventilation shortfalls The objectives of this article are listed below:

- **Objective 1** was to investigate the compressed air network. This was done by evaluating the compressed air usage, while focusing specifically on the compressed air wastage.
- **Objective 2** was to evaluate the ventilation network. Once excessive compressed air wastage areas have been identified, the corresponding ventilation network was evaluated using a current assessment method (examination, surveys, and physical inspection).
- **Objective 3** was to prove that there is a relationship between compressed air wastage and ventilation shortfalls underground.

[7] See Figure 2-1 for more detail regarding discussion points of previous chapters.

3.3 Methodology

This section provides a summary of the methodology used in the article to achieve the objectives outlined in the previous section. A case study methodology [141] [142] approach was used as per Figure 3-2.

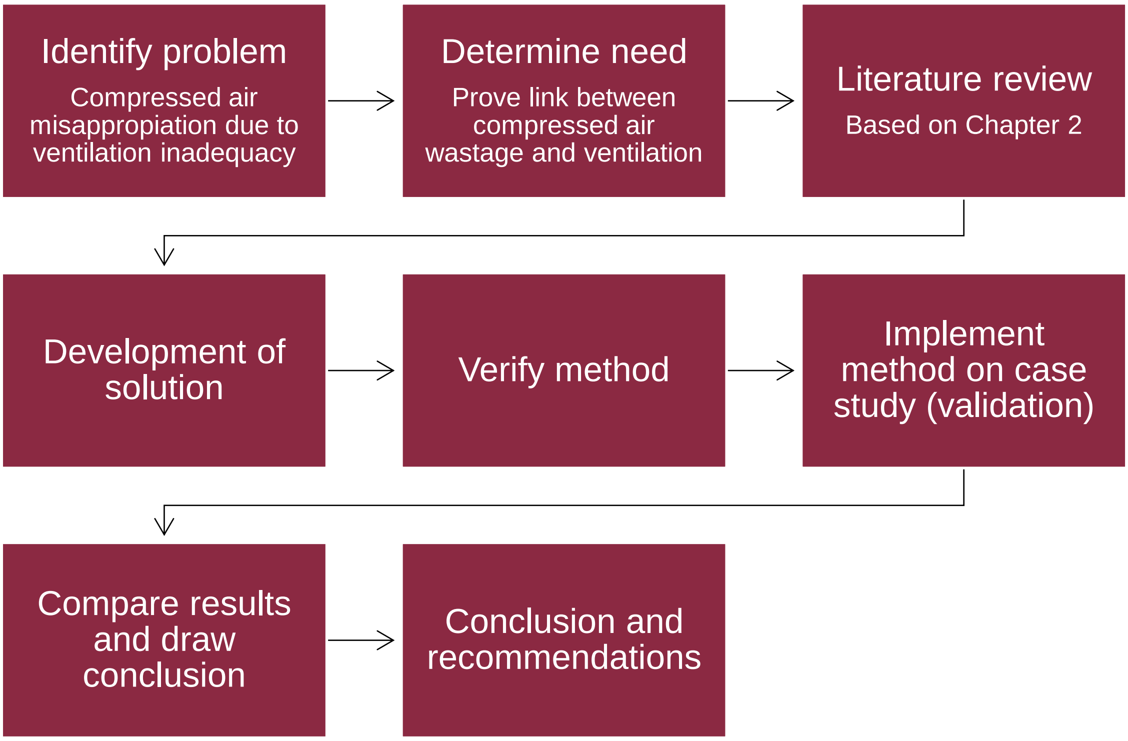

Figure 3-2: Case study methodology approach

3.4 Development of solution

3.4.1 Compressed air

The most significant compressed air end-users, highlighted in Table 2-2 of this study, were further categorised into two classes (for the article) to distinguish between the consumption and wastage thereof. Table 3-1, class 1 depicts the authorised end-users of compressed air while class 2 depicts the end-users which are responsible for compressed air wastage (i.e. prohibited compressed air users).

Table 3-1: Significant end-users of a compressed air network

Class 1: Authorised Compressed air users	Class 2: Prohibited Compressed air user
Equipment: • Rock drills • Loaders • Pumps • Pneumatic actuators Refuge bays	• Open-ended pipes • Valve leaks • Punctured pipelines

After the end-users of the compressed air network were identified, a zero-wastage model was developed to quantify the difference between actual consumption measured and the theoretical zero-wastage consumption. The zero-wastage model is a mathematical model that was utilised to compute the compressed air consumption of class 1 end-users, as specified in Table 3-1. For more detail regarding the zero-wastage model, refer to Appendix A.

3.4.2 Ventilation network

To prove that a link exists, it was required to evaluate the ventilation network utilising an existing assessment method, best described by the term “auditing”. The objective of the ventilation audit was to identify ventilation shortfalls and cross reference them with the excessive compressed air wastage areas to evaluate the link between compressed air wastage and ventilation shortfalls.

The ventilation shortfall was based on the dry- and wet-bulb temperatures as this has a direct impact on the thermal comfort of mine personnel as well as their health and safety highlighted in Chapter 2. Literature indicated that a wet-bulb temperature exceeding 27.4 °C in South African deep-level mines is deemed hot and uncomfortable and requires the implementation of safety measures - code of practice on heat stress management, to protect underground mining personnel [70] [71]. This study will consider a wet-bulb temperature exceeding 27.4 °C as a ventilation shortfall.

3.5 Implementation and results

The developed method was applied to a case study on a deep-level mine to prove that a link exists between compressed air wastage and ventilation shortfalls. The results were analysed to verify and validate the methodology and determine the hypothesis outcome. This section provides a summary of the results obtained. A detailed implementation of the developed method can be found in Appendix A.

To validate that there is a link between compressed air wastage and ventilation shortfalls, the wet-bulb temperatures and corresponding compressed air wastage of 69 additional crosscuts (and stope associated with each crosscut) were collected and examined. This comprehensive data sample ensured that the relationship between wastage and shortfalls was investigated across crosscuts with varying wastage levels (and not just the worst performing crosscuts). Figure 3-3 presents a comparison between the wet-bulb temperatures and corresponding compressed air wastage percentage collected from multiple mines (including case study Mine X). It is divided into four quadrants, based on two categories - a wastage percentage and the ventilation shortfall line (27.4 °C). Each quadrant showcases the percentage of the total crosscuts found within that quadrant specifications. This article considered a wastage percentage above 25% as excessive wastage.

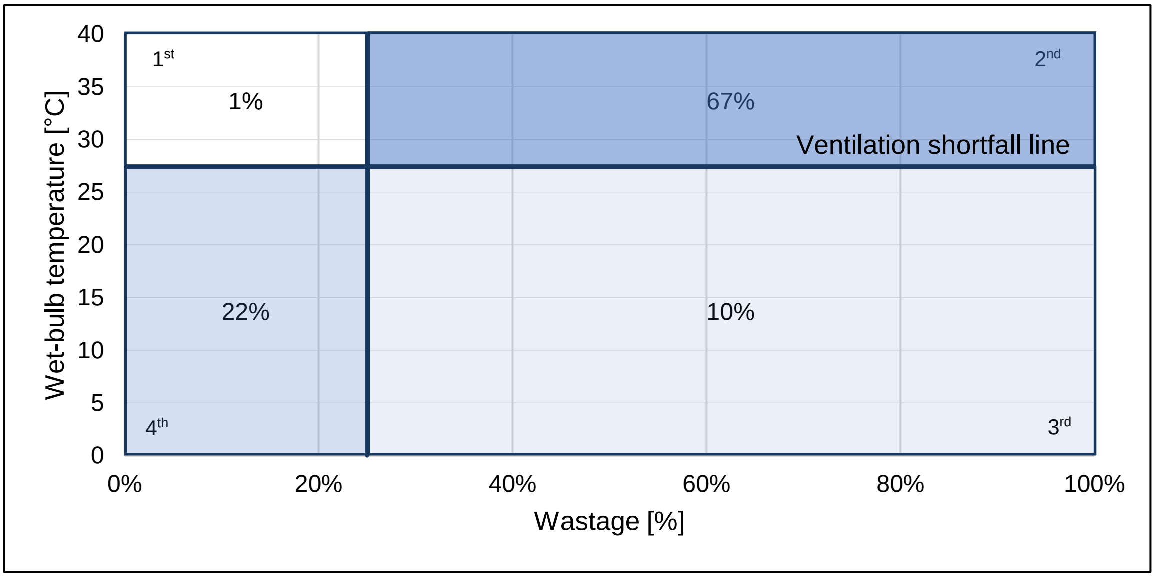

Figure 3-3: Wet-bulb temperature versus compressed air wastage across multiple mines

Figure 3-3 indicates that 67% of the crosscuts which had a temperature above the ventilation shortfall line (thermally uncomfortable) also had excessive wastage. Only 10% of crosscuts which were under the ventilation shortfall line had excessive wastage. Overall, the majority of crosscuts which had an excessive compressed air wastage also exceeded the thermally uncomfortable limit, which is indicative of a ventilation shortfall. This **verifies** that, based on the crosscuts considered at the specific mines, a link exists between compressed air wastage and ventilation shortfalls.

3.6 Conclusion

The primary objective of the article was to prove the hypothesis that a link exists between compressed air wastage and ventilation shortfalls. The hypothesis was supported through a case study implementation on a platinum mine. A zero-wastage compressed air model highlighted a substantial discrepancy between the actual and zero-wastage consumption. Compressed air crosscut audits were performed on the problematic level to identify crosscut(s) with high compressed air consumption and to rank them. The corresponding ventilation network was evaluated to determine if there were any shortfalls.

To further validate the link, the sample data (compressed air wastage and WB temperatures) of 69 additional crosscuts were collected and evaluated. The results provided further evidence of the strong relationship between compressed air wastage and ventilation shortfalls. Crosscuts with high wastage percentages were more likely to have WB temperatures exceeding the ventilation shortfall criteria. Conversely, crosscuts with low wastage percentages had minimal to no ventilation shortfalls. Hence, the article **verified** and **validated** the link between compressed air wastage and ventilation shortfalls. The next chapter elaborates on developing a compressed air benchmark to identify compressed air wastage on a mine.

CHAPTER 4: DEVELOPMENT OF A COMPRESSED AIR BENCHMARK METHOD

4.1 Preamble

Objective 2 of this study is to develop a versatile and less resource-intensive benchmarking method which identifies high compressed air wastage areas. This chapter entails the development and verification of two less resource-intensive and more time-efficient benchmark methods, namely:

- Operational baseload
- Theoretical baseload

Both benchmark methods help to identify and compute the distribution of compressed air wastage throughout a mine. The choice of benchmarking method is contingent upon the availability of underground compressed air consumption data.

These two new benchmark methods form part of a newly developed methodology (further discussed in Chapter 5) to identify ventilation shortfalls, irrespective of the platinum mine configuration.

4.2 Development of benchmark method 1: Operational baseload

The operational baseload testing determines the compressed air distribution underground in a less resource-intensive and more time-efficient manner. The operational baseload benchmark consists of a baseload test followed by processing of the data using the automated data processing (ADP) model, discussed in the section below.

4.2.1 Development of method 1

4.2.1.1 Baseload test

The operational baseload testing method is developed to identify high wastage levels on shafts with only a surface flowmeter. If no flowmeter is present on the surface, a portable flowmeter is used to measure the compressed air consumption. Once the infrastructure requirements have been addressed, the operational baseload testing can commence.

As discussed in Section 2.4.4, the blasting shift has the lowest compressed air consumption since limited personnel are underground and no authorised equipment (past the station area), other than refuge bays, are present. Hence, the operational baseload testing is performed during the blasting shift. The operational baseload testing is further referred to as a baseload test in the remainder of this document.

The following steps are developed to perform a baseload test, as per Figure 4-1 :

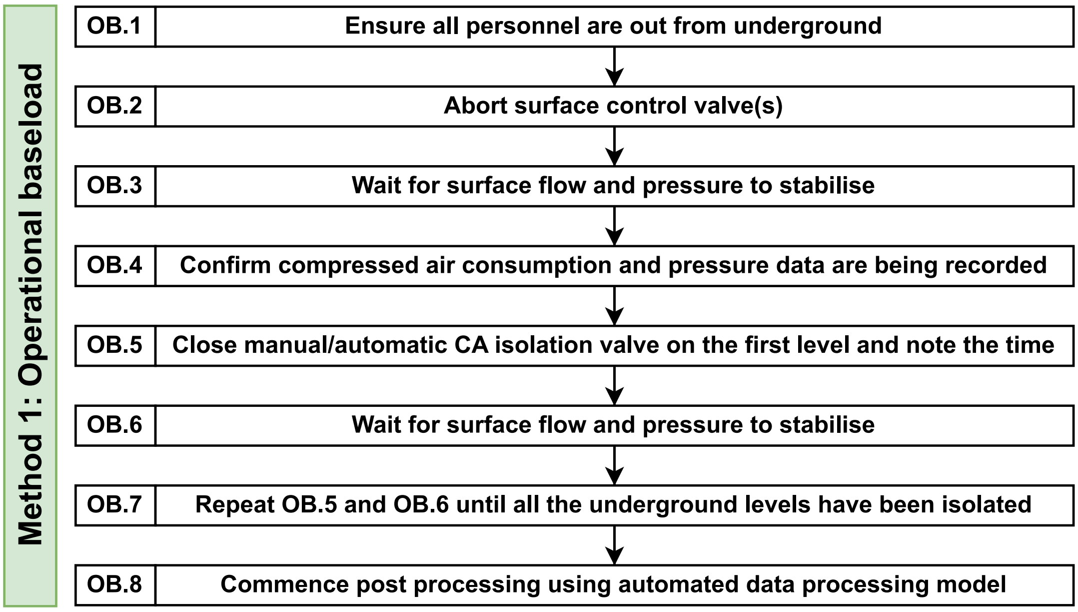

Figure 4-1: Operational baseload test procedure

Once the baseload test is complete, the data needs to be processed to showcase the compressed air wastage distribution across the different levels. A model which is used as a tool to simplify and reduce the time and effort required for processing the data was developed, using Microsoft Excel®. This automated data processing model is explained in more detail below.

4.2.1.2 Automated data processing model

A mathematical model was developed in Microsoft Excel® that extracts and automatically computes the compressed air distribution. The model incorporates automation features to streamline processes and reduce the time taken to process the data. It leverages computational algorithms and software tools to perform complex calculations, generate reports, and visualise results. The data required for the model to compute the compressed air distribution are as follows:

- Surface pressure data (for the past week).
- Surface flowmeter data (for the duration of the baseload test).
- Times when the compressed air isolation valves of the different levels were closed.

Once the required data is collected, it is inserted into the newly developed automated data processing model. The automated data processing model, developed in Microsoft Excel®, can be found in Appendix C. A summary of the model input, processing and output is illustrated in Figure 4-2 to assist in understanding each step in the newly developed model. This is followed by a detailed discussion of each step (denoted as ADP.1 to ADP.6).

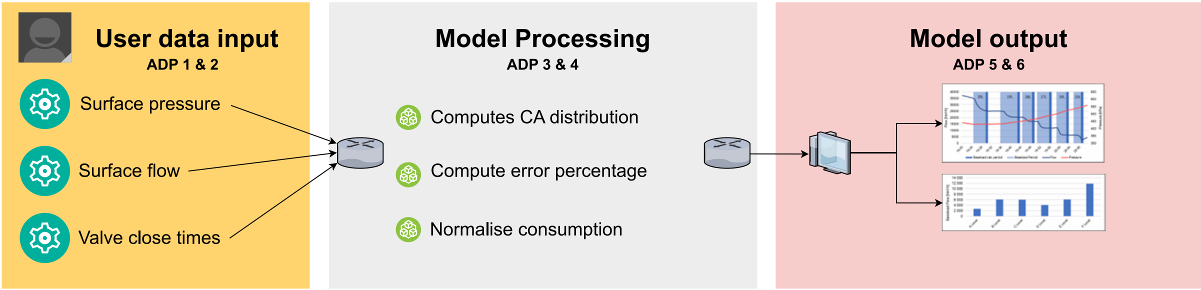

Figure 4-2: Illustration of newly developed automated data processing model

ADP.1: Extract the pressure and flow data and capture it into the model.

ADP.2: Insert the times when the isolation valves were closed into the relevant table provided in the model (example in Appendix C), as per Figure 4-3.

Discussion: The “Time Flow Recorded” should be noted 5-10 minutes after the isolation valves are closed to allow the flow to settle.

Baseload Analysis		
Level	**Time Valve Closed**	**Time Flow Recorded**
A Level	20:06	20:11
B Level	19:59	20:05
C Level	19:51	19:58
D Level	19:45	19:51
E Level	19:36	19:45
F Level	19:25	19:32

Figure 4-3: User input example (from the model) of when level valves are closed

ADP.3: The model computes the compressed air distribution and error percentage.

Discussion: The compressed air distribution is calculated by subtracting the flow rate after the valve has been closed from the flow rate before the valve was closed for each level. It correlates the time inserted into the table with the supplied flowmeter data time stamp. The computation is depicted in Equation ***(5)***[8]:

$$F_{Lx} = F_{Sur\,t_1} - F_{Sur\,t_2} \qquad \textbf{(5)}$$

Where:

F_{Lx} - Consumption of specific level [Nm³/h]

[8] *This equation was developed based on the fundamental law – Conservation of mass and is verified in Section 4.2.2*

$F_{Sur\ t_1}$	-	Surface consumption at time stamp 1 [Nm³/h]
$F_{Sur\ t_2}$	-	Surface consumption at time stamp 2 [Nm³/h]

The time from before the valve on a specific level was closed (t_1) to the elapsed time after the valve was closed (t_2) is referred to as the baseload period. To mitigate noise in the data and increase the accuracy of the consumption after the level was isolated, the model uses t_2 as a reference timestamp and averages the consumption data 2 to 5 minutes before t_2. This average time range is referred to as the baseload calculation period and can be adjusted by the user to reduce the error percentage of the baseload test.

The error percentage is computed by summating the normalised consumption per level and comparing it with the consumption before any valves were closed. The error percentage gives a good indication if the (computed) normalised consumption per level is representative of the total consumption before the baseload test was conducted. The higher the error percentage, the greater the deviation from the actual consumption, indicating a potential issue during the baseload test such as a broken valve that did not completely isolate a specific level. Therefore, the error percentage is a crucial metric to identify any anomalies and ensure the reliability of the results obtained from the baseload test.

ADP.4: Normalise the consumption of each level using the ideal gas law.

Discussion: As the compressed air isolation valves are closed, the demand decreases which results in an increase in pressure. When the pressure increases, there is a corresponding increase in consumption (as highlighted in Section 2.4.5). Thus, the consumption of each level is normalised to a reference pressure using Equation ***(6)***, to account for the change in pressure.

$$F_{Nx} = F_{Lx} \times \frac{P_{ref}}{P_{Sur}} \tag{6}$$

Where:

F_{Nx}	-	Normalised consumption of specific level [Nm³/h]
F_{Lx}	-	Consumption of specific level [Nm³/h]
P_{ref}	-	Reference pressure: 500 [kPa_g]
P_{Sur}	-	Surface pressure at specific time interval [kPa_g]

Normalising the consumption of each level is important as it enables an accurate comparison between levels. Figure 4-4 highlights the importance of normalisation by demonstrating a noteworthy difference in consumption when normalised to a reference pressure. Normalisation eliminates the effect of different operating pressures on consumption, ensuring that the comparison is based on the actual usage of each level. This eliminates any bias that may arise from differences in operating pressures between levels and allows for a more precise analysis of compressed air consumption per level.

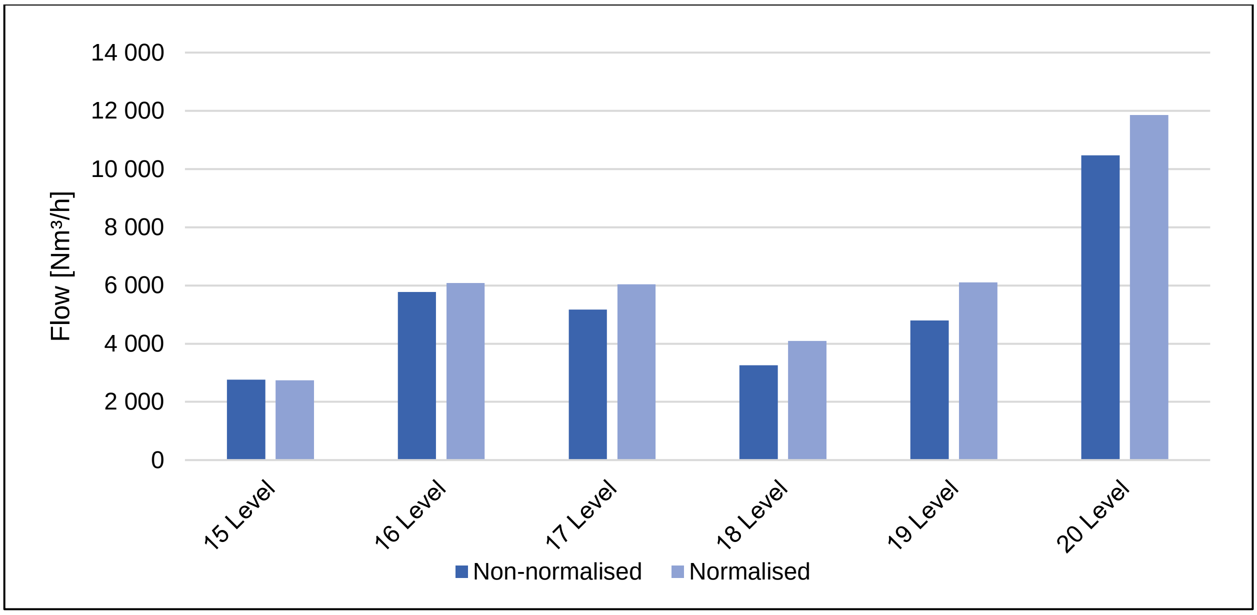

Figure 4-4: Difference between non-normalised consumption compared with normalised consumption

ADP.5: The surface flow consumption and normalised consumption, surface pressure, baseload period and baseload calculation period are illustrated through a graph, as depicted in Figure 4-5.

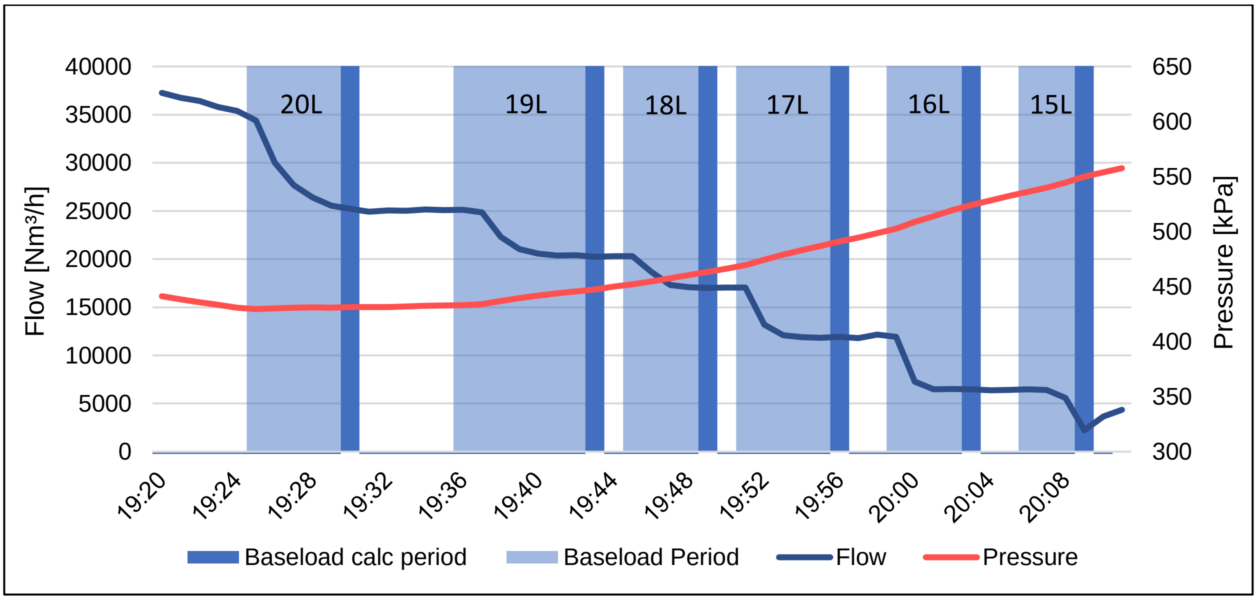

Figure 4-5: Example of normalised surface flow consumption versus pressure during the operational baseload test

Discussion: User data input verification is simplified through the use of an illustrative graph. This allows the cross-correlation between the times when isolation valves were closed, and the corresponding baseload period characterised by a decrease in consumption. This helps users to quickly identify mistakes in their data input. Figure 4-6 shows an example of incorrect user input highlighted in the orange square.

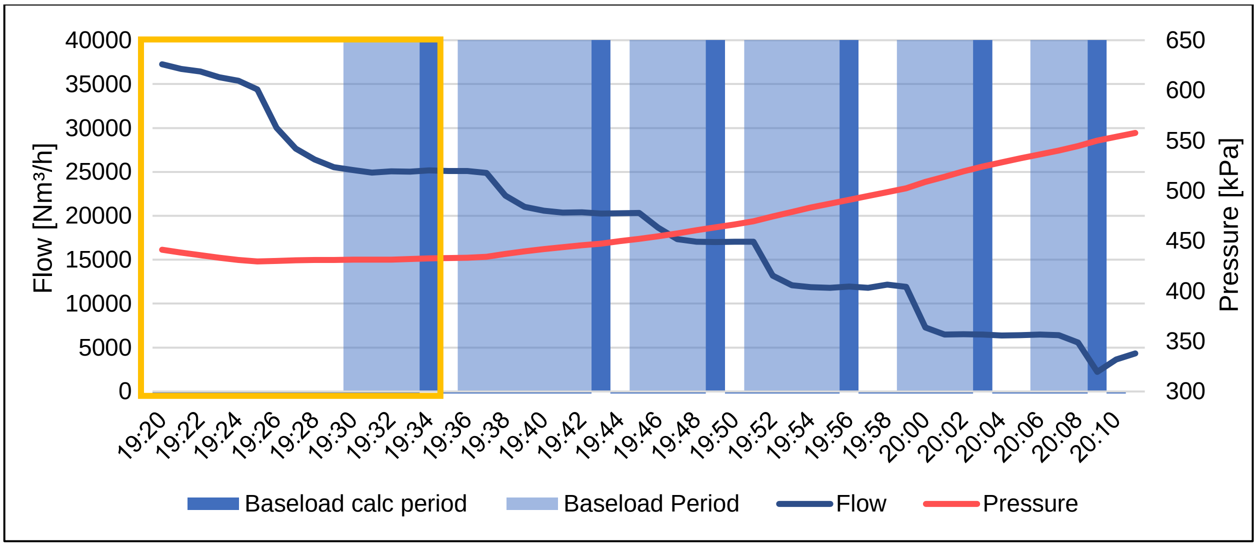

Figure 4-6: Example of incorrect user input (highlighted in orange box)

The figure illustrates that the valve close time input does not correspond with the reduction in compressed air flow, indicating an incorrect user input that needs to be corrected. The simplicity of this verification process promotes efficiency and accuracy by eliminating the need for iterative manual cross-verification.

ADP.6: The normalised consumption of each level is presented graphically.

Discussion: The normalised consumption of each level is depicted to enable the user to quickly identify and rank the worst performing levels. An example is illustrated in Figure 4-7 to assist further in the visualisation of the model.

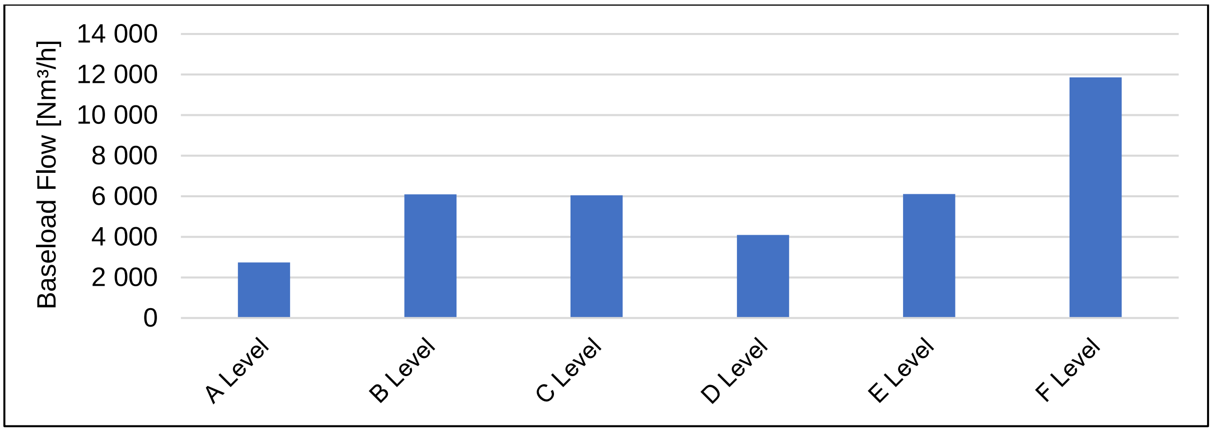

Figure 4-7: Normalised Flow Analysis per level

Upon completion of phase 6 the compressed air distribution between the different levels should be established. Using the baseload method and capturing the data into the newly developed data processing model drastically reduces the resources required and time taken to identify high compressed air wastage areas on a shaft. A big advantage of the operational baseload method is that it requires minimal instrumentation infrastructure, which means it can be utilised on shafts with little to no instrumentation. The newly developed calculation model is designed to be intuitive, user-friendly, and adaptable to accompany different mine layouts and levels of different shafts.

4.2.2 Verification of Method 1: Operational baseload testing

This section discusses the **verification** of the operational baseload testing using the conservation of mass. As mentioned in Section 2.4.1, the compressed air network consists of compressed air production (supply), a distribution network, and compressed air end-users (demand). The principle of mass conservation states that the mass can neither be created nor destroyed in a closed/isolated system [143], as per Equation ***(7)***.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{7}$$

Where:

$\dot{m}_{in}$	-	Mass flow rate into isolated system [kg/s]
$\dot{m}_{out}$	-	Mass flow rate out of isolated system [kg/s]

The distribution network forms a control volume, which is regarded as an isolated system. Compressors produce air mass that enters the control volume, while end-users on different levels consume the air mass produced by the compressed air. Thus, a mass balance can be performed on the control volume. An illustration is depicted in Figure 4-8 to assist in explaining the conservation of mass.

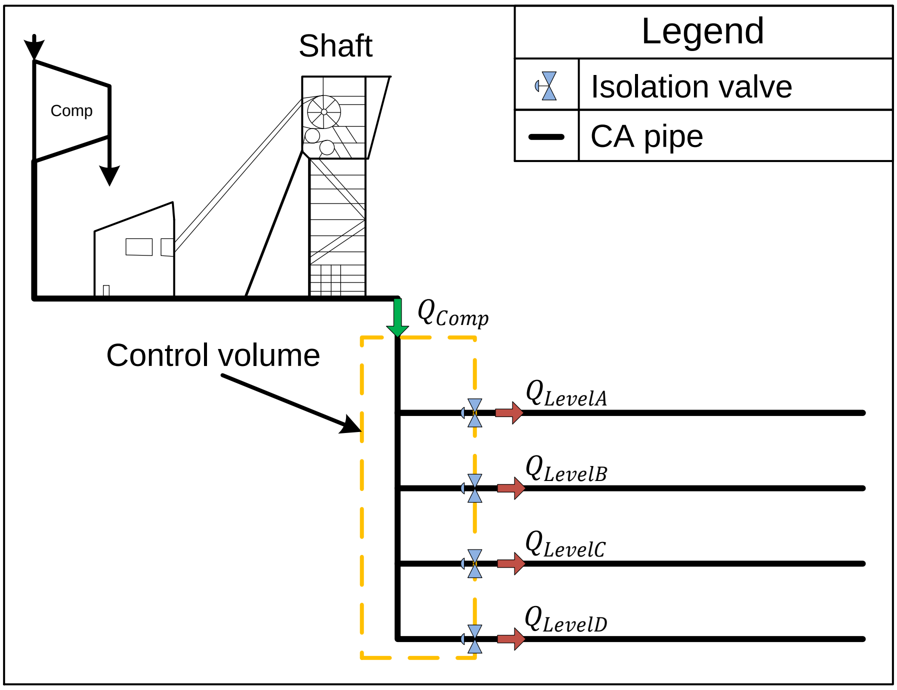

Figure 4-8: Conservation of mass control volume illustration

Figure 4-8 is used as an example to perform the operational baseload test, developed in Section 4.2.1. Applying steps 1 to 3, Equation ***(7)*** is adapted to form Equation ***(8)***:

$$Q_{Sur} = Q_{LevelA} + Q_{LevelB} + Q_{LevelC} + Q_{LevelD} \qquad \textbf{(8)}$$

Where:

Q_{Sur}	-	Compressed air consumption on surface (all levels open) [Nm³/h]
Q_{Levelx}	-	Compressed air consumption of specific level [Nm³/h], with x from A to D

Applying steps 4 to 6 – closing the first isolation valve of underground level D and waiting for surface flow and pressure to stabilise – Equation ***(8)*** leads to Equation ***(9)***:

$$Q_{Sur_D} = Q_{LevelA} + Q_{LevelB} + Q_{LevelC} \qquad \textbf{(9)}$$

Where:

Q_{Sur_D}	-	CA consumption on surface (with level D closed) [Nm³/h]
Q_{Levelx}	-	CA consumption of remaining, non-isolated levels [Nm³/h], with x from A to C

Combining Equations ***(8)*** and ***(9)*** leads to Equation ***(10)***:

$$Q_{Sur} = Q_{Sur_D} + Q_{LevelD} \qquad \textbf{(10)}$$

Using mathematical manipulation, Equation ***(10)*** is re-arranged to form Equation ***(11)***

$$Q_{LevelD} = Q_{Sur} - Q_{Sur_D} \qquad \textbf{(11)}$$

Hence, using the conservation of mass and applying a mass balance on the control volume (the compressed air network found in an underground mine), the consumption of level D is determined from first principles. This procedure can be reiterated until the flow of each level has been calculated. This thus **verifies** the operational baseload as a viable method to determine the compressed air consumption of each level underground.

4.3 Development of benchmark method 2: Theoretical baseload

The theoretical baseload method follows a data-driven approach and utilises a model that was built using Microsoft Excel®, to compute the theoretical compressed air baseload automatically. This model enables mining personnel to identify the worst compressed air consuming level/half-level quickly without having to perform resource-intensive and time-consuming underground level audits. The calculation model is built upon several key principles that underpin its design and functionality. The theoretical baseload and verification are discussed in the sections below.

4.3.1 Development of method 2

Creating a mathematical model that computes the compressed air baseload per level/half-level[9] will reduce the resources and time required to identify the worst performing level/half-level. The automated calculation model (ACM) can be found in Appendix D. This section elaborates on the development of the automated calculation model.

To aid in comprehending each step of the newly developed automated calculation model, a summary of its input, processing, and output is illustrated in Figure 4-9. This is followed by a breakdown and discussion of each step (denoted ACM.1 to ACM.6).

[9] *For simplification, the remainder of this section will refer to level and/or half-level as level only.*

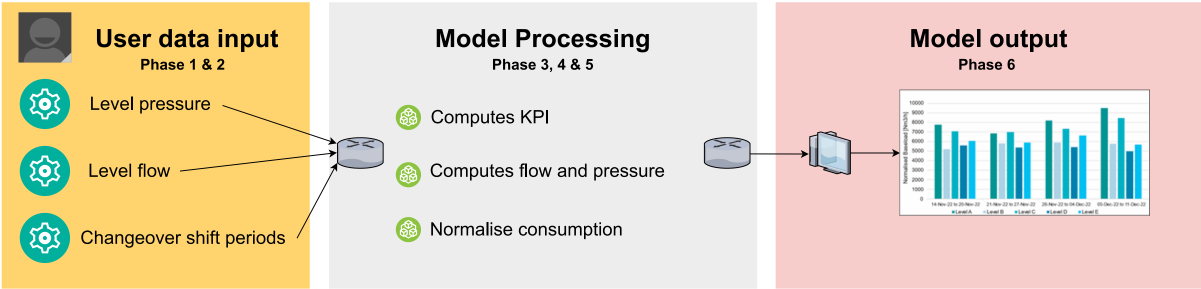

Figure 4-9: Illustration of newly developed theoretical model

ACM.1: Extract the pressure and flow data and capture it into the model.

Discussion: Based on the amount of available data, multiple weeks can be captured into the model so that it can be used to compare the baseload of levels from different weeks. This allows mine managers to compare their current performance with historical performance to evaluate if they have improved or deteriorated over time.

ACM.2: Insert shift period for each level.

Discussion: User is prompted to insert the morning and afternoon shift period (changeover shifts) for each level. An example of user input is depicted in Table 4-1.

Table 4-1: Example of user shift time schedule input

Morning reduction shift time schedule for all levels:				
Level A	Level B	Level C	Level D	Level E
>=04:30:00	>=05:00:00	>=06:00:00	>=06:30:00	>=06:30:00
<06:00:00	<6:30:00	<7:30:00	<08:00:00	<08:00:00
Afternoon reduction shift time schedule for all levels:				
Level A	Level B	Level C	Level D	Level E
>=14:30:00	>=15:30:00	>=16:00:00	>=16:30:00	>=16:30:00
<18:00:00	<18:00:00	<18:00:00	<18:00:00	<18:00:00

ACM.3: Model computes KPI and identifies lowest KPI per level for specified times.

Discussion: Some mines have compressed air control valves that regulate the pressure over the 24-hour mining cycle. Supply pressure directly influences the demand. Thus, if a control valve is limiting the flow of the shaft, the lowest consumption during the specified shifts cannot be regarded as the baseload. Therefore, to increase the versatility of the model, a KPI, namely the performance indicator (PI), was developed to identify the period where the flow, independent of the specific supply pressure, is the lowest. This PI can be equated using Equation ***(12)***.

$$PI = \frac{F_{t_x}}{P_{t_x}} \tag{12}$$

Where:

PI	-	Consumption [Nm³/h] / Pressure [kPa]
F_{t_x}	-	CA consumption of level at specific time x [Nm³/h]
P_{t_x}	-	Pressure of level at specific time x [kPa]

The lowest PI per level during the time span from the user input is calculated. As previously mentioned, the data sample size is the previous 5-day work week. Therefore, the average of the lowest PI per level for each day in the past week is determined to compute an average PI for the week. This approach aids to minimise the effect of any abnormal compressed air consumption (on a level) that may have occurred on a specific weekday (as highlighted in Table 4-2), ensuring that the results are representative of the overall performance of each level.

Table 4-2: Example of average PI computation

Day	Level A Lowest PI [Nm³/h/kPa]	Average PI [Nm³/h/kPa]
01/11/2022	16.65836409	15.01
02/11/2022	12.06638527	
03/11/2022	15.36298945	
04/11/2022	15.41615244	
07/11/2022	15.52179788	

ACM.4: Correlate PI timestamp with specific flow and pressure.

Discussion: Once the lowest PI per day, per level has been identified, it can be cross correlated to the specific date and time. The corresponding pressure and flow data is recorded, and similar to ACM.3, an average of the pressure and flow is computed.

ACM.5: Normalise the consumption of each level.

Discussion: To identify the worst performing level, the consumption of each level needs to be compared with each other. However, due to variations in pressures between levels, the baseload consumption per level may not provide an accurate representation. Therefore, the consumption of each level is normalised to a reference pressure using Equation ***(13)***, to ensure equivalence between the different levels, thereby enabling the identification of the worst performing level.

$$F_{Nx} = F_{Lx} \times \frac{P_{ref}}{P_{L_x}} \tag{13}$$

Where:

F_{Nx}	-	Normalised consumption of specific level [Nm³/h]
F_{Lx}	-	Consumption of specific level [Nm³/h]
P_{ref}	-	Reference pressure - 500 kPa$_g$
P_{L_x}	-	Level pressure [kPa$_g$]

ACM.6: The normalised consumption of each level is illustrated graphically.

Discussion: The normalised consumption of each level is depicted graphically to enable the user to identify the worst performing level quickly. If historical data is available, each level can be compared with its historical performance. An example is depicted in Figure 4-10 to further assist in the visualisation of the model.

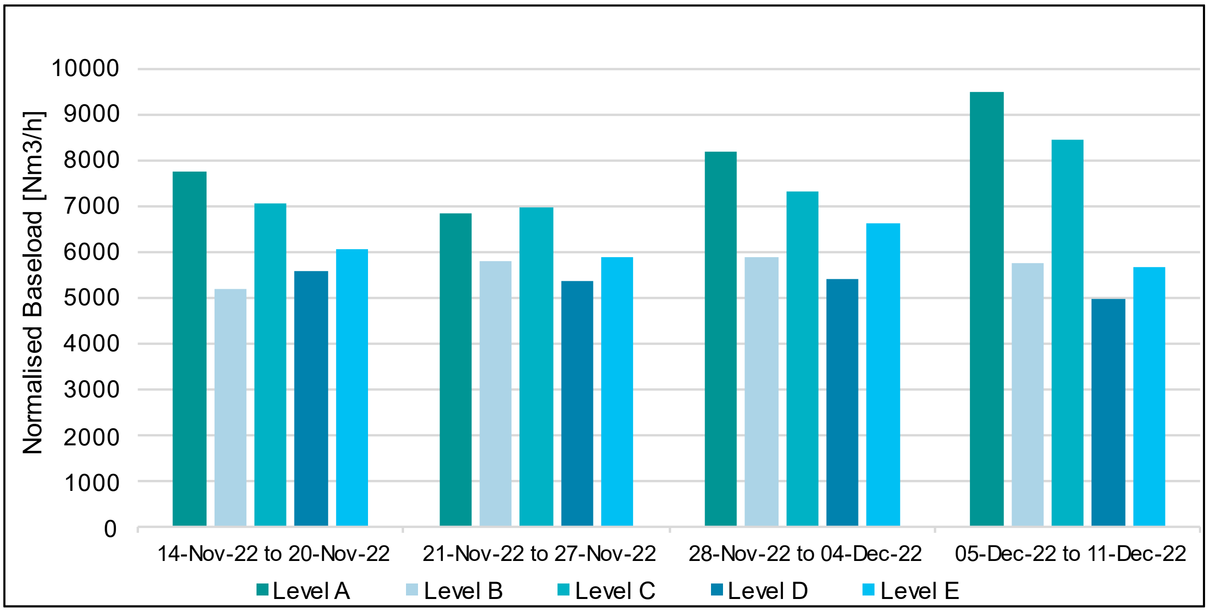

Figure 4-10: Example of normalised baseload flow analysis per level

Upon completion of the theoretical baseload, the compressed air distribution between the different levels should be well known. The theoretical baseload method, coupled with the automated calculation model, drastically reduces the resources and time required to identify high compressed air wastage areas on a shaft. One of the most significant advantages of the theoretical baseload method is that it does not require personnel to conduct underground audits or disrupt mining operations. Additionally, the newly developed model exhibits a high level of simplicity and adaptability, allowing the integration of various mine layouts, operational configurations, and data sources. This enhances its practicality and versatility in identifying and addressing compressed air wastage effectively.

4.3.2 Verification of Method 2: Theoretical baseload

This study has developed a method that can be utilised to determine accurately the baseload of each level/half-level using the consumption and pressure data per level/half-level is available. The theoretical baseload method is a mathematical model that eliminates the need for auditors to close valves underground or perform manual consumption or pressure measurements. The principles on which method 2 is based is used as **verification** for the development of the theoretical baseload.

The theoretical baseload aims to be a minimally invasive method to compute the minimal compressed air consumption. Hence, no valves are to be closed underground which means that a mass/volume balance cannot be applied to determine the compressed air wastage. This requires careful consideration of which period in the 24-hour mining profile to consider that is indicative of compressed air wastage. The logical approach would be to select the blasting shift as there are no authorised compressed air end-users present during this period.

However, most mines close their underground level isolation valves during the blasting shift to save on compressed air consumption [4]. To prevent the mines from having to re-open these valves and cause compressed air to be wasted during Eskom peak demand periods[10], another time period must be selected. As mentioned in Section 2.4.4, there are changeover shifts where mining personnel are not working in the crosscuts. Hence, no pneumatic equipment is being used for production in the crosscuts during these changeover shifts. Thus, changeover shifts are considered appropriate periods to compute the compressed air baseload.

Mining crews that worked during the cleaning shift are taken to the surface during the morning changeover shift. Thus, this period will have a minimum compressed air consumption as no pneumatic loaders or chutes are used. During the afternoon changeover shift, all mining personnel are escorted to the surface to ensure that no crosscut personnel are underground. Only mining personnel that are working on the station are present during this shift. Hence this period will yield the lowest compressed air consumption before the level isolation valves are closed. The selection of these changeover periods is based on the reasoning that limited to no authorised compressed air end-users are present underground during these periods, thereby yielding the lowest compressed air consumption. Thus, changeover shifts are considered appropriate periods to evaluate the compressed air wastage per level/half-level.

[10] Eskom peak period – Winter: 17:00 – 20:00, Summer: 18:00 – 21:00.

To further **verify** this statement, the compressed air consumption profile of a shaft (noted as Shaft X) was evaluated over three months, along with the corresponding shift schedule. The results are depicted in Figure 4-11.

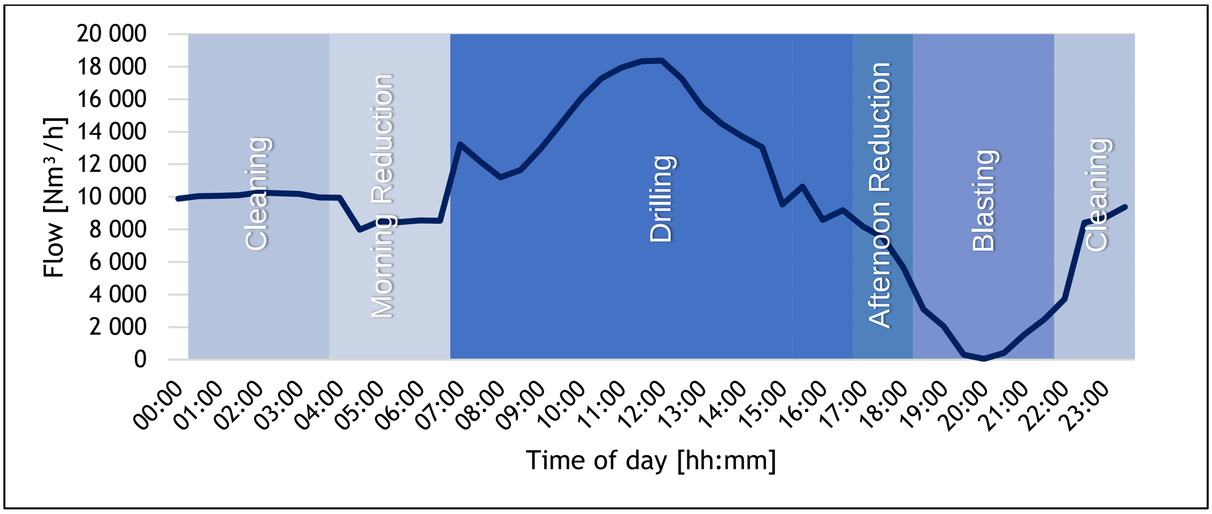

Figure 4-11: Average compressed air consumption profile of Shaft X over a three-month period

Based on the result presented in Figure 4-11, there are two distinct changeover shifts which can be used to determine the compressed air baseload. These are the “morning reduction” and “afternoon reduction” shifts, both of which are changeover shifts. This thus **verifies** the use of changeover shifts as periods to compute the compressed air baseload.

The afternoon shift starts at different times for each level underground as not all the crews can come up to the surface at the same time. This is unique to all mines and must be accounted for. This model incorporates an input from the user to specify the start and end time of the two shifts, to account for the varying shift times. This input is then used to determine the morning and afternoon reduction shifts.

Section 2.4.5 highlighted that supply pressure has a significant effect on the amount of compressed air wastage from leakages. Hence this method must take varying pressures into account to ensure equivalence when the levels/half-levels are compared with each other. The consumption of each level/half-level is normalised to a reference pressure to ensure direct comparison.

To ensure the accuracy of the theoretical baseload computation, it is crucial to consider the appropriate data sample size that will be used to compute the theoretical baseload. If the sample size is too small, the results may not be representative. This study assumes that a weekly theoretical baseload can be conducted on a shaft to evaluate its performance. Mining companies typically adhere to a 5-day work week, with every second Saturday designated as an additional production day. Sundays are usually reserved for maintenance and repair work [55], leading to a significant variation in compressed air consumption on weekends [55]. Therefore, this study will use the 11-

shift fortnight (5-day work week) as the data sample size to compute the theoretical baseload. Data resolution is another important aspect to consider as this will vary depending on the data availability on the specific shaft. This study will use a minimum (averaged) data resolution of 30 minutes to compute the theoretical baseload.

4.4 Summary

Chapter 4 introduced two novel benchmark methods to identify high compressed air wastage efficiently, without the use of advanced simulation software or conventional audits. Both benchmark methods compute the distribution of compressed air wastage in deep-level underground mines in a less resource-intensive and time-consuming manner when compared with the aforementioned traditional methods.

Two different benchmarking methods were developed to account for various underground compressed air data availability. The first method, Operational Baseload, is specifically designed for situations where limited underground compressed air consumption data is available. By conducting a baseload test and using the ADP model, the highest consuming level can be efficiently identified. The baseload test was developed on the conservation of mass and **verified** from first principles. The ADP model was built using Microsoft Excel®, and aids to reduce the time and resources required to process the data gathered during the baseload test.

The second method, Theoretical Baseload, is tailored for situations where compressed air data is available on all levels. It is a data-driven approach, using historical data and the ACM, to compute the compressed air wastage distribution throughout the shaft. The key principles on which the model is built were **verified** through literature and the changeover shifts (used to compute the lowest PI) were **verified** through a case study observation.

The next chapter elaborates on the integration of these two benchmark methods into a newly developed methodology which will aim to maximise the time and resource efficiency to identify ventilation shortfalls.

CHAPTER 5: DEVELOPMENT OF NEW METHODOLOGY TO IDENTIFY VENTILATION SHORTFALLS

5.1 Preamble

Objective 3 of this study is to develop a method (utilising the link between compressed air wastage and ventilation shortfalls) to simplify the identification and prioritisation of ventilation shortfalls in a shorter time period than existing identification methods. Hence, the two new compressed air benchmark methods (developed in Chapter 4) are incorporated into a newly developed methodology to identify ventilation shortfalls. The development of each stage in the new methodology is guided by the criteria identified from literature, as outlined in Table 2-4, to ensure the successful resolution of the identified problem. Table 2-4 is elaborated on below with a solution and corresponding stage to each criterion in the table, which will be used to construct a new methodology (as developed in this chapter).

Table 5-1: Solution and corresponding stage for each criterion identified in Chapter 2

Criteria	Solution	Stage
Obtaining accurate data for model	Data acquisition and verification	Stage 1
Simple, time- and resource-efficient approach (to identify compressed air wastage)	Benchmarking	Stage 2
Tailor results using an appropriate KPI	Normalise results	Stage 3
Ventilation shortfall identification	Perform crosscut baseload analysis	Stage 4
	Perform crosscut audit	Stage 5

The development of each stage will be discussed in detail in the subsequent sections of this chapter. To provide a comprehensive perspective and guide the discussion in the remainder of this chapter, a schematic representation of the newly developed methodology is depicted in Figure 5-1.

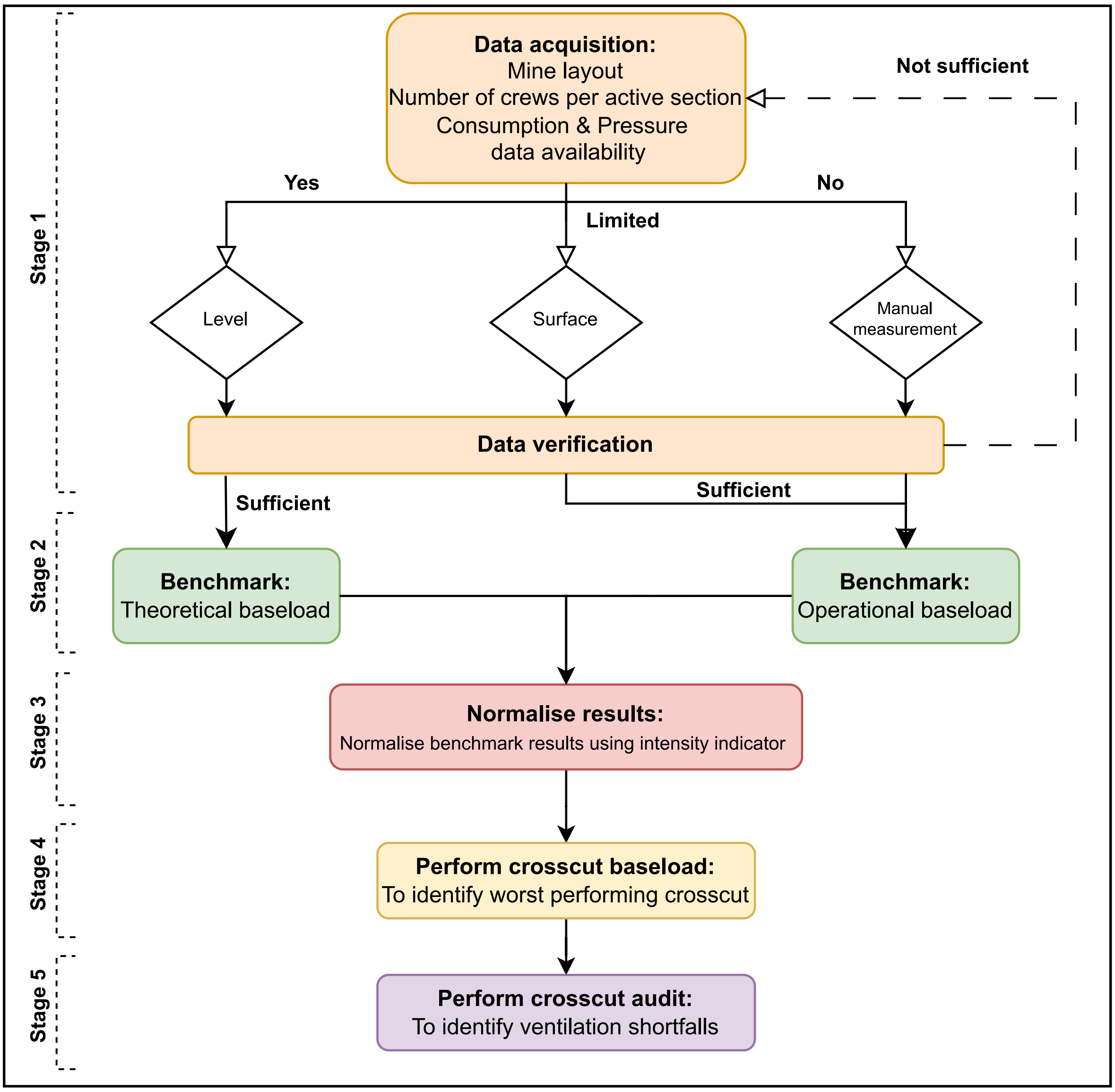

Figure 5-1: Overview of newly developed methodology

Each stage of the approach presented above will be discussed in more detail in the remainder of this chapter. Stage 2, which was discussed in Chapter 4, will be briefly summarised in this chapter. Additionally, each stage in the newly developed methodology will be continuously verified, either through existing research or sample implementation of each stage on mini case studies.

5.2 Stage 1: Data acquisition and verification

A detailed discussion of data acquisition and the importance of verification before proceeding with the newly developed methodology is presented in this section, as shown in Figure 5-2.

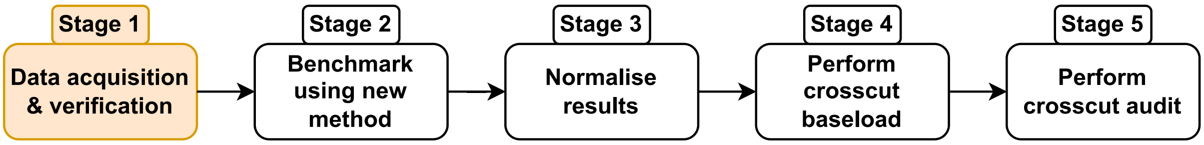

Figure 5-2: Newly developed methodology - Stage 1

Obtaining reliable and accurate data is essential to benchmark the compressed air network accurately. Thus, data acquisition and verification are stage 1 of the benchmark methodology. Data acquisition involves the collection of:

- the detailed mine layout,
- the number of stoping and development crews per active level, and
- pressure and flow data (surface and/or underground levels).

Collecting the mine layout will help to familiarise oneself with the mine and cross-correlate the active crews per level. This will also become important when conducting a crosscut baseload and crosscut audit underground (further discussed in Sections 5.5 and 5.6).

The Mine Health and Safety Act of South Africa mandates that deep-level mining companies maintain accurate and up-to-date underground drawings of the mine layout [144]. Obtaining the number of stoping crews on active levels is also not a problem as mines closely monitor and manage their crews to ensure production targets are met [144]. Both the mine layout and active crews can be collected from the mine surveying department [4] [103]. A typical mine layout network is depicted in Figure 5-3.

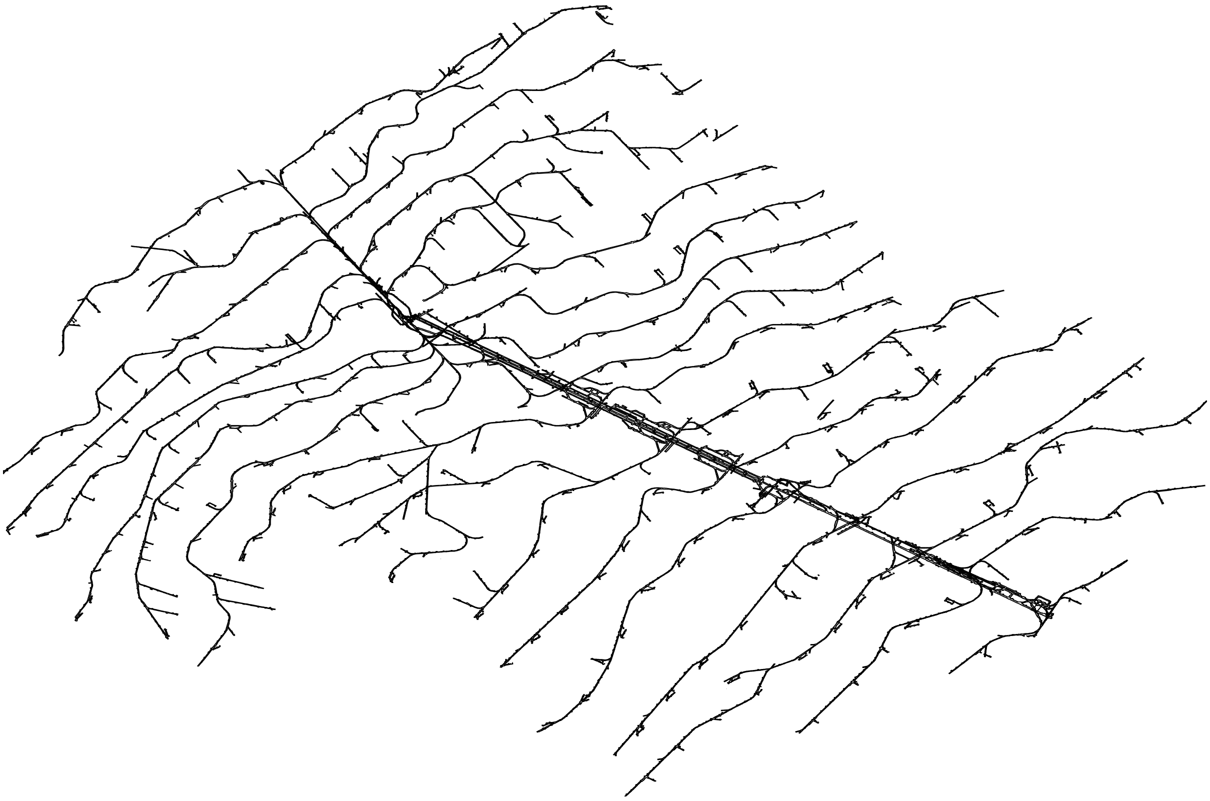

Figure 5-3: Typical mine layout provided by mine surveying department

Collecting the pressure and flow data on the surface and each level is challenging as monitoring instrumentation for compressed air networks often differ significantly between mines [145]. Installing instrumentation often comes with a high initial capital cost [28] [38], which means mines usually only have permanent flow metering instrumentation installed on the compressed air network at the surface and at the station of each level underground [4] [146]. This permanent flow metering instrumentation is known as an insertion flowmeter. It measures the compressed air consumption at a specific time interval and records this information in a historian. This stored data is then used to develop a 24-hour compressed air consumption profile. Figure 5-4 depicts an example of a 24-hour consumption profile (left) and a permanent flowmeter installed on a compressed air pipe at surface (right).

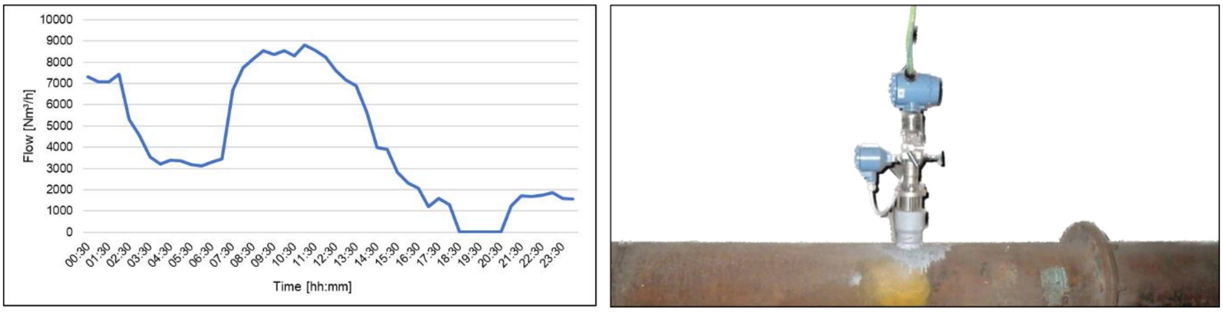

Figure 5-4: 24-hour consumption profile recorded and permanent flowmeter

The availability of flowmeter data on all underground levels can differ between mines [3] [34] [145]. When limited or no flow consumption data is available underground, manual measurements are required to obtain the data for benchmarking. This is done using a calibrated, portable insertion flowmeter, or ultrasonic flowmeter [4] [147]. Calibrated, portable flowmeters are considered accurate instrumentation to measure compressed air consumption [3] [148] and is widely used in industry to confirm the accuracy of permanent instrumentation measurements [28]. This signifies that they have a high accuracy and **verifies** that either one of these flowmeters can be used to acquire reliable compressed air consumption data underground in the absence of permanent installed flowmeter instrumentation. An example of a portable and ultrasonic flowmeter is illustrated in Figure 5-5.

Figure 5-5: Portable insertion and ultrasonic flowmeter instrumentation

Section 2.4.4 indicated that mines extract ore using an array of pneumatically operated equipment. This equipment has minimum pressure requirements to operate effectively (as highlighted in Table 2-2) [4] [50]. Literature also showcased that instrumentation is often available at the station of each underground level [3] [34] [145]. Hence, it assumed that the mines have pressure loggers installed at the station on all the underground levels and no manual pressure data needs to be collected.

Once the data has been collected, it must be verified. Data verification is vital to ensure the accuracy and adequacy of the collected data. If the data collected is deemed inaccurate or insufficient during the data verification stage, and no reasonable assumptions can be made to substitute the inaccurate or insufficient data, the data acquisition step should be reiterated. Once all the data has been collected and deemed accurate and sufficient, stage 2 of the benchmarking procedure can commence. This is discussed in more detail in the following section.

5.3 Stage 2: Benchmarking to identify compressed air wastage

The previous section discussed the data acquisition and verification procedure. It provided an alternative method to acquire compressed air consumption data when limited or no instrumentation is available underground. As per Figure 5-6, stage 2 entails benchmarking (using the new method) to identify compressed air wastage. Chapter 4 provided a detailed discussion of stage 2, hence only a summary is provided in this section.

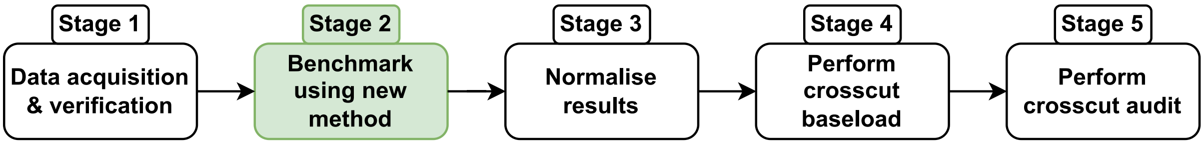

Figure 5-6: Newly developed methodology - Stage 2

Two benchmark methods have been developed to identify areas of high wastage in underground compressed air systems, taking into consideration the availability of data:

- Method 1 - Operational baseload: Utilised when limited underground compressed air consumption and pressure data is available.
- Method 2 - Theoretical baseload: Suitable when compressed air consumption and pressure data is available per level/half-level underground.

By applying one of these benchmark methods, the distribution of compressed air wastage throughout the shaft can be computed. It is important to note that the compressed air distribution is required before the results can be tailored toward ventilation shortfall identification, as per stage 3. This is discussed in more detail in the section below.

5.4 Stage 3: Normalisation of baseload results

The previous section discussed the newly developed method to identify high compressed air wastage area (level specific). **Objective 3** of this study is to utilise the link between compressed air wastage and ventilation shortfalls and expand the benchmark method to identify and prioritise ventilation shortfalls effectively. Hence the baseload results must be tailored toward identifying ventilation shortfalls. As per Figure 5-7, this section discusses stage 3 in the newly developed methodology. It explains how the baseload results can be modified, using a newly developed indicator to highlight the level with the highest compressed air consumption intensity.

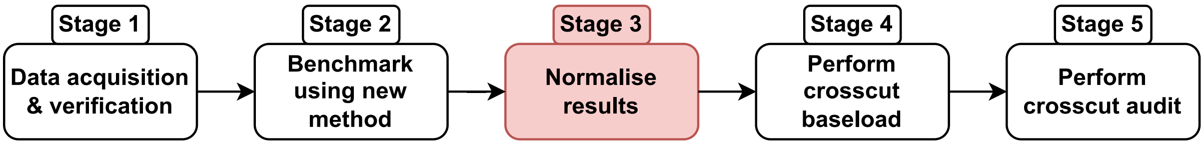

Figure 5-7: Newly developed methodology - Stage 3

5.4.1 Development of Baseload Intensity indicator

Chapter 3 **verified** that there is a link between compressed air wastage and ventilation shortfalls. Thus, based on the results of the baseload test, it would seem logical to investigate the level with the highest compressed air wastage for ventilation shortfalls. However, following this approach may not necessarily yield the most accurate results. This is because the baseload test only indicates the amount of the wastage on the level. It does not indicate the size of the network, number of active crosscut crews, or wastage due to leaks.

Crosscuts have been identified as areas where the majority of compressed air misappropriation happens [4]. Thus, it is reasoned that the more crosscut crews there are per level, the more active the level is and the higher the occurrence of compressed air misappropriation (if ventilation shortfalls exist). However, as the compressed air network extends, the number of leaks also increases [4]. The above-mentioned factors will increase the baseload consumption but will not necessarily correlate with the most severe ventilation shortfall. Data gathered from case study Mine X is used to illustrate the relationship, as per Figure 5-8 below.

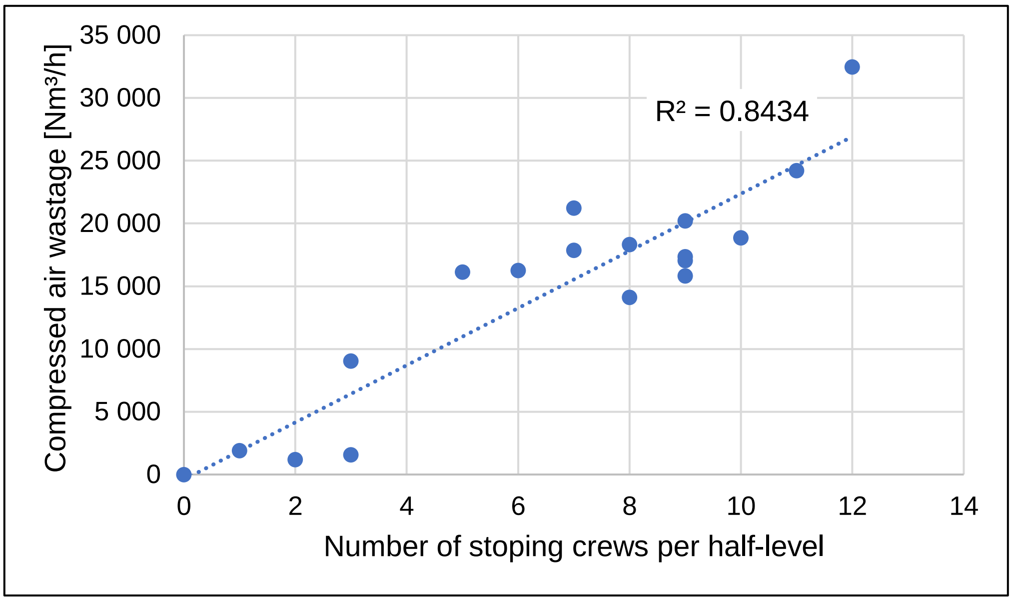

Figure 5-8: Relationship between compressed air wastage and number of stoping crews

The results from Figure 5-8 indicate a linear relationship with an R^2 value of 0.8434, which signifies a strong correlation between compressed air wastage and number of crews. Hence investigating the level with the highest baseload consumption will not lead to the most significant or severe ventilation shortfalls identified.

Thus, to identify the level with the highest potential for and severity of ventilation shortfalls, the compressed air consumption intensity per active crosscut crew must be identified. The compressed air usage per crosscut crew will highlight potential outliers and provide a better indication of the severity of ventilation shortfalls (as a result of self-ventilation rather than leaks), allowing for a more targeted and effective ventilation shortfall identification. It is reasoned that if two levels have exactly the same baseload consumption, but one level has fewer crews, the likelihood and severity of the ventilation shortfall on the level with fewer crews is expected to be more significant than on the level with a larger number of crews. Production is not considered as it does not aid to identify ventilation shortfalls.

Hence, to give an idea of the probability and severity of the ventilation shortfall, the compressed air baseload consumption per level must be divided by the active number of crosscut crews on that level to make each level comparable, independent of the size of the level or number of crews. This is further described as the baseload intensity (BI) indicator and can be calculated using the newly developed Equation ***(14)***:

$$BI = \frac{F_{Nx}}{C_{L_x}} \tag{14}$$

Where:

BI	-	Normalised consumption per crew [Nm³/h/crew]
F_{Nx}	-	Normalised consumption of specific level [Nm³/h]
C_{L_x}	-	Total number of active crosscut crews on specific level

The BI indicator aims to highlight the level with the highest compressed air wastage per crew, increasing the probability of identifying ventilation shortfall and eliminating false-positive results due to the sheer size of the level. This BI indicator aligns with the overarching need for the study, which is to reduce the time taken to identify ventilation shortfalls. The results from the BI indicator are illustrated using a Sankey chart, illustrating the consumption per crew. This helps to highlight the level with the highest consumption per crew which requires further investigation to identify ventilation shortfalls.

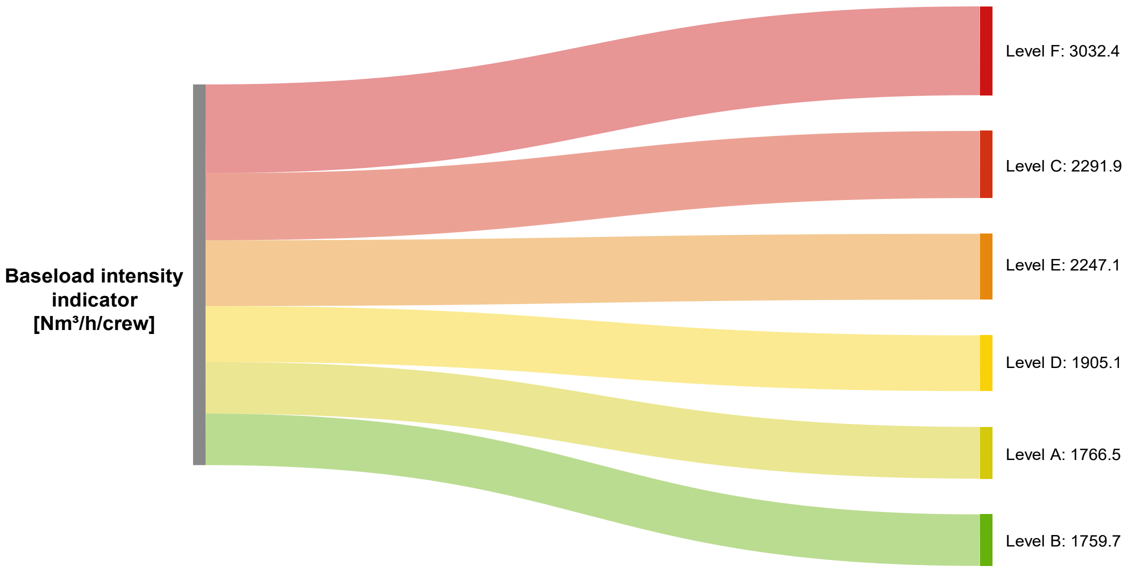

Figure 5-9: BI indicator illustrated using a Sankey chart

5.4.2 Verification of Baseload Intensity indicator

The BI indicator was **verified** through a mini case study conducted on a mine (referred to as Mine A for the purpose of this study). Mine A is equipped with pressure and flow instrumentation on every half-level. Hence, the theoretical baseload method (as introduced in Chapter 4) was used to determine the compressed air baseload per half-level. Applying the BI indicator to the specified levels showcased a discrepancy between the baseload and baseload per crew, as per Figure 5-10. It showcases the importance of normalisation using the BI indicator to identify outliers - levels which have a high consumption but few crews.

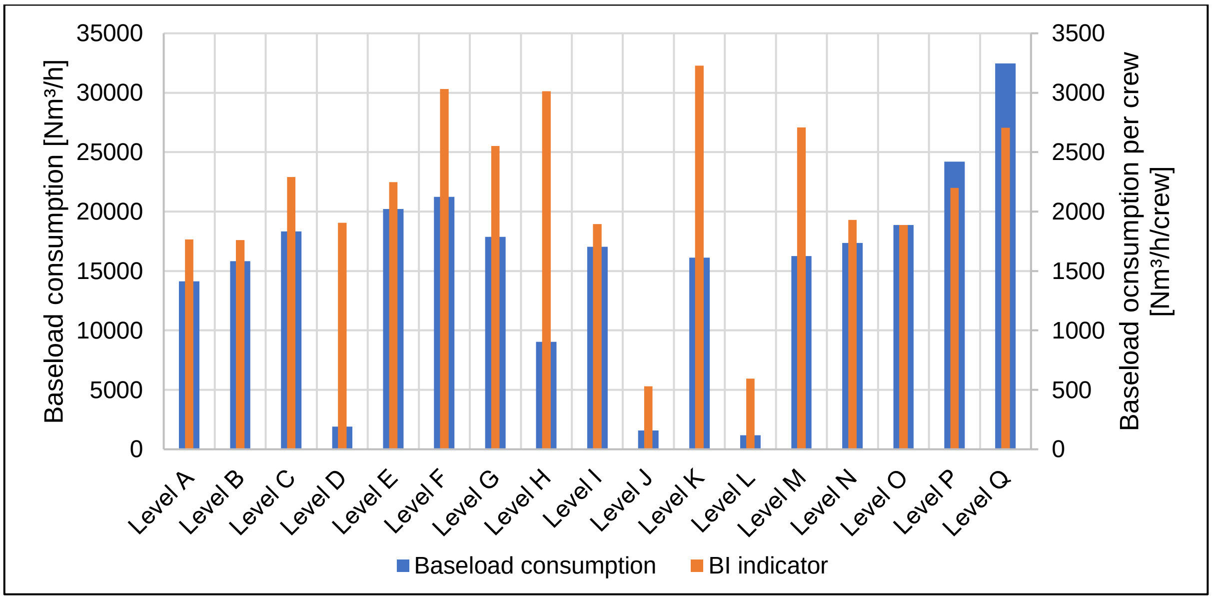

Figure 5-10: Baseload consumption versus BI indicator consumption per crew – Mine A

The results from the BI indicator are further simplified and illustrated in a Sankey chart to showcase the difference between the baseload and the BI indicator results. The units between baseload consumption and baseload consumption are different. Hence, the most effective way to compare the two KPIs with each other is to represent them as a fraction of the total of each KPI.

Visually representing the baseload consumption per crew (per level) as a fraction of the total consumption per crew allows for a clear understanding of the relative proportion of consumption attributed to that particular level. By presenting the data in this manner, it becomes easier to identify the level with the highest baseload consumption per crew and evaluate its significance in relation to the overall consumption per crew. The Sankey chart depicts the baseload and baseload consumption per crew distribution, represented as a fraction, as per Figure 5-11.

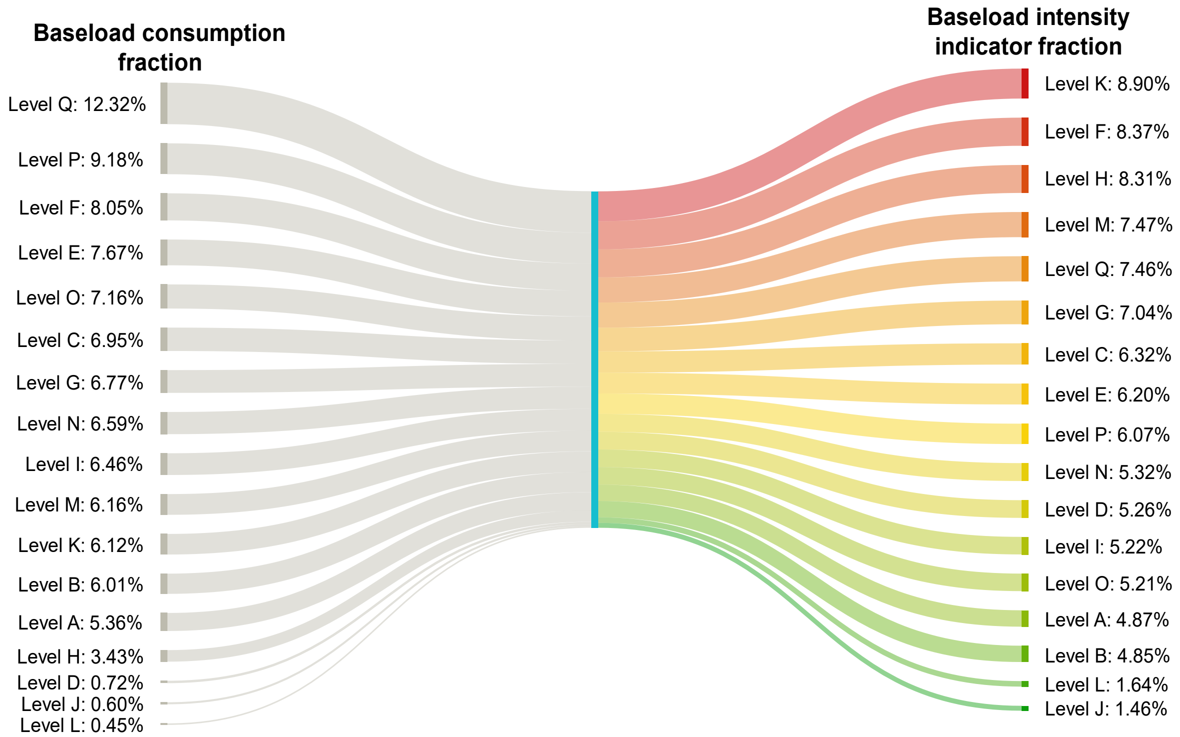

Figure 5-11: Normalised results of Mine A using BI indicator

From the results depicted in Figure 5-11, it is evident that Level K had become the worst performing level when looking at the consumption intensity per active crosscut crew. Level Q which had the highest baseload consumption had a lower consumption intensity compared with Level K. Only these two levels were audited (as this data only serves as **verification** of using the BI indicator).

Upon investigation of Level Q, it was identified that the level had a significant number of leaks and one 4-inch hose almost fully open in one of the inactive crosscuts, as per Figure 5-12. Temperatures were recorded throughout the duration of the audit, and none were found to be above 27.5 °C WB.

Figure 5-12: 4" Open compressed air pipe found in an inactive crosscut of Level Q

Level K was also audited, and the results showcased significantly higher WB temperatures, with one crosscut measuring 31.5 °C WB, which is above the ventilation shortfall criteria. There were minor leaks as a result of compressed air network deterioration, but multiple open-ended hoses (used for self-ventilation). This correlation thus **verifies** the BI indicator, using the number of crews to indicate the highest likelihood of compressed air wastage as a result of self-ventilation.

5.5 Stage 4: Crosscut baseload analysis

Once the worst level has been identified, a crosscut baseload is performed to identify the crosscut with the highest wastage. As per Figure 5-13, this section discusses stage 4 in the newly developed methodology.

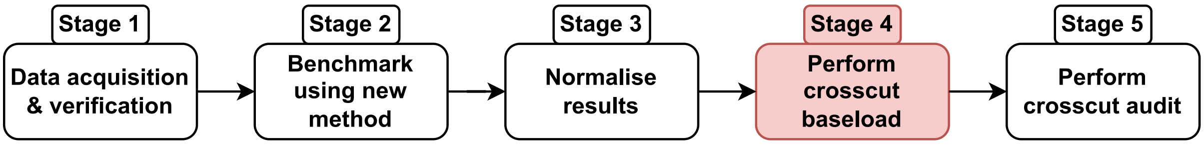

Figure 5-13: Newly developed methodology - Stage 4

The crosscut baseload method is an adaptation of the step-testing method discussed in Section 0. Step-testing is widely used in industry to identify leakages in fluid systems and has proven to be successful, making it a viable solution for identifying high consuming crosscuts. The crosscut baseload method was built on the core principles of step-testing and adapted to be used on mining compressed air networks, thereby **verifying** the use of the crosscut baseload method to identify high consuming crosscuts. Chapter 3 also showcased the successful application of this method to identify crosscuts to be audited which further **verifies** this approach.

A crosscut baseload enables auditors to localise compressed air wastage to individual crosscuts, without the need for a comprehensive audit of the entire compressed air network (including the stopes) on the level. This is beneficial as auditors do not have to go into stopes of a crosscut. The crosscut method is thus a safer method compared with conventional auditing. Performing a crosscut baseload follows a similar approach as the operational baseload. Since no personnel are allowed past the underground station of each level during the blasting shift, the crosscut baseload cannot be performed during the blasting shift.

As mentioned in Section 2.4.4, there are changeover shifts where mining personnel are not working in the crosscuts. Hence, no equipment is being used for production in the crosscuts. The crosscut baseload can thus be performed during this time. As an alternative, the crosscut baseload can also be performed during the cleaning shift, when no authorised pneumatic equipment is operated in the crosscuts.

One common challenge highlighted in Section 2.4 is the lack of pressure or flow instrumentation underground, which means the pressure across each level is often unknown. To address this issue, the crosscut's isolation valve will be temporarily closed for a brief period of 5-10 minutes to allow the flow to settle. Subsequently, the isolation valve will then be re-opened to allow the pressure to stabilise and return to the pressure before any crosscuts were closed. This approach will result in more accurate measurements of crosscut wastage as opposed to closing all the valves. Pertaining to the above discussion, the following infrastructure is required to perform a crosscut baseload successfully:

1. Permanent installed level flowmeter or portable flowmeter
2. Operational crosscut isolation valves

An example of an operational manual crosscut isolation valve is shown in Figure 5-14 below.

Figure 5-14: Operational crosscut isolation valve example

The procedure to conduct a crosscut baseload is summarised in Figure 5-15.

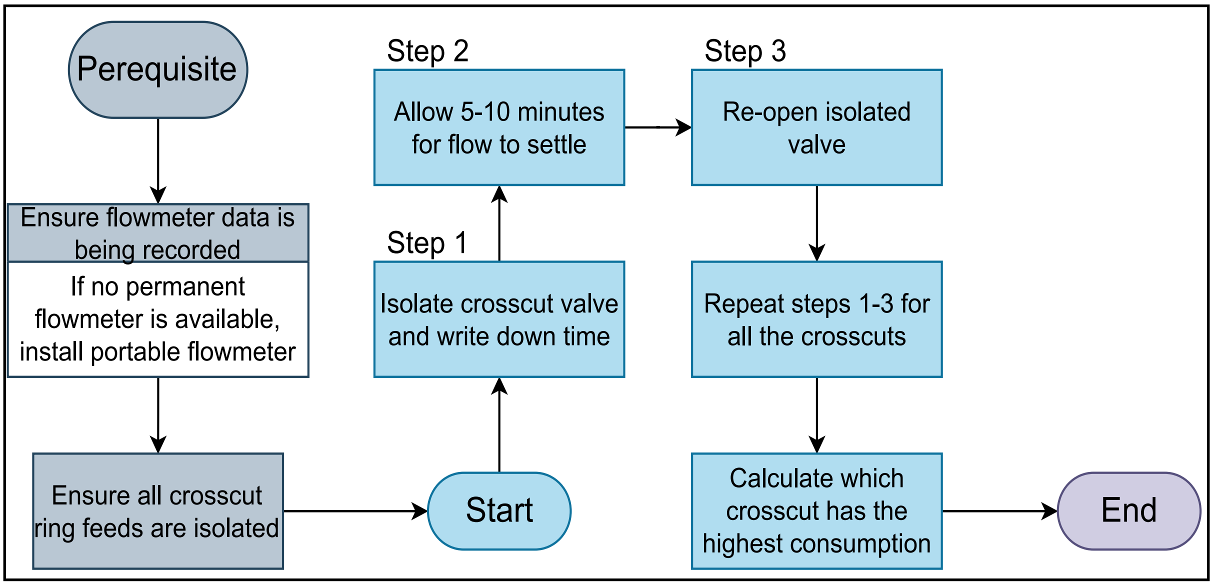

Figure 5-15: Procedure to conduct a crosscut baseload

Conducting a crosscut baseload test allows auditors to identify the worst performing crosscut without having to audit all the crosscuts. Once the crosscut baseload test is completed, the data is represented through a graph. An example is depicted in Figure 5-16 below.

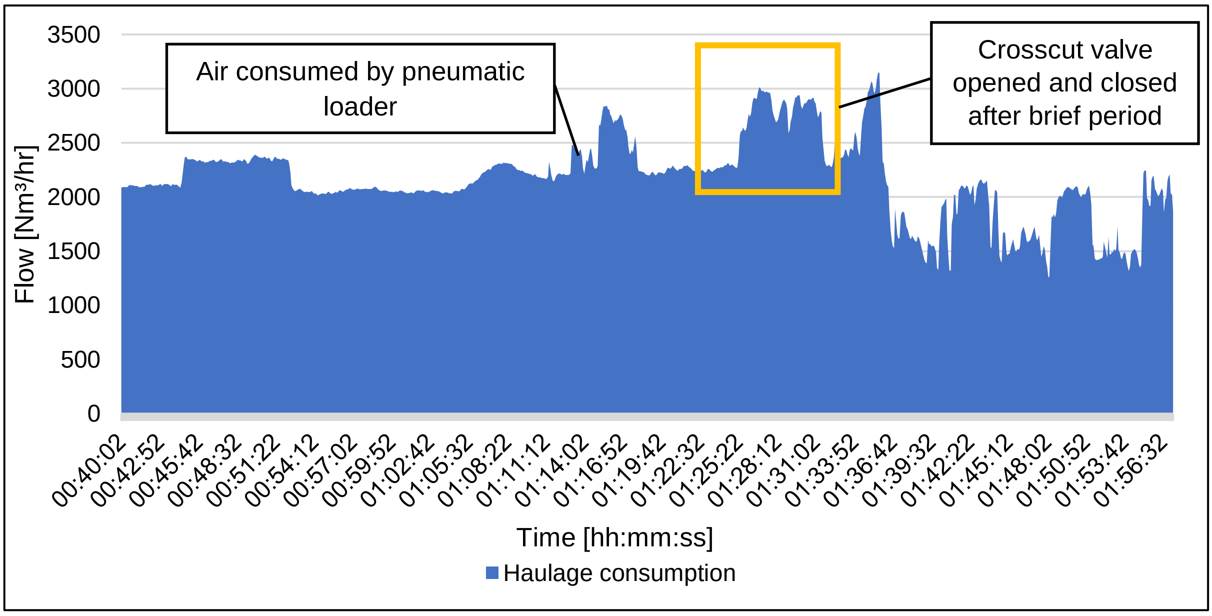

Figure 5-16: Crosscut baseload result illustration example

Mine personnel often close crosscut valves when they are not at the workplace. If the crosscut baseload is conducted and the crosscut valve is closed, it can simply be opened and closed after a short period. An example of this is highlighted in orange in Figure 5-16.

5.6 Stage 5: Crosscut audit

As per, Figure 5-17, the crosscut audit (inclusive of the associated stope) is the final step in the newly developed methodology and is required to determine if there are any ventilation shortfalls in the worst performing crosscut identified through the crosscut baseload test. If there is no permanent temperature instrumentation available in the crosscut and/or stope, there is no alternative method, other than a conventional audit, to measure the wet-bulb temperatures inside the crosscut and stope.

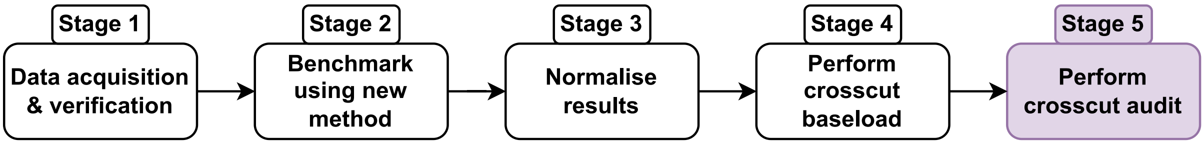

Figure 5-17: Newly developed methodology - Stage 5

In Section 2.2.2 the three main objectives of ventilation were highlighted, namely:

- To dilute the concentration of potentially hazardous gases
- To eliminate dangerous dust particles that have been released
- To ensure working area temperatures are within the legal limit

The auditors should use these objectives as criteria to evaluate ventilation efficacy during the crosscut (inclusive of stope) audit. If any of these criteria is not adhered to, it can be regarded as a ventilation shortfall. However, to prioritise the health and safety of mining personnel and promote their thermal comfort, this study will use temperature as the leading indicator for ventilation shortfalls. The parameter outlined in Chapter 3 will be used to determine ventilation shortfalls. This parameter defines a wet-bulb temperature measurement above 27.4 °C as a ventilation shortfall. The selection of this parameter is based on literature that indicated this temperature as the maximum before workforce efficiency is negatively affected.

It is reasoned that identifying a ventilation shortfall (based on the 27.4 °C threshold) before it exceeds the industry legal limit (32.5 °C WB) reflects a pro-active approach to ventilation network management and prioritises the health and safety of mining personnel. Conversely, choosing a higher temperature parameter, such as 32 °C, may lead to disregarding a wet-bulb temperature of 30 °C as a ventilation shortfall. However, the efficiency and safety of the workforce is already compromised at this temperature. The above discussion thus strengthens the argument to use temperature (27.4 °C WB) as an appropriate indicator to determine ventilation shortfalls.

5.7 Summary of verification of newly developed methodology

The newly developed methodology should be applied on a mine to **validate** if this methodology can be used to identify ventilation shortfalls effectively. For **validation**, only the top prioritised levels from the newly developed methodology should be investigated to determine if there are ventilation shortfalls. Additionally, if we apply the methodology described in this chapter and we find WB temperatures above 27.4 °C, those findings indicate that there is a ventilation shortfall and thus **verifies** that we can use compressed air as a leading indicator for ventilation shortfalls. To further validate the newly developed methodology, the time taken to identify ventilation shortfalls is compared with conventional audit procedures.

A summary where each stage in the newly developed methodology was verified is summarised in Table 5-2 below.

Table 5-2: Summary of verification of each stage in newly developed methodology and criteria addressed

Stage	Verification	Section	Criteria addressed
1 – Data acquisition and verification	Accurate and updated mine layouts are required by law. Mines routinely monitor the number of active stoping crews, and this information is frequently updated, ensuring that it is current and relevant. Flowmeters are accurate instrumentation, verified through literature, that are used to measure compressed air.	Section 5.2	Obtaining accurate data for model
2 – Benchmark using new method 1: Operational baseload	The time period (shift) selection was verified through literature. Benchmark method is based on conservation of mass - mathematically verified.	Sections 2.4.4 and 4.2.2	Simple, time- and resource-efficient approach (to identify compressed air wastage)
- Newly developed calculation model	Linear normalisation of pressure is based off literature. The results are computed mathematically.	Sections 2.4.5 and 4.2.1.2	
2 – Benchmark using new method 2: Theoretical baseload	The time period (shift) selection was verified through literature and a case study. Linear normalisation of pressure is based off literature.	Sections 2.4.4, 2.4.5, 4.3.2	
3 – Normalise results	BI indicator was verified through a case study.	Section 5.4.2	Tailor results using KPI
4 – Perform crosscut baseload	Built on the core principles of step-testing and adapted to be used on mining compressed air networks.	Sections 2.5.3 and 5.5	Ventilation shortfall identification

Stage	Verification	Section	Criteria addressed
5 – Perform crosscut audit	Using conventional ventilation audit.	Sections 2.3.1 and 5.6	
Temperature as leading indicator	Parameter used from author's published article [57]. Also highlighted by literature as maximum temperature before thermal comfort is negatively affected.	Sections 3.4 and 5.6	

It is evident that each stage was verified through literature or sample implementation on a mini case study. The case study that was used to verify Stage 3 (the BI indicator in Section 5.4.2) also serves as the **verification** of the entire newly developed methodology as it was applied to the case study to identify ventilation shortfalls successfully.

5.8 Summary

Chapter 5 introduced a novel approach to identify ventilation shortfalls in a deep-level underground mine, which is less resource-intensive and time-consuming compared with traditional methods. Additionally, it is a much safer approach compared with current methods utilised by mining companies. Chapter 2 highlighted that compressed air is misappropriated due to ventilation shortfalls. Chapter 3 **verified** and **validated** that there is a link between compressed air wastage and ventilation shortfalls. Hence, this new approach utilises compressed air as a metric to identify ventilation shortfalls.

To utilise compressed air wastage, two novel benchmark methods, to identify high compressed air wastage efficiently, without the use of advanced simulation software or traditional audits, were developed in Chapter 4. These methods and tools were integrated into a newly developed methodology which maximised the resource and time efficiency to identify ventilation shortfalls.

The methodology was split into 5 distinct stages. The study developed two different benchmarking methods, based on the amount of data available. If limited data is available, method 1 – operational baseload must be implemented to identify the highest compressed air consuming level. If data is available on all the levels, method 2 – theoretical baseload is applied to identify the worst compressed air performing level.

The methodology was designed to tailor the baseload benchmark method to the identification of ventilation shortfalls. Hence, a BI indicator was developed, using the number of crews, to predict the likelihood of compressed air wastage because of misappropriation. This was done to maximise the efficiency of identifying ventilation shortfalls by minimising the risk of investigating the incorrect level ("false-positive event").

After the worst performing level was identified, it was narrowed down to the highest compressed air consuming crosscut. This was achieved by adapting a method commonly employed in industry and applying it on the compressed air network in the deep-level mining industry. The final stage in the methodology is performing a conventional audit of the worst performing crosscut to identify ventilation shortfalls. It also serves as **verification** of the novel approach to use compressed air as a metric to identify ventilation shortfalls in a less resource and time-consuming way.

The next chapter discusses the validation of the newly developed methodology through practical implementation on two case studies.

CHAPTER 6: VALIDATION OF DEVELOPED METHODOLOGY THROUGH PRACTICAL IMPLEMENTATION

6.1 Preamble

In this chapter, the compressed air benchmarking approach to be used as a metric to identify ventilation shortfalls that was developed in Chapter 5 is applied to deep-level platinum mines in the North West province of South Africa. These mines are used as case studies for the implementation of the novel methodology. The results from these case studies are used to validate the new methodology.

The solution was implemented on two shafts in the Rustenburg area to showcase both baseload methods applied within the newly developed methodology. Case study 1 showcases the operational baseload (new benchmark method 1) implemented on a shaft, further referred to as Mine Y. This is followed by case study 2, on which the theoretical baseload (new benchmark method 2) is implemented on a shaft, further referred to as Mine Z. The results are discussed in the sections below.

The link between compressed air wastage and ventilation shortfalls has already been verified and validated in Chapter 3. It is of critical importance to note that this chapter aims to validate objectives 2 and 3, as stated in Section 1.4.2. Study objective 2 is to develop a versatile, less resource-intensive benchmarking method to identify areas with high compressed air wastage. Stages 1 and 2 in the newly developed methodology form part of the benchmark method to identify areas with high compressed air wastage. Objective 3 is to apply the method to effectively identify and prioritise ventilation shortfalls in a shorter period compared with existing identification methods by utilising the link between compressed air wastage and ventilation shortfalls. Stages 3 to 5 in the newly developed methodology are specifically tailored to identify and prioritise ventilation shortfalls. Combining stages 1 to 5, to form the newly developed methodology, aims to identify ventilation shortfalls in a less resource and time-consuming manner, thereby addressing objective 2 and 3. Figure 6-1 further aids to illustrate how the newly developed methodology addresses objective 2 and 3.

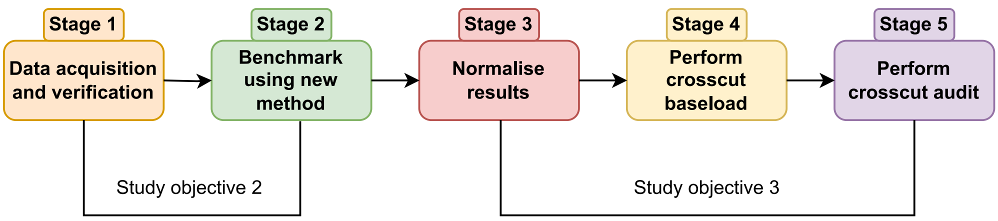

Figure 6-1: Study objective 2 and 3 addressed in newly developed methodology

For these case studies, only the worst performing crosscut on every level/half-level is investigated. Levels with a low compressed air wastage will not be investigated as it was proven, through a case study in Chapter 3, that few to no ventilation shortfalls are present in crosscuts with a low compressed air wastage. Applying either one of the two new benchmark methods and identifying high wastage areas will **validate** the new benchmark approaches as suitable methods to identify high compressed air wastage areas. Investigating the crosscuts with the highest compressed air wastage and identifying ventilation shortfalls will **validate** the newly developed methodology as a suitable method to identify ventilation shortfalls. Comparing the time and resources required to identify ventilation shortfalls to conventional methods will **validate** whether the newly developed methodology is indeed less resource-intensive and time-consuming.

6.2 Validating methodology on Case Study 1 using Operational Baseload

6.2.1 Stage 1: Data acquisition and verification

Data acquisition on Mine Y began by collecting the mine layout and number of active crews per level, from the mine survey office. The mine layout was investigated, and five active mining levels supplied by one compressed air column were identified,. A control valve was installed on the surface and manual isolation valves were present on every level. The data gathered was compiled into a simplified version of the mine layout, with the crews of each level, as depicted in Figure 6-2 below.

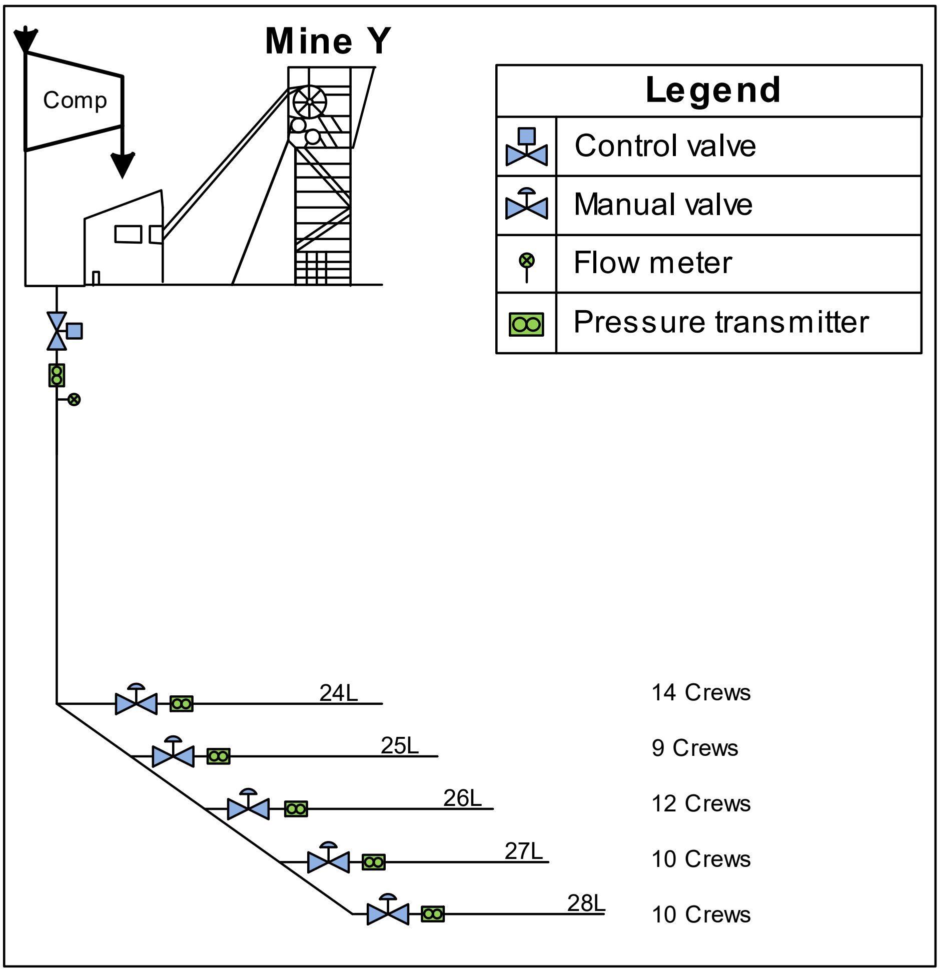

Figure 6-2: Simplified layout summary of Mine Y with crews per level

The analysis of existing instrumentation revealed that Mine Y only had a surface flowmeter, which is permanently installed to measure the total shaft consumption, as well as pressure transducers on every level. Section 5.2 confirmed the use of a permanent insertion flowmeter as a reliable and accurate measurement of the compressed air consumption. Thus, the consumption data was deemed accurate and reliable. All the pressure sensors were operational, and their accuracy was verified using portable pressure transducers. Further analysis revealed that Mine Y stored all their recorded data on SCADA. Thus, the data was readily available and did not have to be manually measured, recorded, or collected.

Upon completion of data acquisition and verification, the worst-case scenario was considered when deciding which benchmark method to use based on data availability. Since no flowmeters were available per level, data availability was rated as limited. Based off the criteria of the new methodology developed in Chapter 5, it was concluded that the operational baseload benchmark approach should be used. The selection of which baseload to use, based on the new methodology, is illustrated in Figure 6-3 below.

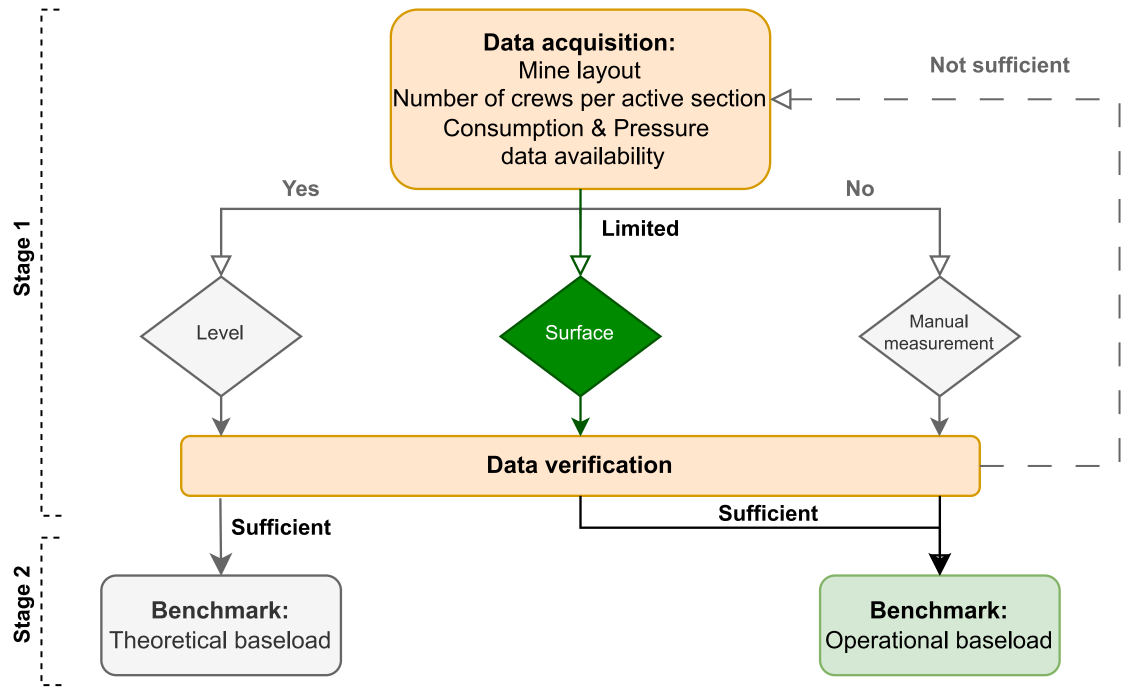

Figure 6-3: Criteria on which baseload method to use to benchmark the compressed air of Mine Y

6.2.2 Stage 2: Operational baseload benchmark

The next step in the newly developed methodology was to benchmark the compressed air consumption, in order to determine the worst performing level. The operational baseload benchmark discussed in Section 4.2 was applied to Mine Y. Before commencing the baseload test, the surface control valve was aborted to prevent throttling of compressed air underground. After the pressure and flow stabilised, all the underground compressed air level isolation valves were sequentially closed.

Once the baseload test was complete, the data was populated into the automated data processing model presented in Appendix C. The valve close times per level and average calculation period of three minutes were inserted before the model began processing. The flow distribution per level was calculated and normalised to the reference pressure. For this case study, a reference pressure of 500 kPa_g was selected. Upon completion, the model illustrated the surface flow consumption and normalised consumption, surface pressure, baseload period, and baseload calculation period through a graph, as per Figure 6-4.

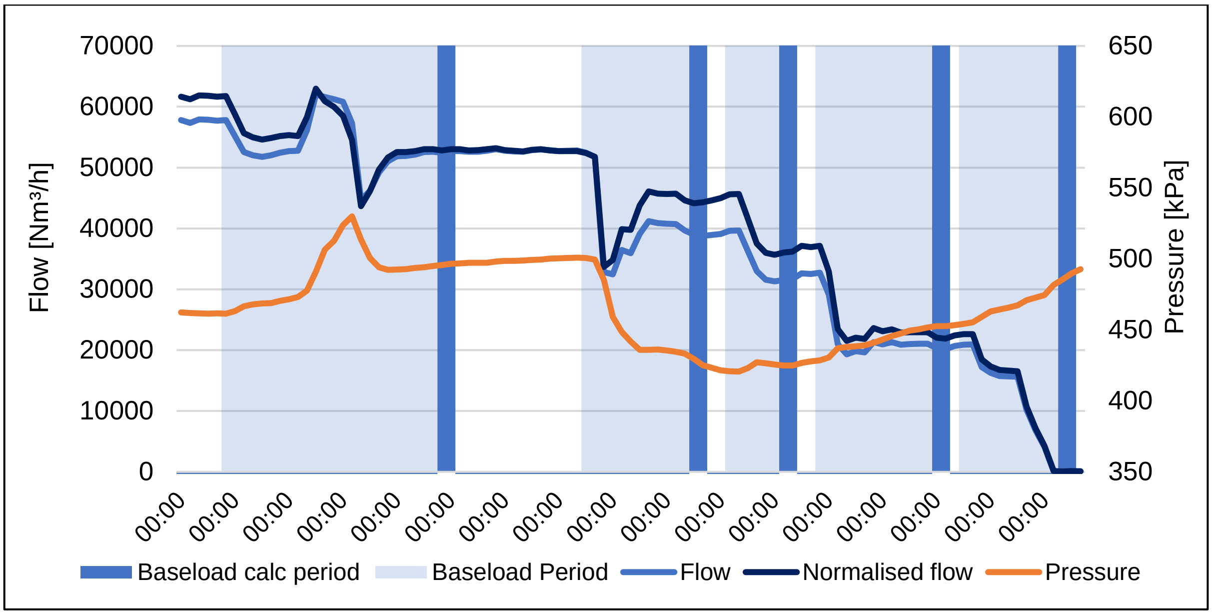

Figure 6-4: Surface and normalised flow versus surface pressure - Mine Y

Upon investigation of Figure 6-4, it was confirmed that the baseload period coincides with the valve close times. Normalising the baseload consumption to a reference pressure enables the comparison of compressed air consumption across the different levels, providing a clear picture of the most significant contributor to compressed air wastage. The normalised baseload analysis yielded an error of -0.56%, which is considered negligible. The normalised consumption of each level is illustrated in Figure 6-5.

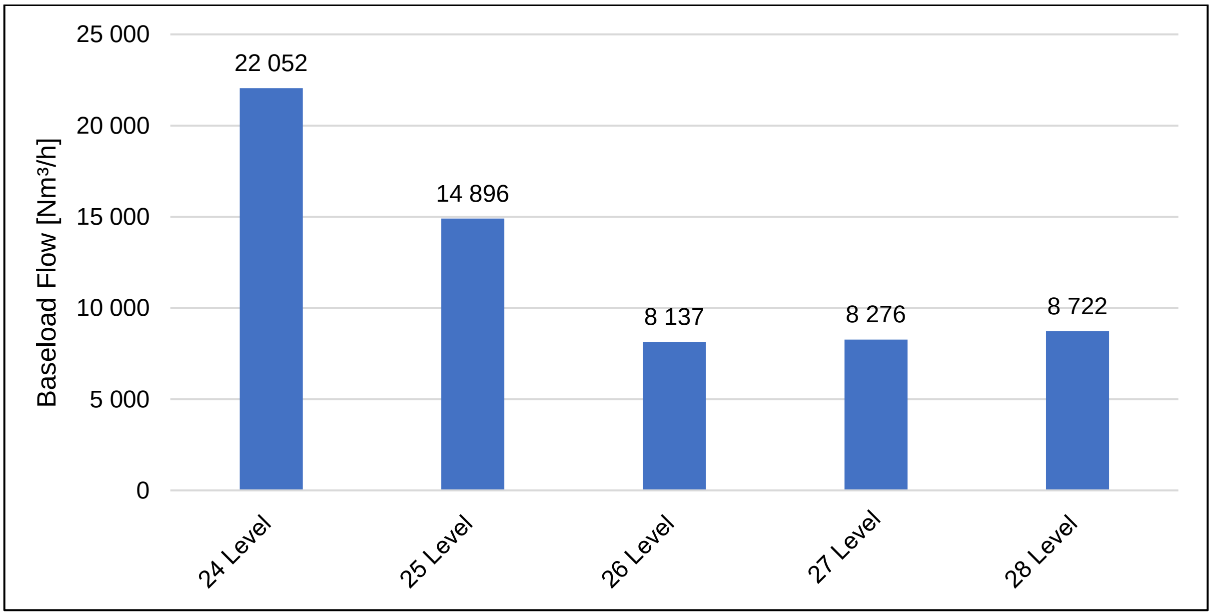

Figure 6-5: Pressure normalised Flow Analysis of Mine Y

Upon investigation of the results depicted in Figure 6-5, it is observed that the compressed air baseload flow on 26 to 28 level is significantly lower compared with 25 level.

6.2.3 Stage 3: Normalisation of results

The aim of this study is on the identification of the worst performing level in terms of the highest possibility of multiple ventilation shortfalls, rather than the level with the highest baseload consumption impact. To achieve this, the compressed air baseload consumption is normalised using the BI indicator, developed in Section 5.4, to prioritise the level with the highest baseload compared with the number of active crosscut crews. This makes each level comparable and ensures that variations in level sizes do not skew the results. The normalisation is crucial as it enables mine personnel to prioritise their focus on the level with the highest possible occurrence of ventilation shortfalls. Each level is illustrated as a fraction of the total consumption per crew (BI indicator fraction) in a Sankey chart in Figure 6-6 below.

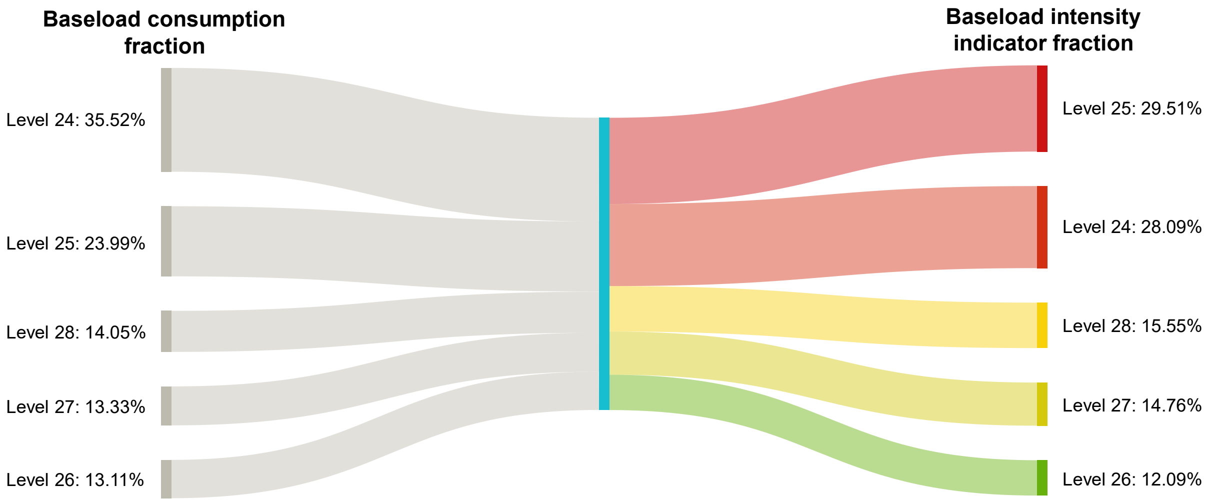

Figure 6-6: Normalised results of Mine Y using BI indicator

The normalised results using the BI indicator provide a clear and concise overview of the relative consumption per crew of each level, facilitating effective decision-making on which level(s) require further examination. The normalised results illustrated in the Sankey chart indicate that 25 Level has the highest compressed air consumption per crew. Notably, 24 Level which had the highest baseload has the second largest consumption per crew. It is evident that 25 Level has a significantly higher compressed air intensity per crew when compared with 26 to 28 Level and further investigation of ventilation shortfalls on 25 Level is imperative to promote efficient mining operations.

6.2.4 Stage 4: Crosscut baseload analysis

Once the level with the highest compressed air consumption per crew has been identified, the level is narrowed down to the working place with the highest consumption through a crosscut baseload analysis, developed in Section 5.5.

Prior to conducting the crosscut baseload analysis, the mine layout, collected during the data acquisition phase in Section 6.2.1, was examined. This allowed the auditors to examine the layout of the worst performing level closely to determine the number of half-levels and active crosscuts (XCs), which in turn will reduce audit time. 25 Level had two half-levels, namely 25 Level Merensky North (25L MN) and 25 Level Merensky South (25L MS), on which a crosscut baseload was conducted. The mine layout is illustrated in Figure 6-7.

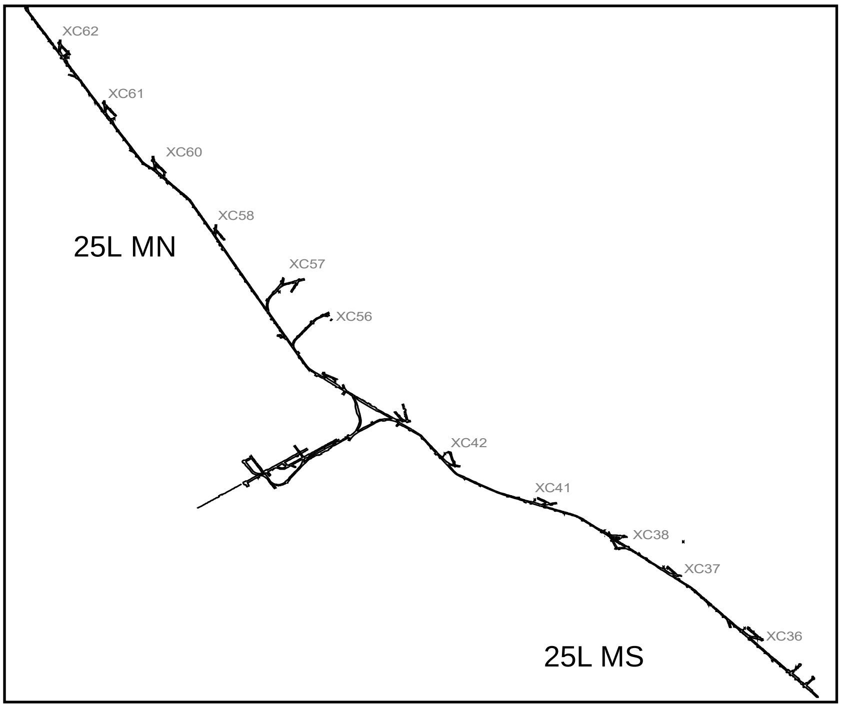

Figure 6-7: 25 Level mine layout and crosscuts - Mine Y

Using the information provided in Figure 6-7, a list of active and inactive crosscuts on the level were summarised into a table with the aim of ensuring that the active crosscut consumption is correlated after the crosscut baseload. The list of active and inactive crosscuts on the half-levels are summarised in Appendix E.

With all the necessary information obtained, the crosscut baseload, developed in Section 5.5, was conducted on the active crosscuts of both half-levels. The crosscut baseload was conducted during the cleaning shift and the compressed air consumption results for 25L MN and 25L MS were obtained. The results for 25L MS are illustrated in Figure 6-8 below.

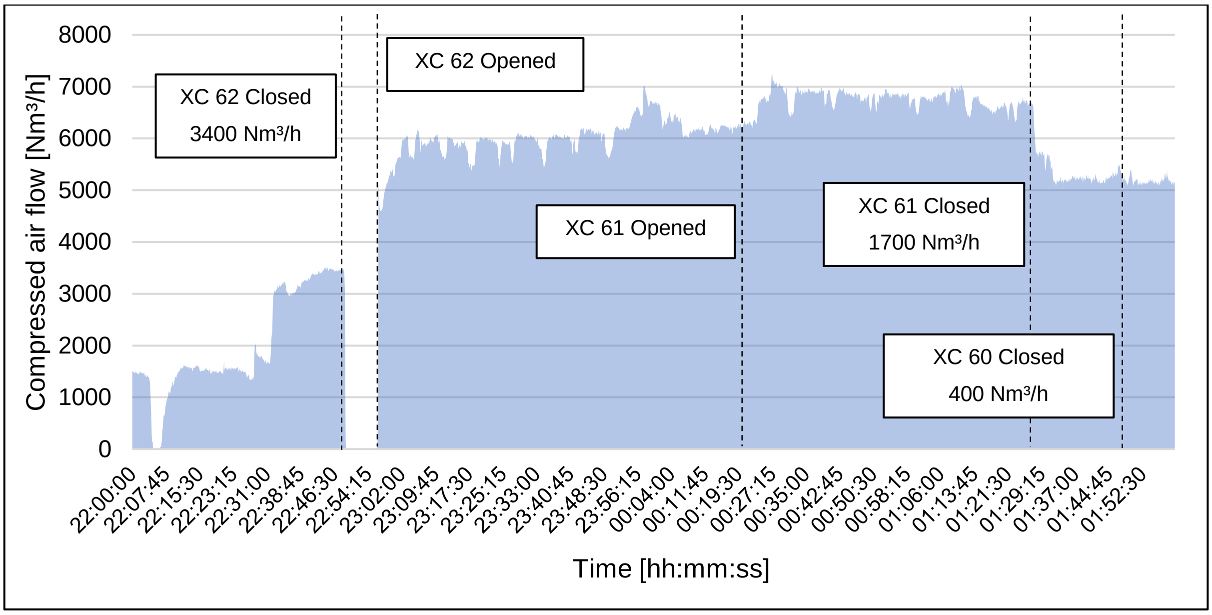

Figure 6-8: Crosscut baseload results on 25L MS - Mine Y

Feedback inspected from the auditors noted that the valve installed at active crosscut 58 was broken, presumably due to the harsh underground environment. The inactive crosscuts (56 and 57) were blanked and consequently did not consume any compressed air. From the results presented in Figure 6-8, crosscut 62 had a compressed air consumption of 3400 Nm³/h, accounting for 47.5% of the total half-level consumption. Its consumption was significantly higher compared with the other crosscuts, indicating a potential ventilation shortfall.

The crosscut baseload results of 25L MN are illustrated in Figure 6-9 below.

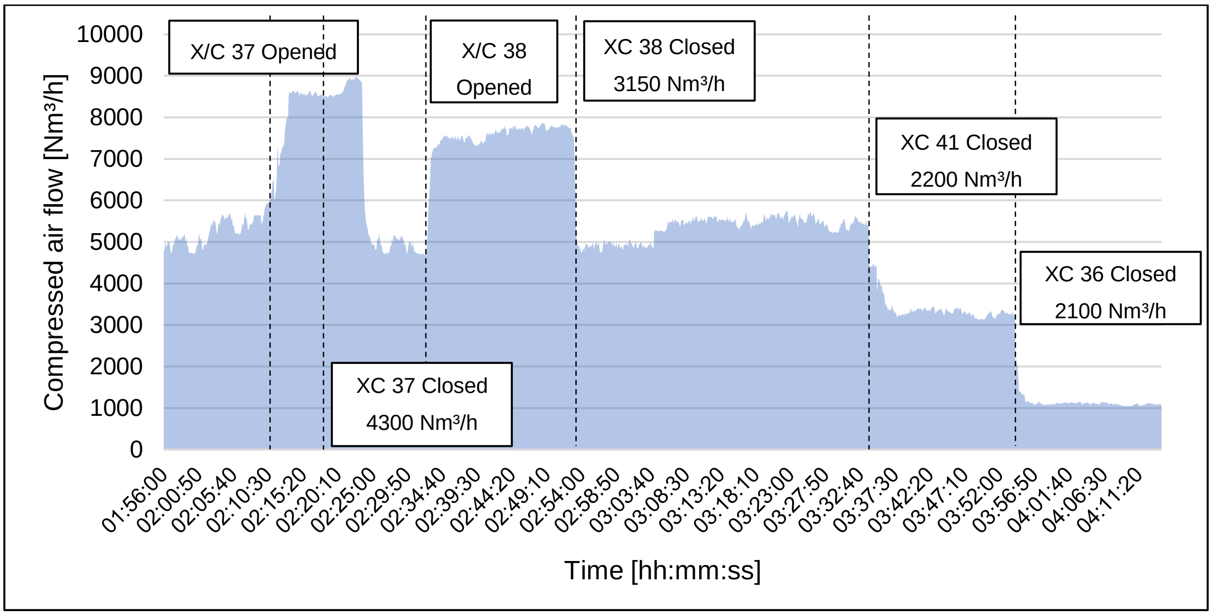

Figure 6-9: Crosscut baseload results on 25L MN - Mine Y

The auditors reported that the valve at active crosscut 36 could initially not be closed as there were mine personnel using a pneumatically operated water pump inside the stope, which is not a routine task. However, at the end of the crosscut baseload, crosscut 36 could be successfully closed. Additionally, the inactive crosscut 42 was closed by means of a valve and based on the results illustrated in Figure 6-9, the crosscut consumed approximately 1000 Nm³/h. Notably, crosscut 37 had the highest compressed air consumption of 4300 Nm³/h which yielded a 48% reduction in the half-level consumption, as illustrated in Figure 6-9.

The crosscut baseloads conducted on 25L MN and 25L MS provided a valuable source of information to identify the worst performing crosscut. The results indicated that crosscut 37 on 25L MN had the highest compressed air consumption, which accounted for 48% of the compressed air consumption on the half-level. Similarly, on 25L MS, crosscut 62 accounted for 47.5% of the total half-level consumption. Crosscuts 37 and 62 consumed 24.93% and 19.71% respectively of the total level consumption. These findings highlight the significance of using the crosscut baseload method, developed in Section 5.5, to identify the worst performing crosscuts quickly. Further investigation is required to confirm if there are any ventilation shortfalls in these crosscuts which will further validate the crosscut baseload method and the newly developed methodology developed in Chapter 5.

6.2.5 Stage 5: Crosscut audit

There was no temperature instrumentation available in the crosscuts on Mine Y. Hence, a conventional audit of the crosscuts was required to measure the WB temperature and verify if there were any ventilation shortfalls present. The following section provides a detailed discussion of the results obtained from the conventional audit of crosscuts 62 and 37.

6.2.5.1 Crosscut 62 audit results

A simplified schematic, depicting the layout of crosscut 62, is illustrated below to showcase all the compressed air misappropriation found during the audit as well as temperatures recorded during the audit. Temperatures were recorded near all the open-ended hoses to determine if there was a ventilation shortfall based on the criteria developed in Section 5.6. The complete audit results are included in Appendix E. A summary of the results is provided below.

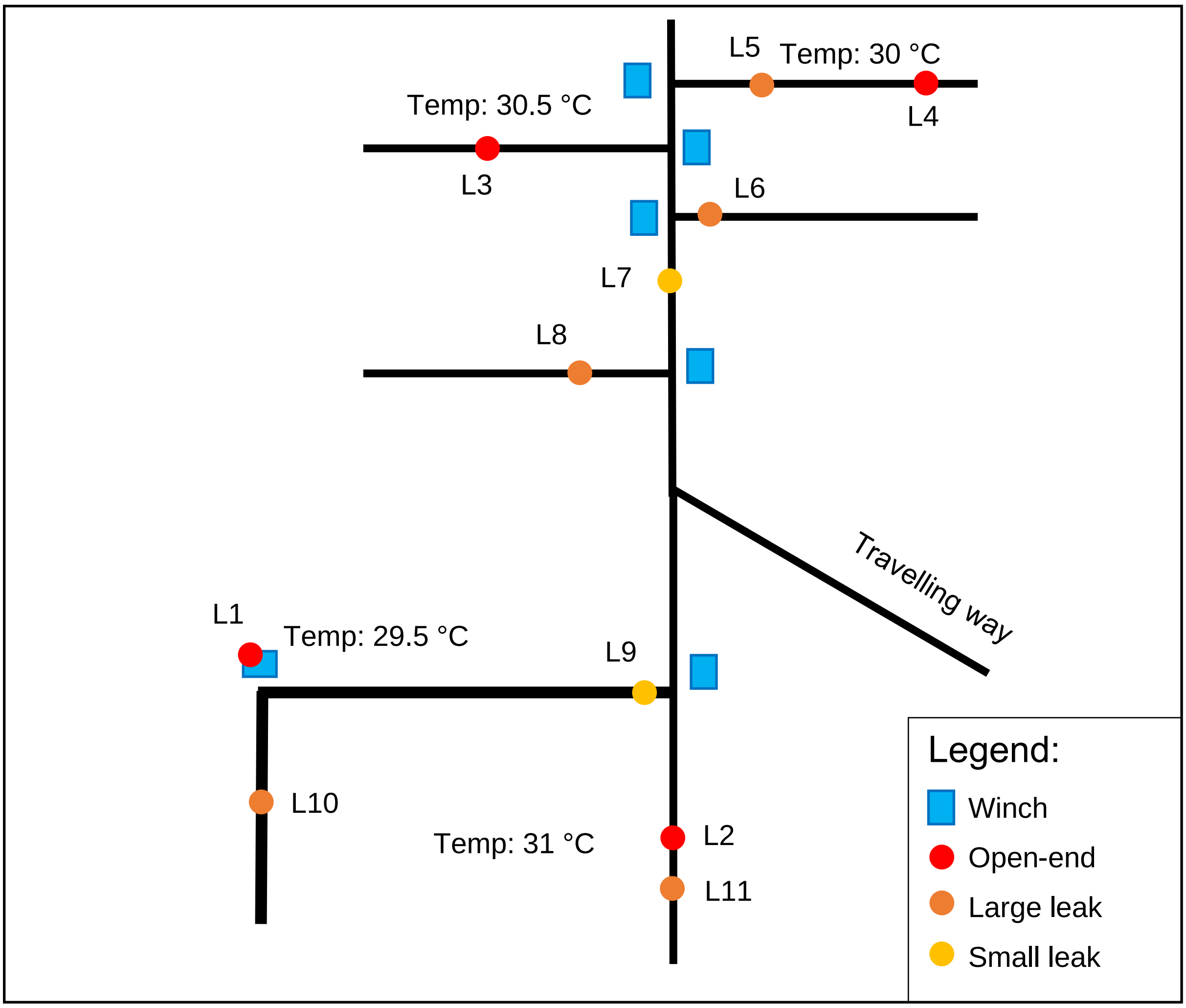

Figure 6-10: 25L MN, crosscut 62 layout with temperatures - Mine Y

During the audit of crosscut 62, a total of 12 compressed air misappropriation occurrences were identified, of which six were punctured holes in the plastic pipes and four were open-ended hoses. Photos of the four open-ended hoses are provided in the figure below as proof of self-ventilation to cool the working place. The WB temperatures recorded during the audit ranged from 29.5 °C to 31.5 °C, revealing a significant ventilation shortfall (as it was above the 27.4 °C shortfall criteria) in several locations within the crosscut. The audit of the crosscut also revealed poor ventilation infrastructure (limited ducting and no ventilation brattices) and some of the ventilation infrastructure, like the ducting (as per the bottom left photo in Figure 6-11) was damaged.

Figure 6-11: Proof of open-ended hoses used for self-ventilation in crosscut 62 – Mine Y

The audit also confirmed that open-ended hoses were used for self-ventilation to cool the workplace as the WB temperatures measured were all above the 27.4 °C limit. These findings suggest that crosscut 62 has multiple ventilation shortfalls and **validates** the operational baseload, BI indicator and crosscut baseload method to determine the crosscut with the highest compressed air wastage and subsequently highest possibility and occurrence of ventilation shortfalls.

6.2.5.2 Crosscut 37 audit results

The audit findings for crosscut 37 are presented in Figure 6-12. A simplified schematic, depicting the layout of crosscut 37, is illustrated below to provide a visual representation of all the misappropriation found during the audit as well as temperatures recorded during the audit. Temperatures were recorded near all the open-ended hoses to determine if there was a ventilation shortfall, according to the criteria developed in Section 5.6. The complete audit results are also included in Appendix E.

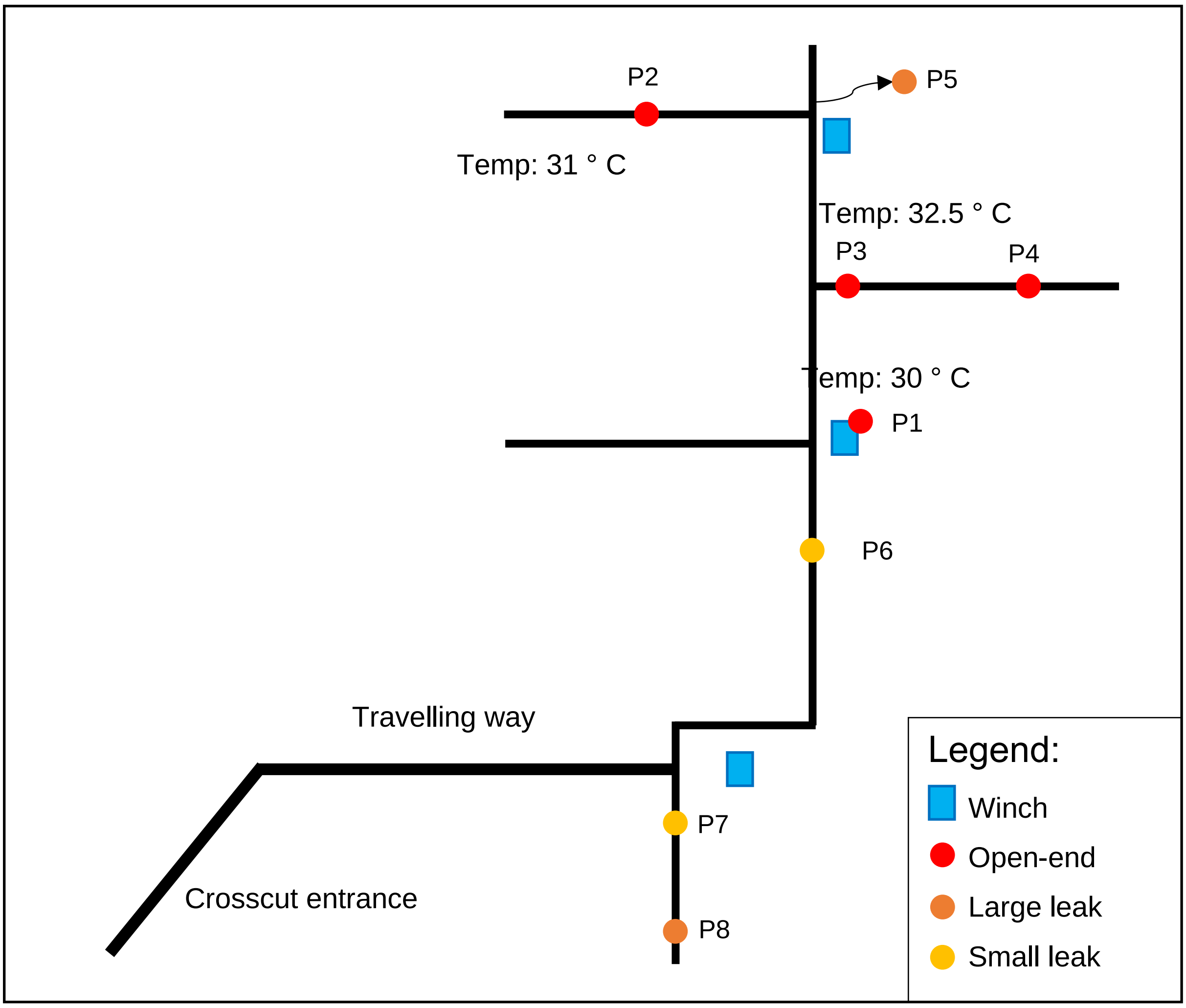

Figure 6-12: 25L MS, crosscut 37 layout with temperatures - Mine Y

During the audit of crosscut 37, a total of 8 compressed air misappropriation occurrences were identified, of which four were open-ended hoses, three were small leakages on the pipes, and one was a manifold with multiple partially opened valves. The results of the audit revealed a range of WB temperatures recorded during the audit from 30 °C to 32.5 °C, which is above the ventilation shortfall criteria of 27.4 °C WB.

The audit of the crosscut further revealed the limited ventilation infrastructure, with only partial ducting infrastructure, and no ventilation brattices were present. The partial ducting (as depicted in the top right corner of Figure 6-13) was not damaged but had no auxiliary fan connected to it to improve circulation, which contributed to the high WB temperatures observed in this crosscut. Photos of the four open-ended hoses are provided in Figure 6-13 below, providing evidence of self-ventilation. The high WB temperatures are substantiate proof that the open-ended hoses were used as an interim solution to attempt to cool the working place.

Figure 6-13: Proof of open-ended hoses used for self-ventilation in crosscut 37 – Mine Y

The results from case study 1 **validate** the use of the newly developed methodology and its sub-methods, using compressed air wastage as a metric and normalising it to identify ventilation shortfalls.

6.2.6 Interpretation of practical application

Each stage within the methodology was validated. However, objective 3 states that the new methodology must identify ventilation shortfalls in a shorter time period. Hence a comparison between conventional ventilation audits and the newly developed methodology was done.

A conventional audit was conducted on Mine Y and used as a benchmark to compare the time taken to identify ventilation shortfalls using the operational benchmark approach in the newly developed methodology. The new methodology identified the worst performing level and confirmed ventilation shortfalls in a single (worst performing) crosscut on both half-levels. Hence, the benchmark is evaluated on the time taken to identify the same two worst performing crosscuts and subsequently, the ventilation shortfalls on both half-levels. The results are summarised in Table 6-1.

Table 6-1: Time study comparison for case study 1 – Mine Y

Description	Conventional audit	New methodology – Operational benchmark (Mine Y)
Resources required	4	2
Hours taken to identify ventilation shortfalls (per resource)	152	22
Total number of hours	608	44
Hours taken to identify ventilation shortfall (in a single crosscut) on <u>both half-levels</u>	121.6*	44

* *Assuming the best-case scenario where the auditors knew the compressed air consumption per level and performed the ventilation audit in a descending consumption order.*

From the results in Table 6-1, it is evident that the new methodology was 64% more time efficient and required 50% less resources to identify the two worst performing crosscuts on the level, compared with the conventional audit, thereby **validating** the use of the newly developed methodology to identify ventilation shortfalls effectively and in a less resource-intensive and more time-efficient way.

6.3 Validating methodology on Case Study 2 using Theoretical Baseload

6.3.1 Stage 1: Data acquisition and verification

The same data acquisition process followed in Section 6.3.1 was done on Mine Z. The mine layout and number of active crews per level were gathered from the mine survey office. When the mine layout was investigated, seven levels were identified, of which one was inactive. All the levels were supplied by one compressed air column going down the shaft barrel. A control valve was installed on the surface and automatic isolation valves were present on all six active levels. Additionally, the changeover shift periods were collected to be used as input for the model.

The analysis of existing pressure and flow instrumentation revealed that Mine Z had permanently installed flowmeters and pressure transducers on all the active levels. Section 5.2 confirmed the use of a permanent insertion flowmeter as an accurate measurement of the compressed air consumption. Mine Z also stored all its recorded data on SCADA, which meant that the data was readily available. All the pressure transducers were operational, and their accuracy was supported using portable pressure transducers. The data acquired was compiled into a simplified version of the mine layout, with the total number of crews per level, as depicted in Figure 6-14.

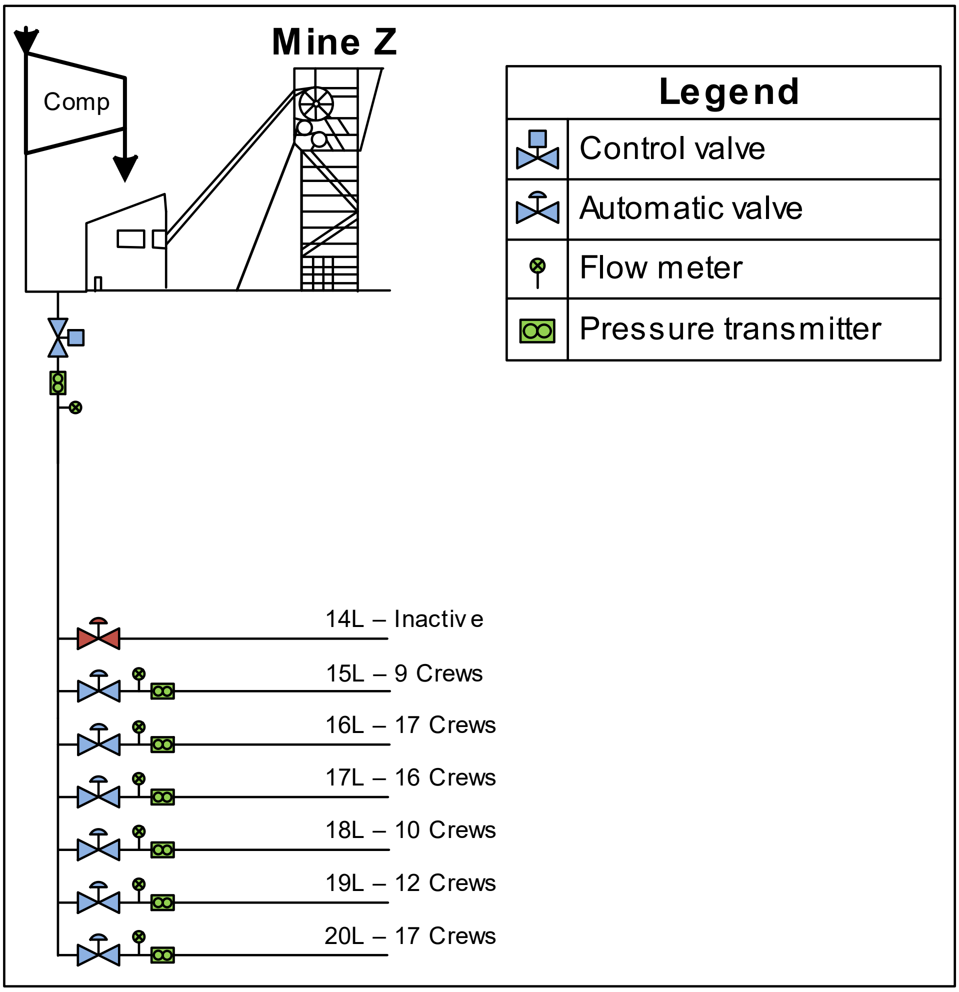

Figure 6-14: Simplified layout summary of Mine Z with crews per level

The shaft data availability met all the conditions to enable the use of the theoretical baseload benchmark approach. Unfortunately, no half-level flowmeters were installed on Mine Z, which meant the theoretical baseload could only narrow down the worst performing level. If half-level flowmeters were installed, the theoretical baseload benchmark could narrow down the worst performing half-level. The selection of which baseload to use, based on the criteria of the new methodology, is illustrated in Figure 6-15.

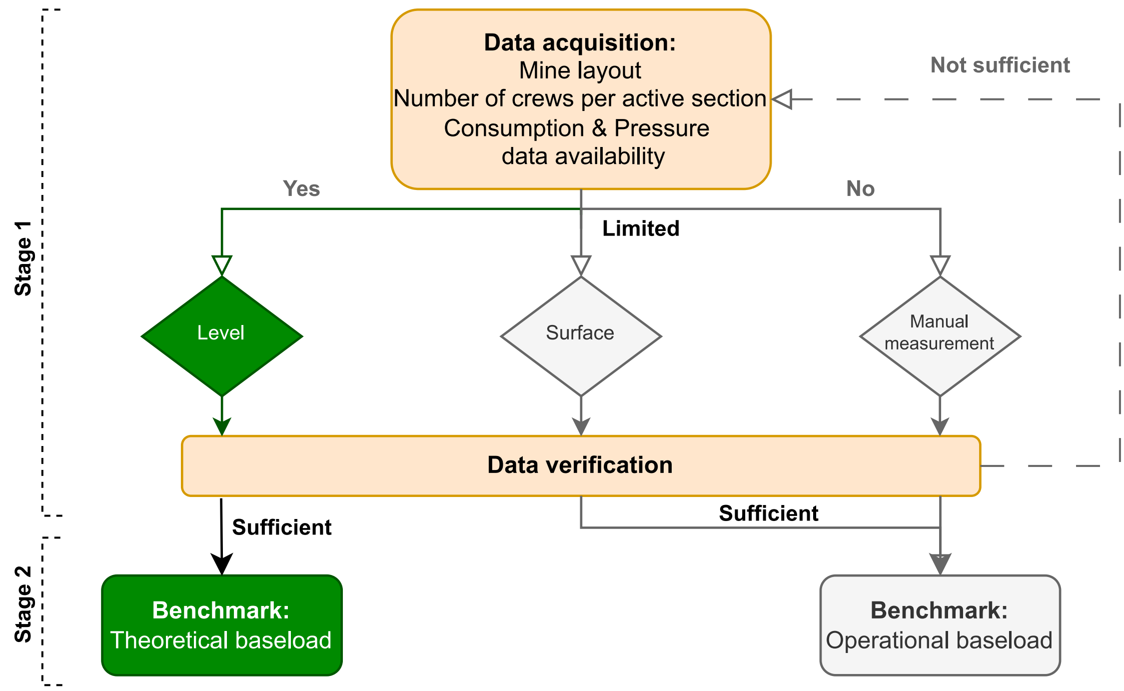

Figure 6-15: Criteria on which baseload method to use to benchmark the compressed air of Mine Z

6.3.2 Stage 2: Theoretical baseload benchmark

The next step in the newly developed methodology was to apply the theoretical baseload benchmark, developed in Section 4.3, to Mine Z. Compared with the operational baseload, the theoretical baseload benchmark approach will theoretically identify the worst performing level much more quickly as it is a non-disruptive benchmark method, relying solely on historical data.

To compute the lowest compressed air usage per level, the model required the flow, pressure, and shift changeover periods. The historical flow and pressure data were obtained from the SCADA and captured into the model. However, the shift changeover periods for every level were not readily available and the shaft only provided the drilling period of each level. The shaft also noted that they had a standard blasting period of three hours from 18:00 to 21:00. Hence, the collected data was different from what the model required. The model was easily modified to accept the drilling and blasting period of each level as input and exclude the corresponding periods to compute and identify the lowest PI. The drilling period data collected for input is summarised in Table 6-2.

Table 6-2: Drilling shift time schedule per level - Mine Z

Drilling shift time schedule for all levels:					
Level 20	Level 19	Level 18	Level 17	Level 16	Level 15
>=06:30:00	>=06:30:00	>=06:30:00	>=06:00:00	>=06:30:00	>=06:30:00
<16:30:00	<16:00:00	<16:00:00	<16:30:00	<17:00:00	<16:00:00

Adapting the model to use the available drilling and blasting shift data was crucial in obtaining accurate results. This highlights the importance of having a versatile model that is easily adapted to different data inputs. The ability to modify the model according to the available data not only improves accuracy but also increases the flexibility of the model. This is a valuable feature as it allows the model to be used for various applications, providing efficient and reliable results.

The historical pressure and flow data of four weeks were captured into the model. Each week was used as the data sample size to compute the average weekly PI using the lowest daily PI of each 5-day work week. The lowest PI as well as the corresponding pressure and normalised baseload flow results for each level can be found in Appendix F. The graph depicting the normalised baseload consumption per level over the four-week period is illustrated in Figure 6-16.

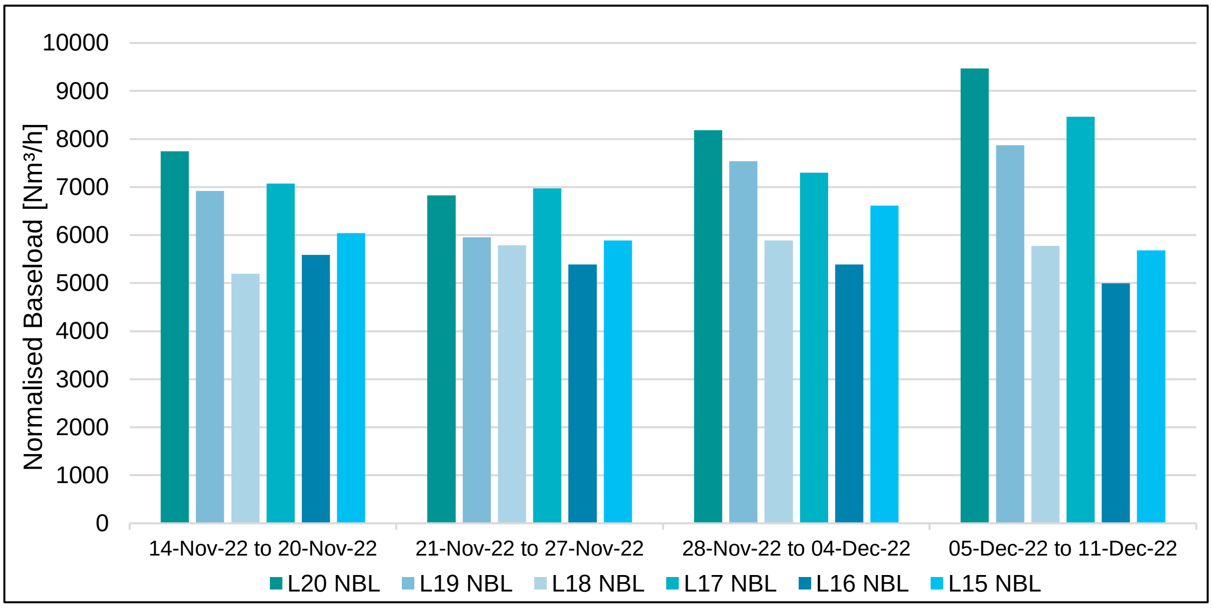

Figure 6-16: Computed normalised baseload results of each level from the model - Mine Z

6.3.3 Stage 3: Normalisation of results

To identify the level with the highest chance of multiple ventilation shortfalls, the compressed air baseload consumption was normalised, using the BI indicator. This made each level comparable and ensured that the level sizes did not skew the results. Each level was illustrated using a Sankey chart to depict the fractional distribution of compressed air consumption per crew on each level. Only the last week is depicted in the Figure 6-17 below. Results from the other weeks can be found in Appendix F.

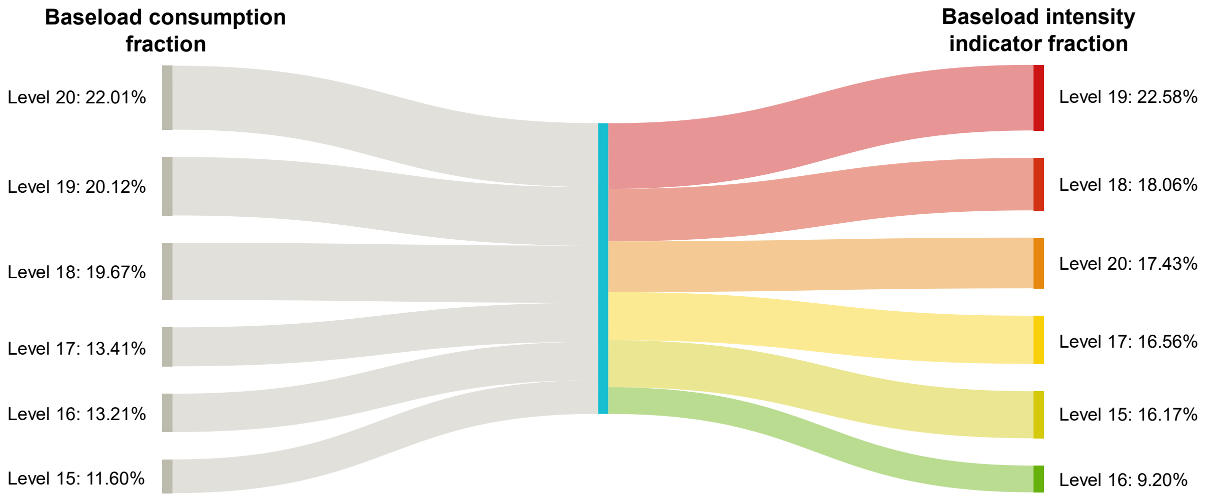

Figure 6-17: Normalised results of Mine Z using BI indicator

The BI indicator results illustrated in the Sankey chart indicate that 19 Level has the highest compressed air consumption per crew, accounting for 22.58% of the total compressed air consumption per crew. A crosscut baseload analysis is required to further narrow down the identification of ventilation shortfalls to a single crosscut. The results from the crosscut baseload analysis are discussed in the following section.

6.3.4 Stage 4: Crosscut baseload analysis

The crosscut baseload analysis, developed in Section 5.5, enabled the identification of the worst performing crosscuts on 19 Level. Prior to conducting the crosscut baseload analysis, the mine layout, collected during the data acquisition stage in Section 6.3.1, was examined. The examination showcased that 19 Level had two half-levels, namely 19 Level Chrome North (19L UN) and 19 Level Chrome South (19L US), on which a crosscut baseload was conducted. The mine layout collected is illustrated in Figure 6-18.

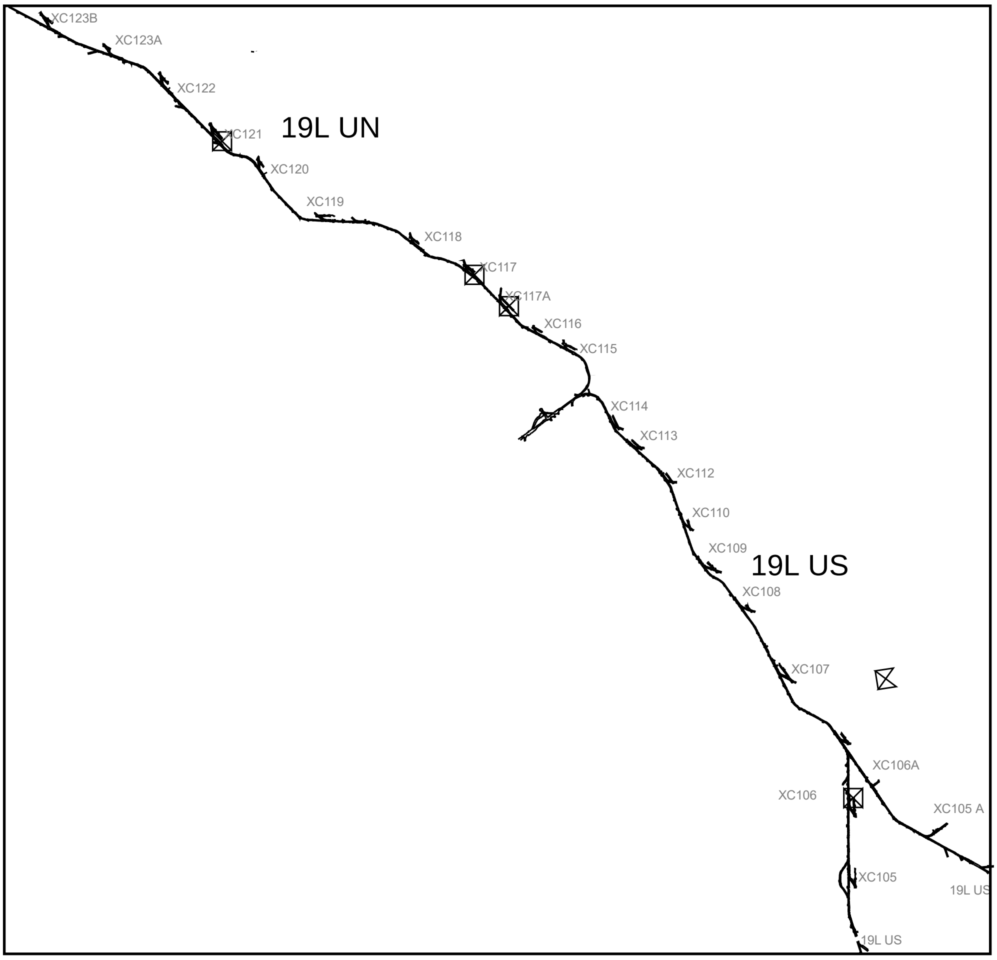

Figure 6-18: 19 Level mine layout and crosscuts - Mine Z

Using the layout and information provided by the mine survey department, the active crosscuts were identified. The list of active and inactive crosscuts can be found in Appendix F. Although this level is a large level, most of the crosscuts were inactive. Only the crosscuts near the end of development (EoD) were still active. The final step was to conduct the crosscut baseload, developed in Section 5.5. The results obtained are presented in Figure 6-19 to Figure 6-20.

Before the crosscut baseload, the mine instructed the auditors to close the crosscuts and keep them closed to save compressed air. Since this could potentially affect the consumption results, a pressure transducer was installed at the EoD of each half-level to monitor the pressure change when closing the crosscuts. The pressure was used to normalise the consumption for the pressure variations during the closing of the crosscut valves. The results of the active crosscuts for 19L UN are depicted in Figure 6-19.

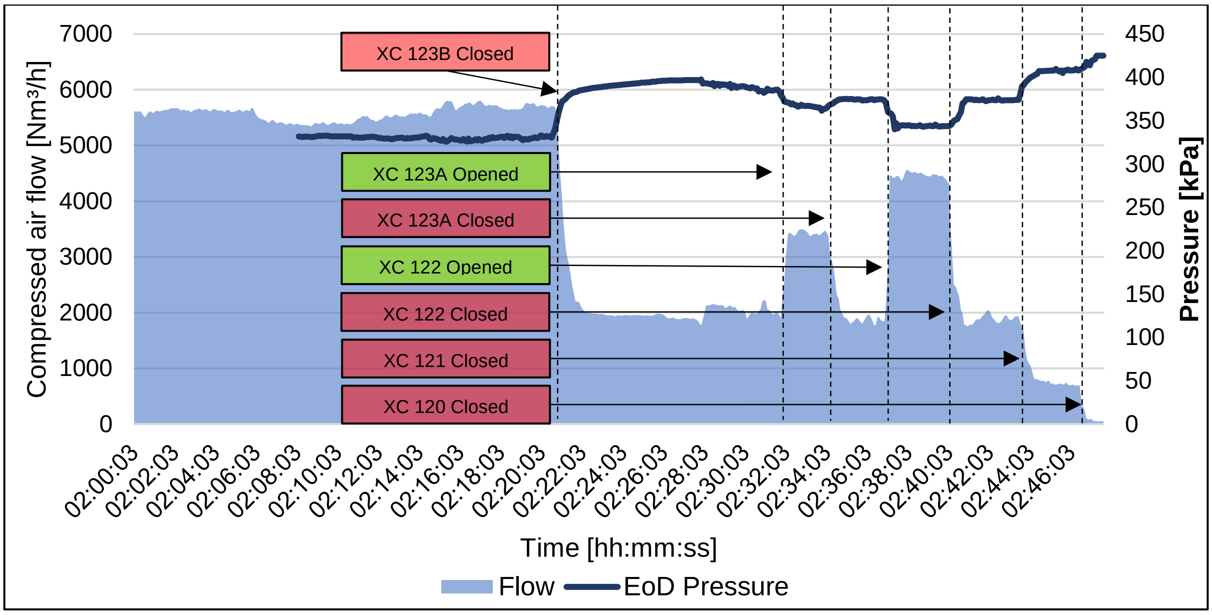

Figure 6-19: Crosscut baseload results on 19L UN - Mine Z

The consumption of each crosscut was normalised to a reference pressure of 500 kPa_g, using Equation ***(12)*** and is summarised in Table 6-3 below.

Table 6-3: Normalised crosscut consumption on 19L UN - Mine Z

Crosscut number	Pressure [kPa]	Normalised consumption [Nm³/h]
123B	331.2	5 290.73
123A	361.1	1 962.27
122	310.8	3 342.76
121	330.3	1 548.78
120	408.2	798.085

The auditors reported that all the crosscut isolation valves were operational except for crosscut 119. The valve could not be closed, and it is assumed that the remaining flow is attributed to crosscut 119. The results from Table 6-3 showcase that crosscut 123B consumed 5 290 Nm³/h, which resulted in a 40.8% reduction. Its consumption was significantly larger compared with the other crosscuts, indicating a potential ventilation shortfall. The results obtained from crosscut baseload for 19L US are depicted in Figure 6-20 below.

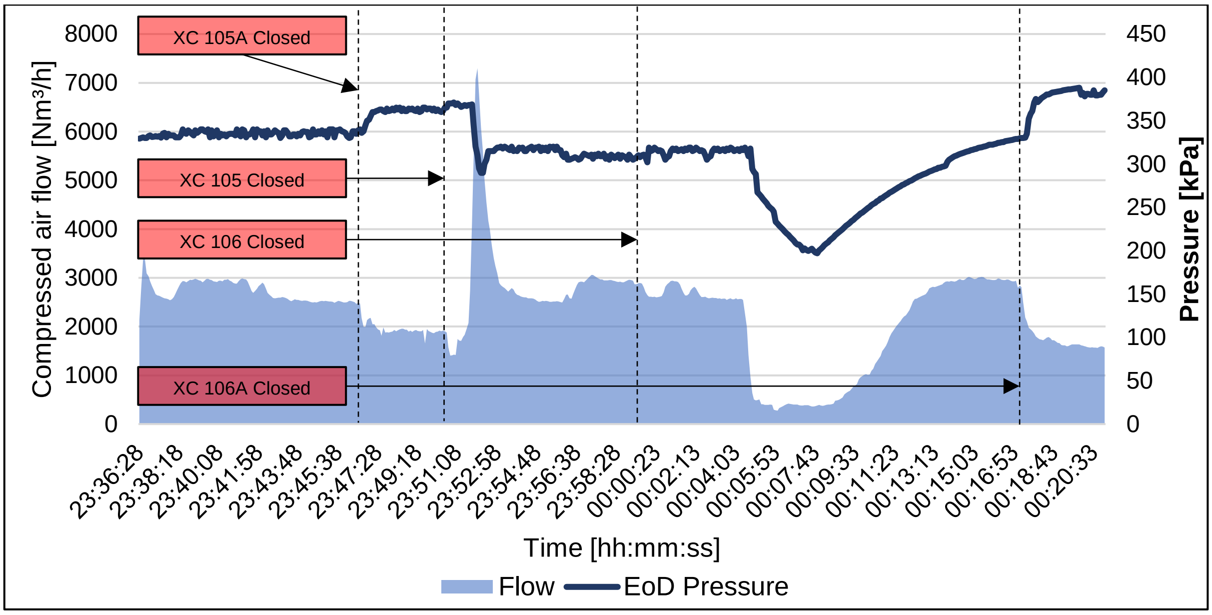

Figure 6-20: Crosscut baseload results on 19L US - Mine Z

The consumption of each crosscut was normalised to a reference pressure of 500 kPa_g, using Equation ***(12)*** and is summarised in Table 6-4 below.

Table 6-4: Normalised crosscut consumption on 19L US - Mine Z

Crosscut number	Pressure [kPa]	Normalised consumption [Nm³/h]
106	331.2	816.46
106A	361.1	200.13
105	310.8	484.19
105A	330.3	1 777.52

The auditors reported that all the crosscut isolation valves of the active crosscuts were operational. The results from Table 6-4 showcase that crosscut 105A consumed 1 777 Nm³/h, which resulted in a 54% reduction. Its consumption was larger compared with the other crosscuts, but significantly less compared with the highest consuming crosscut on 19L UN (even though the pressures were very similar). Hence, it is expected that if there is a ventilation shortfall, the occurrence will be less compared with the highest consuming crosscut on 19L UN. The results from the comprehensive ventilation audit conducted on both crosscuts are discussed in the following section.

6.3.5 Stage 5: Crosscut audit – Mine Z

The crosscut audit is the final step in the newly developed methodology and is required to identify if there are any ventilation shortfalls in the crosscuts highlighted in Section 6.3.4. A conventional audit of the crosscuts is required to measure the WB temperature and verify if there are any ventilation shortfalls present. The following section provides a detailed discussion of the results obtained from the conventional audit of crosscuts 123B and 106A.

6.3.5.1 Crosscut 123B audit results

A simplified schematic, depicting the layout of crosscut 123B is illustrated below to showcase all the compressed air misappropriation found during the audit as well as temperatures recorded near all the open-ended hoses. The complete audit results are included in Appendix F.

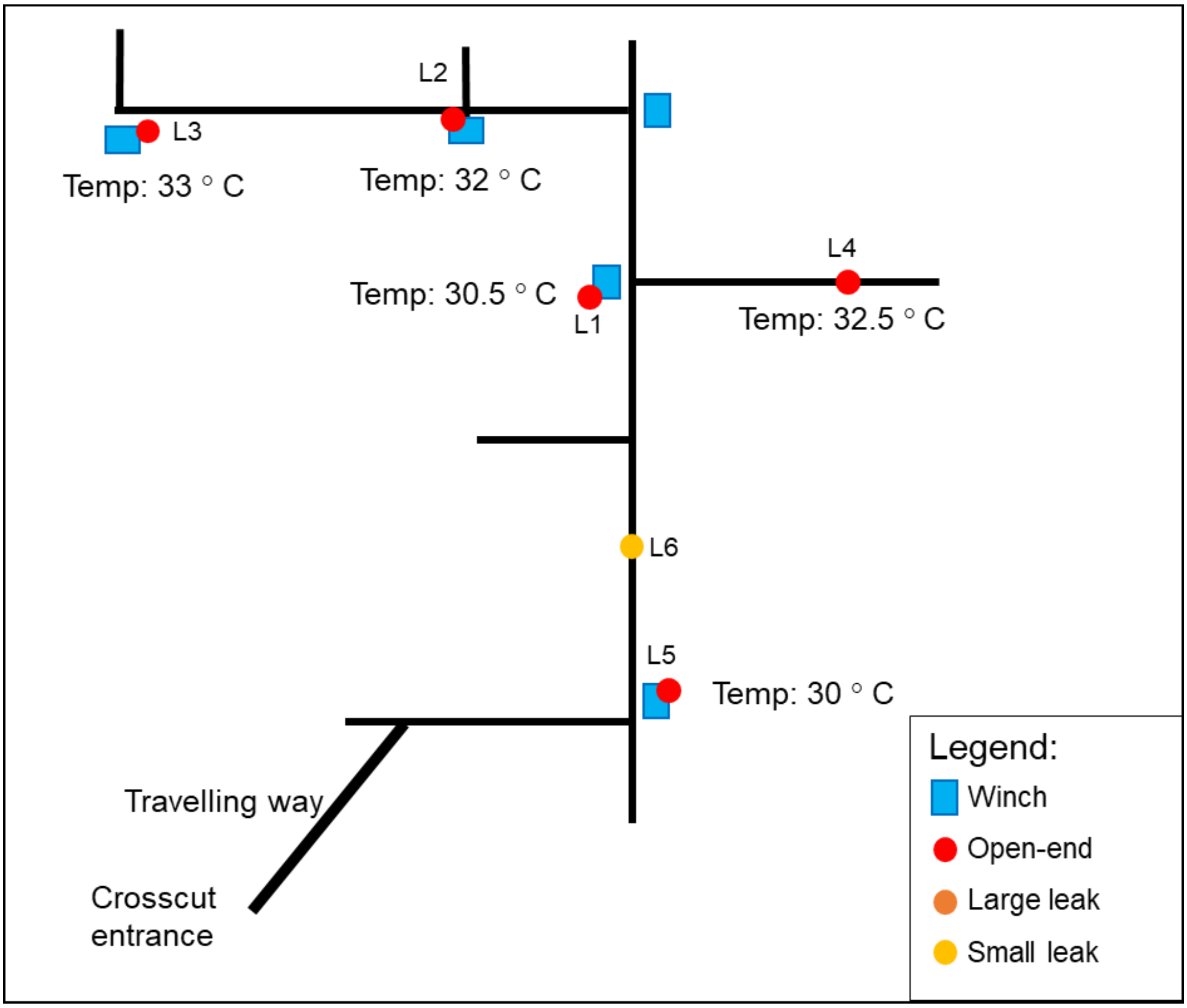

Figure 6-21: 19L UN, crosscut 123B layout with temperatures -Mine Z

During the audit of crosscut 123B, a total of six compressed air misappropriation occurrences were identified, of which five were open-ended hoses. One open-end was a 4-inch pipe used to cool the workplace. Photos of the five open-ended hoses are provided in Figure 6-22 below as proof of self-ventilation to cool the working place. The WB temperatures recorded during the audit ranged from 30 °C to 33 °C, revealing a significant ventilation shortfall. The audit of the crosscut also revealed poor ventilation infrastructure (no ducting or ventilation brattices).

Figure 6-22: Proof of open-ended hoses used for self-ventilation in crosscut 123B – Mine Z

The audit also confirmed that open-ended hoses were used for self-ventilation to cool the workplace as the WB temperatures measured were all above the 27.4 °C ventilation shortfall limit. These findings confirm that crosscut 123B has multiple ventilation shortfalls and **validates** the theoretical baseload and crosscut baseload method to determine the crosscut with the highest compressed air wastage and subsequently highest possibility and occurrence of ventilation shortfalls.

6.3.5.2 Crosscut 106A audit results

The audit findings for crosscut 106A are presented below. A simplified schematic, depicting the layout of crosscut 106A is illustrated below to showcase all the compressed air misappropriation found during the audit as well as temperatures recorded near all the open-ended hoses. The complete audit results are included in Appendix F.

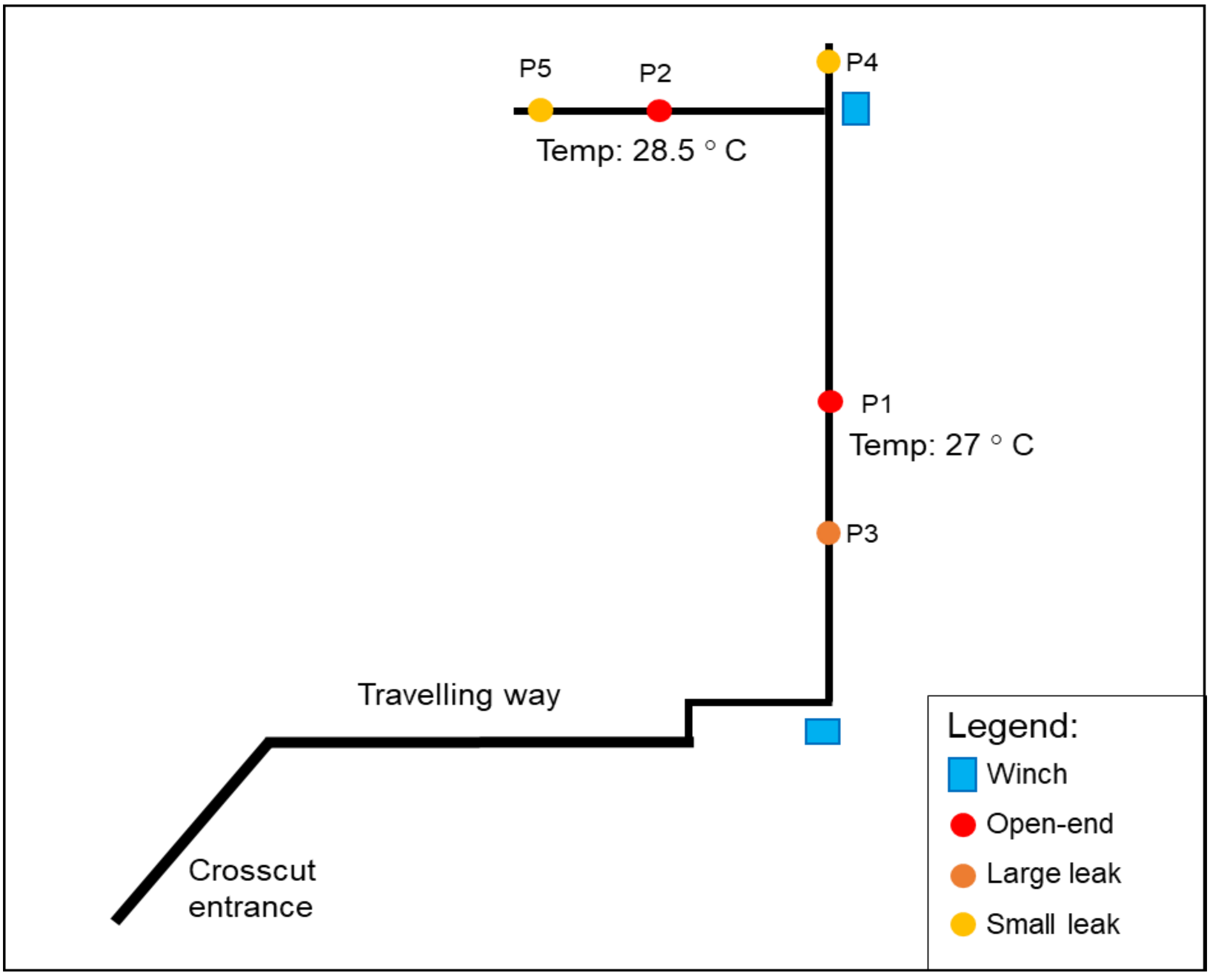

Figure 6-23: 19L US, crosscut 106A layout with temperatures -Mine Z

During the audit of crosscut 106A, a total of four compressed air misappropriation occurrences were identified, of which two were open-ended hoses. Photos of the two open-ended hoses are provided in Figure 6-24. The WB temperatures recorded during the audit ranged from 27 °C to 28.5 °C, revealing only one ventilation shortfall within the crosscut.

Figure 6-24: Proof of open-ended hoses used for self-ventilation in crosscut 106A – Mine Z

These findings indicate that crosscut 106A has minor ventilation shortfalls as only one WB temperature was above the ventilation shortfall criteria developed in Chapter 5. When compared with the highest consuming crosscut on 19L UN, it is evident that the wastage and the severity of the ventilation shortfall are significantly less. This validates the statement that the severity of the ventilation shortfall is less when the wastage of the crosscut is also less. Additionally, it **validates** the theoretical baseload and crosscut baseload method to determine the crosscut with the highest compressed air wastage and subsequently the highest possibility and occurrence of ventilation shortfalls.

The results from case study 2 **validate** the use of the newly developed methodology, using compressed air wastage as a metric and normalising it to identify ventilation shortfalls.

6.3.6 Interpretation of practical application

A time and resource benchmark comparison was also done for case study 2. Assuming the number of resources and time taken to identify ventilation shortfalls in a single crosscut on a half-level (using a conventional audit) are constant, the conventional audit conducted on Mine Y (case study 1) was used as a benchmark for case study 2. The hours taken to identify ventilation shortfalls on case study 1[11] (using a conventional audit) were used to theoretically compute the total hours taken to identify the ventilation shortfalls in the two crosscuts on both half-levels for case study 2. The results are summarised in Table 6-5 below.

Table 6-5: Time study comparison for case study 2 – Mine Z

Description	Theoretical conventional audit (Mine Z)	New methodology – Theoretical benchmark (Mine Z)
Hours taken to identify ventilation shortfalls (in a single crosscut) on both half-levels	121.6*	34

* *Assuming the best-case scenario where the auditors knew the compressed air consumption per level and performed the ventilation audit in a descending consumption order.*

From the results in Table 6-5, it is evident that the new methodology was 72% more time efficient and required 50% less resource to identify the two worst performing crosscuts on the level, compared with the conventional audit, thereby **validating** the use of the newly developed methodology to effectively identify ventilation shortfalls in a less resource-intensive and more time-efficient way.

[11] Hours taken to identify ventilation shortfalls (in a single crosscut) on both half-levels for case study 1: 121.6 hours

6.4 Conclusion

This section provides a summary of the interpretation of the results applied to the two case studies. A detailed summary of the methodology and whether each outcome was reached can be found in Appendix G.

A conventional audit was conducted on Mine Y and used as a benchmark comparison (for case study 1 and 2) to compare the time taken to identify ventilation shortfalls for both the operational and theoretical benchmark approach in the newly developed methodology.

When the results obtained through the newly developed methodology were compared with the comprehensive ventilation audit by the mine, it was evident that the methodology was more effective in narrowing down the ventilation shortfalls to two half-levels and more specifically, two crosscuts. The newly developed methodology required 50% fewer resources and 64% (operational benchmark) and 72% (theoretical benchmark) less time to locate and identify the ventilation shortfalls effectively, as per Table 6-6. This thus **validates** the use of the newly developed methodology to effectively identify ventilation shortfalls in a less resource-intensive and more time-efficient way.

Table 6-6: Time study comparison summary for case study 1 and 2

Description	Conventional audit	New methodology – Operational benchmark (Mine Y)	New methodology – Theoretical benchmark (Mine Z)
Resources required	4	2	2
Hours taken to identify ventilation shortfall (in a single crosscut) on both half-levels	121.6	44	34

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

7.1 Summary of the study

The aim of this section is to provide an overview of each chapter such that the key information in every chapter is clearly conveyed.

Chapter 1 began by investigating the South African deep-level mining industry, with specific focus on the deep-level platinum mining industry. It highlighted that the platinum mining industry is faced with numerous challenges which place financial strain on mining companies. There is limited focus on energy management as mines are governed by production output. However, with the increasing cost of electricity, mining groups are starting to realise the vital role of energy management in sustaining profitability.

It was concluded that compressed air is a significant contributor to the total energy cost of deep-level platinum mines. A large proportion of the total energy cost is a result of compressed air misappropriation due to inadequate ventilation networks. Ventilation is a complex and dynamic utility that plays a critical role in deep-level mining operations. It ensures safe and habitable working conditions, which affect the production output of a mine.

Without an effective method to identify ventilation shortfalls, the health and safety of mine personnel are at risk. Additionally, the production as well as total compressed air cost is negatively impacted by inadequacies in ventilation networks and the lack of identifying these inadequacies. A need was identified to address the high energy cost of compressed air and the lack of identifying substandard ventilation networks, which directly impacts compressed air energy cost.

Chapter 2 provided a detailed overview of both ventilation and compressed air in platinum mines. Ventilation was investigated to evaluate the complexity of a deep-level underground ventilation network critically. Previous studies that focussed on optimising ventilation networks and identifying ventilation shortfalls were evaluated. Studies that focussed on optimising ventilation networks (and not specifically identifying ventilation shortfalls) were included as they provide foundational knowledge of how to address the issue of identifying ventilation shortfalls. Investigating current methods used by the mining industry to evaluate a ventilation network highlighted that it is a resource-intensive and time-consuming process to evaluate large underground ventilation networks continuously.

Compressed air was comprehensively discussed in Chapter 2 to provide an overview of compressed air, its critical role in the mining operation, and root cause(s) for compressed air wastage. The literature analysis revealed that compressed air systems were very inefficient. The inefficiencies were exaggerated by compressed air misappropriation, exponentially increasing the cost of compressed air. Existing energy efficiency initiatives implemented on the compressed air networks on South African deep-level platinum mines identified that an energy reduction can be achieved through supply- and demand-side management. Although supply-side management is an effective method to reduce the cost of compressed air energy, it is an artificial reduction in compressed air energy cost. Hence, the focus of the study was on demand-side management initiatives.

To facilitate a better understanding of the demand-side management initiatives, a comprehensive background of compressed air systems used in the South African platinum mining industry was provided. The background provided a general overview of compressed air networks from compressed air production (supply) to compressed air distribution and demand. The different compressed air end-users (i.e. authorised and prohibited), pressure requirements of authorised end-users, and 24-hour mining cycle on which authorised end-users operate were discussed. Chapter 2 revealed that the misappropriation of compressed air by prohibited end-users accounted for a significant amount of the compressed air wastage in deep-level mining operations.

Benchmarking is an effective approach, widely utilised in literature as an energy management strategy, to evaluate the energy efficiency of systems. Benchmarking requires fewer resources compared with the above-mentioned DSM initiatives, which aligns with the objective of this study. Hence, benchmarking was extensively investigated in this study as it would form a critical part in developing a new approach to identifying ventilation shortfalls. Previous benchmarking studies on deep-level mines were thoroughly investigated to identify shortcomings in existing approaches.

Chapters 1 and 2 highlighted that compressed air is often misappropriated due to ventilation shortfalls. This created an opportunity to use compressed air wastage as a metric to identify ventilation shortfalls. However, before using compressed air as a metric, a clear link between compressed air wastage and ventilation shortfalls had to be established. Once this link has been confirmed, compressed air could be further utilised as a metric for ventilation shortfall identification. Chapter 3 investigated the possible link between compressed air wastage and ventilation shortfalls.

Chapter 3 presented a journal article whose the primary author was also the author of this study [57]. The article utilised a zero-wastage model to determine compressed air wastage in various crosscuts, which was plotted against the corresponding WB temperatures on a graph to evaluate a potential relationship between compressed air wastage and ventilation shortfalls. The results showcased that the majority of crosscuts which had excessive wastage were above the ventilation shortfall criteria. Crosscuts which had little to no wastage were below the ventilation shortfall criteria. The results from this comprehensive approach proved that a link does exist. This newly proved discovery was the first step in developing a new methodology to use compressed air as a metric to identify ventilation shortfalls.

In Chapter 4, the new methodology was developed to address the study objectives identified in Chapter 1. The methodology was developed such that it is versatile, dynamic, and applicable to any deep-level platinum mine. The methodology was comprised of different stages used to do the following:

- Identify the highest compressed air wastage areas,
- Tailor the results to the highest likelihood of ventilation shortfalls,
- Localising the area of possible ventilation shortfalls to a single crosscut,
- Verifying the existence of ventilation shortfalls, and
- Validating the sub-methods and new methodology as a suitable approach to identify ventilation shortfalls.

Stage 1 of the methodology involved investigating the existing compressed air network of the deep-level platinum mining operation in question and collecting the necessary data. Stage 1 was also focussed on data verification to ensure that the data gathered was accurate and reliable. Data verification ensured that all the data requirements were satisfied and determined which method in Stage 2 to use (based on the availability of data).

Stage 2 was the development of a new benchmark method to identify the level with the highest compressed air wastage. Two new methods were developed to accompany the different availability of instrumentation and data. Benchmark method 1 – operational baseload was mathematically verified, while the principles of method 2 – theoretical baseload were verified through literature (discussed in Chapter 2) and a case study on a mine.

For the operational baseload method, an automated processing model was built using Microsoft Excel® to simplify the data processing and reduce the time taken to identify the worst performing level. The theoretical baseload method is based on historical data. An automated calculation model was developed to streamline the data processing and compute the worst performing level/half-level. This model was developed such that it can take an array of different data as input. The model uses a KPI and pressure normalisation to compute the baseload consumption per level on a shaft.

Stage 3 of the methodology was developed such that the baseload consumption is normalised using the BI indicator. This tailors the compressed air consumption to highlight the level with the highest possibility of a ventilation shortfall and ensures that the size of a level does not skew the results. The results from the BI indicator normalisation were illustrated in a Sankey chart to creatively demonstrate the compressed air consumption per crew distribution throughout the shaft.

Stage 4 of the methodology entailed performing a crosscut baseload, such that the worst performing crosscut on the level/half-level can be localised. This reduces the time taken to localise and identify ventilation shortfalls which aligns with the overarching aim of the study.

The finals stage of the methodology, Stage 5, was to perform a conventional ventilation audit, placing specific focus on the WB temperature within the worst performing crosscut. Even though crosscuts are high risk areas, conducting a conventional audit of only the worst performing crosscut is considered a manageable task. The new methodology requires a conventional ventilation audit to verify if there are ventilation shortfalls.

In Chapter 6, the methodology developed in Chapter 5 was practically applied to two case studies, which serve as the validation of the study. The two case studies were deep-level platinum mines located in the North West province of South Africa. For confidentiality purposes, the shafts were referred to as Mine Y (case study 1) and Mine Z (case study 2).

Based on the criteria from the new methodology, the operational baseload benchmark approach was used to identify the worst performing level on Mine Y. The baseload consumption was normalised using the BI indicator and highlighted that 25 level had the highest compressed air consumption per level, indicating the highest possibility for ventilation shortfalls. 25 Level had two half-levels on which a crosscut baseload was conducted.

The results from the conventional audit confirmed that both crosscuts had substantial ventilation shortfalls, with the measured WB temperature, far above the ventilation shortfall criteria developed in Chapter 3. This **validated** the new methodology and its sub-methodologies as a suitable approach to localise and identify the ventilation shortfalls.

For case study two, the theoretical baseload benchmark approach was used to identify the worst performing level on Mine Z. The historical data for four weeks was captured into the automated calculation model developed in Chapter 4 to compute the theoretical baseload consumption of each level per week. The consumption was normalised using the BI indicator which indicated that 19 Level had the highest compressed air consumption per crew. 19 Level had two half-levels on which a crosscut baseload was conducted.

A conventional ventilation audit was conducted on the two worst performing crosscuts which revealed that both crosscuts had significant ventilation shortfalls, with the measured WB temperature far above the ventilation shortfall criteria. The conventional audit confirmed that there was indeed a ventilation shortfall in both crosscuts, further **validating** the new methodology and its sub-methodologies as a suitable approach to localise and identify the ventilation shortfalls.

Lastly, the time taken to localise and identify ventilation shortfalls was compared with a conventional ventilation audit conducted on Mine Y. In the control study, it took four auditors an average of 60.8 hours to audit a half-level, amounting to a total of 121.6 hours to identify the ventilation shortfall in the two crosscuts. Conversely, by applying the new methodology and using the operational baseload benchmark, it took two auditors only 22 hours to localise and identify the ventilation shortfalls.

By applying the new methodology and using the theoretical baseload benchmark method on Mine Z, it took two auditors 17 hours to localise and identify the ventilation shortfalls in the two crosscuts. No conventional audit was conducted on Mine Z. However, assuming it took auditors the same amount of time to audit a half-level (as per control study on Mine Y), it would have taken them seven times longer to localise and identity the ventilation shortfalls in the two crosscuts, using the conventional ventilation audit.

The time comparison between the new methodology and the control study verified and validated that the new methodology, utilising either benchmark method, is indeed a more resource- and time-efficient approach to localise and identify ventilation shortfalls in the crosscuts. Overall, the successful implementation of the new methodology highlights its potential as a valuable tool for identifying ventilation shortfalls in deep-level underground mining operations. When the ventilation shortfalls are identified and resolved, it could also help to address the compressed air wastage as compressed air misappropriation should decrease with an increase in ventilation adequacy.

A financial model for quantifying the financial impact of this study was not included in the evaluation. This decision was based on the rationale that the initiatives proposed in previous studies could be readily implemented, and their associated financial impacts would naturally ensue. It is crucial to emphasize that this study was primarily focused on the development of a method tailored to the identification of compressed air wastage and ventilation shortfalls. The core objective did not encompass the execution of initiatives to mitigate wastage or ascertain the precise financial ramifications. This allows for a more comprehensive understanding of the broader financial impact without unduly expanding the scope of this thesis.

7.2 Study objective analysis

The purpose of this section is to determine if the objectives of the study have been adequately satisfied. The study objectives, as outlined in Section 1.4.2, required methods to be developed to address the need identified in Chapter 1. A critical analysis of each study objective is presented below:

Study objective 1

Prove the link between compressed air wastage and ventilation shortfalls.

In Chapter 3 the link between compressed air wastage and ventilation shortfalls was proved, and the content was published in the SAJIE. A zero-wastage model was developed to identify the level with the highest discrepancy between actual consumption and zero-wastage. The zero-wastage model was applied to a case study, Mine X.

The worst performing compressed air consumption level was identified, whereafter the highest compressed air consuming crosscut was identified through a crosscut baseload (as developed in

Chapter 4). A conventional ventilation audit was conducted which revealed multiple ventilation shortfalls, indicative of a link. The WB temperatures and corresponding wastage of 69 additional crosscuts (which had varying wastage) were collected across different mines, to further verify the link. The results plotted on a graph showcased that most crosscuts which had little wastage were below the ventilation shortfall criteria and crosscuts which had high wastage were above the ventilation shortfall criteria. This provided proof of a clear link between compressed air wastage and ventilation shortfalls, therefore validating the link. Thus, study objective 1 was adequately satisfied.

Study objective 2

Develop, a versatile, simplified and less resource-intensive benchmarking method to identify areas with high compressed air wastage.

In Chapter 4, two new versatile benchmark methods were developed such that the compressed air wastage could be determined. User-friendly, intuitive and versatile mathematical models were developed for both benchmarking methods. These new models simplified data processing, meaning fewer resources and less time were required to determine the compressed air distribution on a mine.

When the two benchmark methods were applied to case studies on Mine Y and Mine Z, the compressed air wastage per level was successfully determined, and the worst performing level clearly identified. Thus, the benchmark methods satisfy the second objective of the study.

Study objective 3

Utilise the link between compressed air wastage and ventilation shortfalls to develop a method to effectively identify and prioritise ventilation shortfalls in a shorter time period than existing identification methods.

In Chapter 4, the results from the benchmark methods (referred to in objective 2) were tailored to focus specifically on ventilation shortfalls. A BI indicator was developed to tailor the benchmark results to identify the level with the highest possibility of ventilation shortfalls. The BI indicator ensures that the size of the level and total compressed air consumption do not skew the results. The ventilation shortfalls were further localised to a single crosscut by performing a crosscut baseload. Applying the BI indicator and performing a crosscut baseload on the two case studies validated that it is a suitable approach to identify ventilation shortfalls.

The sub-methods formed part of the new methodology which contributed to effectively localise and identify ventilation shortfalls. A time comparison between the new methodology and a control study verified that the new methodology could localise and identify ventilation shortfalls much faster compared with conventional identification methods (conventional audits). This satisfies the requirements of objective 3.

A summary is provided in Table 7-1, to showcase where the methods (to satisfy the objectives) were developed, verified, implemented, and validated.

Table 7-1: Sections where the objectives were satisfied

Obj.	Development	Verification	Implementation	Validation
1	Section 3.4	Sections 3.4, 6.2.5 and 6.3.4	Section 3.5	Sections 3.5 and 3.6
2	Sections 4.2.1and 4.3.1	Sections 4.2.2, 4.3.2 6.2.2	Sections 6.2.2 and 6.3.2	Sections 6.2.2 and 6.3.2
3	Sections 5.4, 5.5 and 5.6	Sections 5.4.2, 5.5 and 5.6	Sections 6.2.3, 6.2.4, 6.3.3 and 6.3.5	Sections 6.2.5, 6.3.5 and 6.4

7.3 Recommendations for future work

There is significant scope to improve compressed air wastage and mitigate ventilation shortfalls if they can be identified. Various shortcomings were identified in literature. However, this study specifically focussed on addressing the lack of identifying ventilation shortfalls. No investigation was done into improving the ventilation shortfalls and the positive effect this is expected to have on compressed air. Hence, other shortcomings still warrant further investigation. Recommendations for future work are made based on the shortfalls noted in this study, as well as from literature.

Recommendation 1:

This study focussed on developing a benchmark to identify the worst compressed air performing level/half-level. It did not focus on quantifying the cost of the electricity usage of compressed air wastage. It is recommended that the compressed air wastage is quantified.

Recommendation 2:

Methods were developed in Chapter 4 to localise and determine the baseload consumption of crosscuts. The leakage rate and the effect of repairing leaks were not investigated. It is recommended that a method is developed to determine what the effect would be if leakages are repaired.

Recommendation 3:

The effect of improving the ventilation networks in the identified ventilation shortfall areas were not evaluated. It is recommended that the effect on the worker productivity and compressed air consumption is evaluated and quantified once the ventilation improvements have been done.

Recommendation 4:

The two new benchmark approaches developed in Section 4.2 and 4.3 were not compared with other benchmark results found in literature. The benchmark approach was only compared with conventional audits used by the mining industry to identify high compressed air usage levels. It is recommended that the results are compared with other benchmark methods to compare the number of resources and the amount of time required to perform each benchmark method.

Recommendation 5:

The newly developed methodology was developed for the use on platinum mines. The BI indicator used to tailor the results to ventilation shortfalls is based on the number of crews. The underground infrastructure and layout may differ between different mining groups. This also means that the crosscut baseload, developed in Section 5.5, might be less effective to localise ventilation shortfalls. Hence, the BI indicator and crosscut baseload method must be further evaluated to determine the effectiveness on other types of mines.

Recommendation 7:

The newly developed methodology in Chapter 4 utilised a single KPI, namely the BI indicator, to modify the results specifically to highlight the level with the highest possibility of a ventilation shortfall. It is recommended that further studies are done to evaluate the effectiveness of using multiple KPIs to tailor the results to ventilation shortfall identification.

Recommendation 8:

Both models developed in Sections 4.2.1.2 and 4.3.1 to process the benchmark results, were built using Microsoft Excel®. It is recommended that these models are further developed, using other software, for mining companies to tailor these models to their specific shafts to better utilise the effective processing capabilities of these models.

Recommendation 9:

The BI indicator uses the number of crews per level/half-level to determine the compressed air intensity per crew. However, the size of the crew can vary significantly between different mining companies. Hence, it is recommended to scale by the size of crews and number of crews when comparing different mining houses as the crew size can differ.

Recommendation 10:

The financial impact of this study was not evaluated as it would unduly expand the scope of this thesis. It is recommended that using the new methodology to identify compressed air wastage and ventilation shortfalls, initiatives from other studies be implemented on compressed air wastage and ventilation to accurately evaluate the financial impact.

7.4 Closure

Ventilation networks in deep-level platinum mines play a crucial role in the health and safety of mine personnel. Inadequate ventilation is one of the primary causes for the high operational cost of compressed air due to compressed air being misappropriated as an interim solution to inadequate ventilation. This study provides an efficient and effective solution, utilising compressed air wastage as a metric to identify ventilation shortfalls in deep-level underground mines.

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Appendix A Published Article

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INVESTIGATING THE LINK BETWEEN COMPRESSED AIR WASTAGE AND VENTILATION SHORTFALLS IN DEEP-LEVEL MINES

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ABSTRACT

As part of mining development, mines are constantly increasing in size and depth, resulting in a dynamic environment. There is often a recurring shortfall in ventilation adequacy in these mines, as mine planning and design are primarily driven by production considerations. As a result, compressed air is often misappropriated for underground 'self-ventilation'. Instrumentation, simulations, and physical examinations are three commonly used methods for ventilation assessment, each with its own shortcomings and limitations. There is a need for an alternative method to identify ventilation shortfalls in underground mines. This study investigates the hypothesis that a link exists between compressed air wastage and ventilation shortfalls. Both the compressed air and the ventilation network were benchmarked, which showcased a direct link, thus proving the hypothesis true. Using this premise, a methodology could be further developed to investigate compressed air wastage as a metric for identifying ventilation shortfalls.

OPSOMMING

As deel van mynbou-ontwikkeling neem myne voortdurend in grootte en diepte toe, wat 'n dinamiese omgewing tot gevolg het. Daar is dikwels 'n herhalende tekort in ventilasietoereikendheid in hierdie myne, aangesien mynbeplanning en -ontwerp hoofsaaklik deur produksie-oorwegings gedryf word. Gevolglik word hoë-druklug dikwels wanaangewend vir ondergrondse "selfventilasie". Instrumentasie, simulasies en fisiese ondersoeke is drie algemeen gebruikte metodes vir ventilasie-assessering, elk met sy eie tekortkominge en beperkings. Daar is 'n behoefte aan 'n alternatiewe metode om ventilasietekorte in ondergrondse myne te identifiseer. Hierdie studie ondersoek die hipotese dat 'n verhouding bestaan tussen hoë-druklug lugvermorsing en ventilasietekorte. Beide die hoë-druklug en die ventilasienetwerk is vergelyk teen 'n maatstaaf, wat 'n direkte verhouding getoon het - wat dus die hipotese bevestig. Deur hierdie uitgangspunt te gebruik, kan 'n metodologie verder ontwikkel word om hoë-druklug lugvermorsing te ondersoek as 'n maatstaf vir die identifisering van ventilasietekorte.

1. INTRODUCTION

Mines are constantly increasing in size and depth, which creates a dynamic environment that faces many challenges. The deepening of a mine is accompanied by an exponential increase in operating costs [1]. In addition, increasing electricity tariffs are placing further strain on the South African deep-level mining industry, resulting in a need to reduce energy consumption to contain electricity costs [2][3]. Deep underground mines are highly energy-intensive [4][5], and electricity is a very large expenditure item of a typical platinum mine, second only to mining operational costs [6]. Figure 1 showcases the typical electricity cost distribution of a deep-level platinum mine.

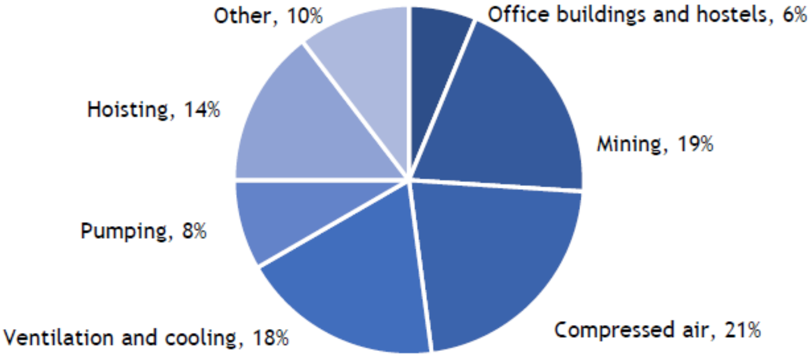

Figure 1: Typical deep-level platinum mine electricity cost breakdown (adapted from [7])

Energy savings and optimisation are essential to maintain the profitability of mines [8]. Figure 1 indicates that compressed air contributes the largest portion of the electricity cost of a typical deep-level platinum mine. Previous studies have shown that compressed air is often misappropriated for underground 'self-ventilation' [9][10][11] - that is, the unregulated act of opening compressed air pipelines to supply additional ventilation to workers [2]. Leaks and such open-ended pipes are mainly attributed to local ventilation shortfalls, and are the largest contributors to compressed air wastage [2]. This unregulated consumption also leads to unwanted and fluctuating compressed air demands. Thus, a further investigation into ventilation system shortfalls is needed.

There is often a recurring shortfall in ventilation adequacy in mines, as mine planning and design are primarily driven by production considerations rather than by ventilation requirements [12]. Ventilation typically affects production in two ways:

Sufficient ventilation ensures safe and habitable working conditions in line with the occupational safety and health mining regulations set by the Mine Health and Safety Council of South Africa [13]. If the health and safety standards are not adhered to, the mine could be forced to close a specific section, which would negatively impact production.

The thermal comfort of mine personnel greatly influences the production output of the mine [14]. This is because precision, speed, and workforce are negatively affected, while errors become more frequent in these thermally uncomfortable conditions [15]. Thus, the quality of a ventilation network directly impacts production output.

Ventilation networks are vast and complex, and are composed of numerous components that operate in unison to form a single ventilation network. These components include auxiliary fans, booster fans, extraction fans, ventilation branches, air coolers, and regulators [16]. Air coolers and regulators are used to regulate the air temperature, while the air is distributed throughout the ventilation network by fans.

Suction pressure is created on the surface by large extraction fans. This pressure differential causes a flow down the downcast shaft, then through the mine ventilation network, allowing for the ventilation of various areas, and then back up the upcast shaft, as illustrated in Figure 2. Auxiliary fans are usually installed in areas where additional ventilation is required [17].

Figure 2 is a simplified representation of the complicated configuration of an underground ventilation network. Compressed air networks are also often complex because of the size of the network [18], the multiple components, and a large number of end users. If either of these networks is not managed properly, it can cause significant problems, such as unsafe working conditions, production halts, and increased fatalities [18][19].

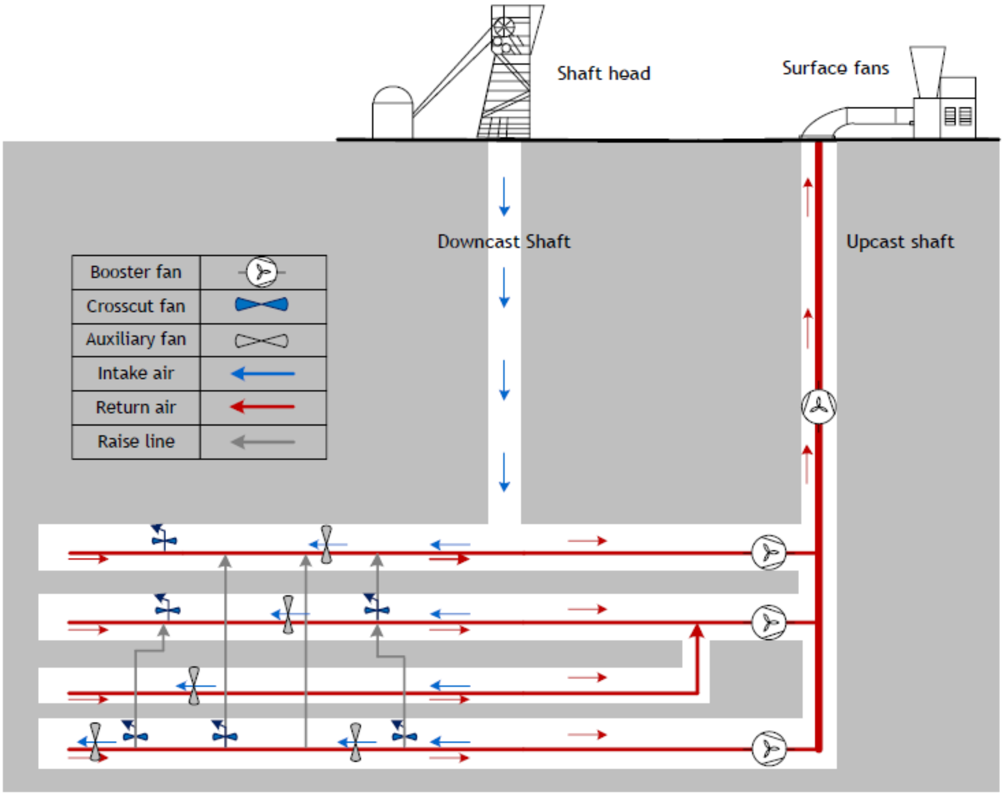

Figure 2: Typical configuration of an underground ventilation network

As a mine expands, the airflow demand increases, creating a significant increase in ventilation requirements for the mine [14]. Various fan types are used for these expanding deep-level mines, as seen in Figure 2. Such fans are used to compensate for the increased airflow demand by overcoming the growing airflow resistance. This can cause the size and complexity of a ventilation system to increase rapidly, which in turn increases the difficulty of managing the ventilation network [12] and of identifying possible shortfalls.

It is essential that the ventilation network operate at optimal efficiency with minimal shortfalls. Previous studies have shown that, to minimise shortfalls, ventilation networks must be monitored and assessed continuously [20][17]. Existing methods to actively manage and assess ventilation networks for possible ventilation shortfalls include:

- **Simulation**: Simulation has become a critical part of the planning and development of ventilation networks [12]. It has proven to be a useful optimisation tool to manage a dynamic underground environment effectively. However, these simulation models are highly dependent on the accuracy, reliability, and continuity of the multivariable data sets as inputs. Collecting the data required for the simulation models is challenging because of the dynamic nature and harsh conditions of deep-level mines. The use of simulation packages is also often time-consuming, and requires skilled workers [2].

- **Equipment and instrumentation**: Instrumentation forms a critical part of ventilation management and identifying shortfalls, as well as ensuring that health and safety standards are adhered to. Health and safety criteria, such as gas emissions, air pressure, airflow, and temperature, are actively monitored by equipment and instrumentation. These are all critical elements by which the efficacy of a ventilation network is evaluated. However, the instrumentation is often limited and expensive, and the installation time and resource costs are demanding, often constraining the full potential of the ventilation network efficacy.

- **Physical examinations, inspections, and surveys:** These typically depend on the primary aim, but usually entail the collection of data on the air mass flow rate, pressure, and air thermal quality throughout the ventilation system [19]. Information about the infrastructure of the ventilation network is also required [21]. The information that is collected varies, depending on its purpose, and it might also include the location, status, and performance of fans, doors, regulators, underground coolers, and ducting infrastructure.

The above methods to manage and assess ventilation networks are often used after identifying ventilation systems with scope for the optimisation of shortfalls such as mine fan assemblies, installation locations, and ducting infrastructure, which all form part of the mine ventilation network. However, prior to addressing these shortfalls, a method is required to identify these shortfalls.

Figure 3 showcases the current process to identify ventilation shortfalls, and highlights the lengthy and resource-intensive process that needs to be followed. Thus, there is a need for a simpler approach to identify ventilation shortfalls.

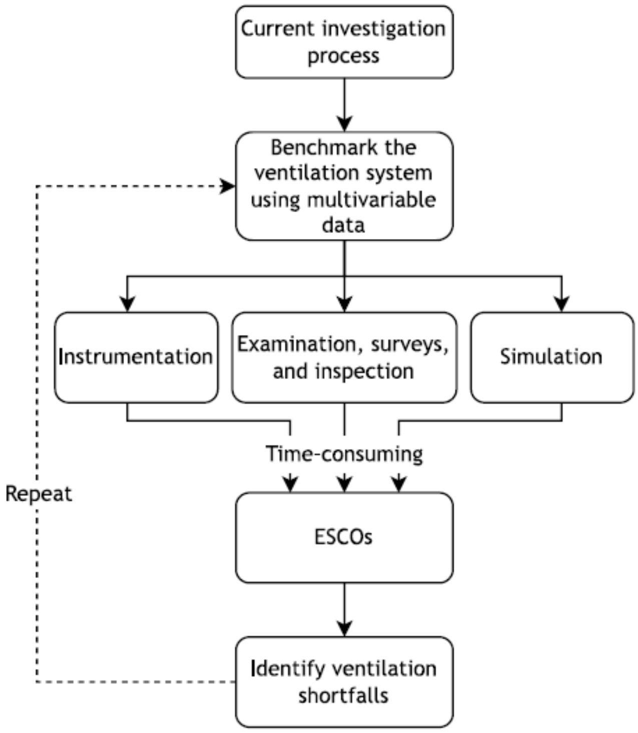

Figure 3: Current assessment methods to identify ventilation shortfalls (adapted from [12], [17], [19], [20])

No literature could be found that explicitly evaluates a possible link between compressed air wastage and ventilation shortfalls. Thus, this study investigates the hypothesis that compressed air wastage could be used to identify ventilation shortfalls quickly and effectively by proving the link between compressed air wastage and ventilation shortfalls. To prove that such a link exists, it is necessary to investigate both compressed air and ventilation. Figure 4 below illustrates the proposed testing method - Hypothesis testing [22] - that will be followed to prove the possible link between compressed air wastage and ventilation shortfalls.

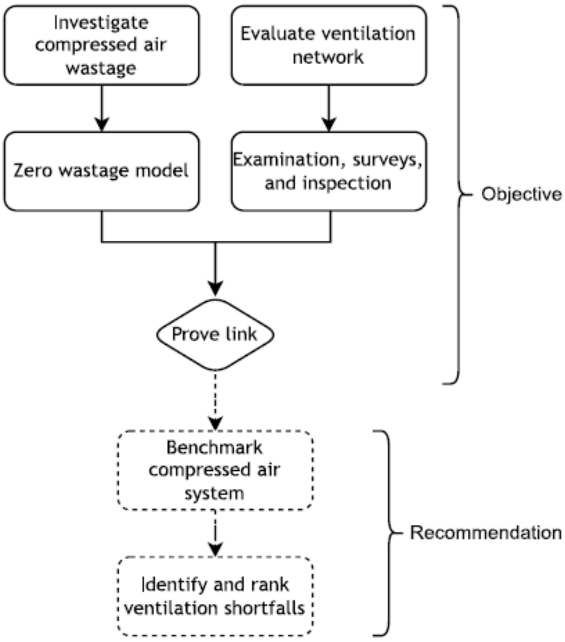

Figure 4: Hypothesis testing method and objectives of this study

Compressed air wastage must be investigated first, after which the ventilation network must be evaluated in the areas where compressed air wastage has been identified. It is important to understand that compressed air wastage originates from multiple sources, but that the term 'wastage' forms a single variable that can be quantified. If a link exists between compressed air wastage and ventilation shortfalls, it could be used in future studies to be evaluated as a single parameter to identify possible shortfalls in ventilation.

The objectives of this study are listed below:

- **Objective 1** is to investigate the compressed air network. This will be done by evaluating the compressed air usage while focusing specifically on compressed air wastage.
- **Objective 2** is to evaluate the ventilation network. Once excessive compressed air wastage areas have been identified, the corresponding ventilation network will be evaluated using a current assessment method: examination, surveys, and physical inspection.
- **Objective 3** is to prove that there is a causal relationship between compressed air wastage and ventilation shortfalls underground.

For the purpose of this study, 'ventilation shortfall' is defined as a deficit of sufficient ventilation to maintain habitable working conditions in a deep-level mine.

2. DEVELOPMENT OF SOLUTION

As mines expand for further development, the ventilation demand increases. To meet the demand, ventilation networks expand rapidly, causing them to become large and complex systems. The complexity of these systems often results in shortfalls in their adequacy, which in turn results in the increased energy consumption of other systems (such as compressed air). Thus, compressed air and ventilation networks are discussed in more detail below.

2.1. Compressed air

This paper defines 'compressed air wastage' as the action of using compressed air 'carelessly' and without authorisation. It is therefore important to distinguish between compressed air consumption and compressed air wastage. For this study, the most significant end users of an underground compressed air network will be categorised into two classes to distinguish between consumption and wastage. In Table 1, class 1 depicts the authorised end users of compressed air, while class 2 depicts the end users who are responsible for compressed air wastage (i.e., prohibited compressed air users).

Table 1: Significant end users of a compressed air network

Class 1: Authorised compressed air users	Class 2: Prohibited compressed air users
Equipment:	Open-ended pipes
Rock drills	Valve leaks
Loaders	Punctured pipelines
Pumps	
Pneumatic actuators	
Refuge bays	

2.2. Zero-wastage model

After the end users of the compressed air network have been identified, a zero-wastage model needs to be developed to quantify the difference between actual consumption measured and the theoretical zero wastage consumption. The zero-wastage model is a mathematical model that is used to compute the compressed air consumption of class 1 end users, as specified in Table 1. For the development of the zero-wastage model, three key aspects need to be considered to determine accurately the compressed consumption, as discussed below.

2.2.1. Operational area

The first aspect to consider is the different areas where compressed air end users will be present. This zero-wastage model will include eight compressed air demand areas that are typically found in a deep-level mine. These areas are:

1. Stoping: A stepped excavation that forms as successive layers of ore are extracted from underground.
2. Ledging: Ledging is the process by which a portion of the reef is removed to provide a starting place for the stoping crew to begin the mining operation.
3. On-reef development: Development prior to stoping, to ensure that all necessary infrastructure and services are in place.
4. Cleaning: Area where the ore is removed from underground.
5. Flat development: Development into flat-bedded deposits on a reef.
6. Redevelopment: Redeveloping previously discontinued stopes to extract additional ore.
7. Refuge bay: Emergency area in the mine, equipped with basic emergency equipment.
8. Auxiliary: Area with additional end users, such as pumps, that are not used all the time.

Each area includes some or all of the class 1 end users defined in Table 1.

2.2.2. Equipment operational time and flow

The second aspect is the operational time and consumption of the class 1 end users. The operational time is used to compute the total consumption of the equipment. The consumption of each piece of equipment is gathered from its corresponding design specifications. This design specification includes the consumption of the equipment at a specific reference pressure. Because this consumption is measured in cubic meters per hour [Nm^3/h], 'operational time' refers to the total time that the end user uses compressed air during an hour period, reflected as a percentage value. The reference consumption needs to be normalised to the actual pressure at the time of use by using Equation (1).

$$F_N = F_{ref} \times \frac{P_{actual}}{P_{ref}} \tag{1}$$

Here:

F_N	Normalised flow [Nm³/h]
F_{ref}	Reference flow of equipment [Nm³/h]
P_{actual}	Actual pressure [kPa]
P_{ref}	Reference pressure [kPa]

2.2.3. *Operational end-users*

The third aspect to consider is the number of end users (i.e., the total amount of equipment used within a 24-hour period). The number of end users differs throughout the day, as there are different shifts in a mine. These shifts are usually specific to each mine, but for this study, seven commonly found shifts in a mine will be considered for the zero-wastage model. Each shift uses different equipment, and the operational time differs for each piece of equipment in the different shifts. Table 2 shows the different shifts that are considered, as well as their respective start and end times.

Table 2: Common shifts found in a 24-hour period of mining operations

Shift	Start time	End time
Drilling	07:00	15:30
Post-drilling	15:30	17:00
Afternoon reduction	17:00	18:30
Blasting	18:30	21:00
Night reduction	21:00	22:00
Cleaning	22:00	04:00
Morning reduction	04:00	07:00

The number and type of end users in each shift is determined by the operational information supplied by the mine. Thus, the continuous evaluation and adjustment of the number of end-users per shift are crucial for the accuracy of the zero-wastage model.

2.2.4. *Zero-wastage flow*

The total zero-wastage flow per shift can be mathematically computed by summating the end users in each of the eight areas mentioned above, using Equation (2). The operational time is taken as the average utilisation rate of the specific equipment within an hour. This information can either be obtained from the mine or collected through physical observation of a typical 24-hour operation period. A wastage factor is included in Equation (2) to account for inefficiencies, equipment design specification discrepancies, sub-standard equipment, and assumptions regarding operational time.

$$F_z = W_F \times \sum_{n=1}^{8} F_N \times T_{Op} \times N \tag{2}$$

Here:

F_z	Zero-wastage flow of shift [Nm³/h]
W_F	Wastage factor [%]
n	Number of areas
F_N	Normalised flow of specific equipment [Nm³/h]

T_{Op} Operational time [hour]

N Number of same items of equipment used

The zero-wastage flow profile is calculated and plotted on a graph for a 24-hour period using Equation (2). Figure 5 is a graphical representation of the different shifts in a 24-hour period, as well as examples of a plotted zero-wastage and an actual flow consumption profile.

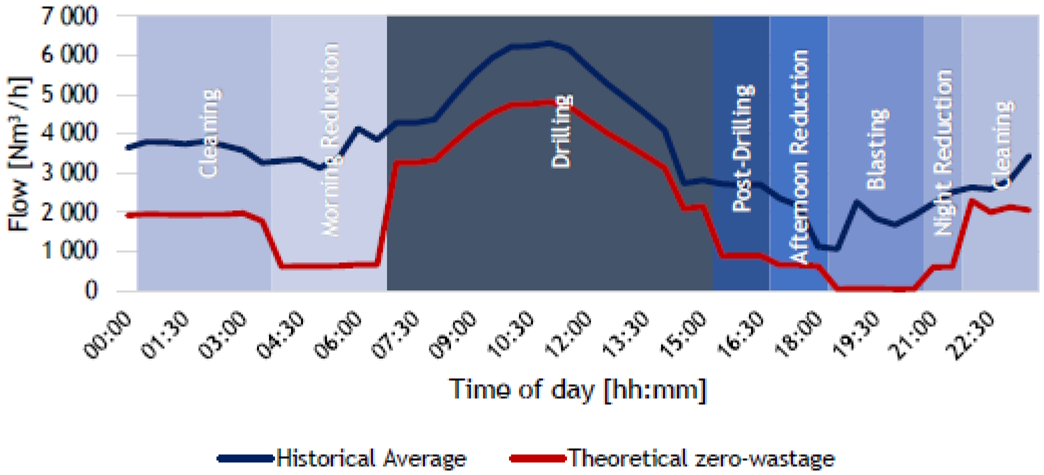

Figure 5: Shift visualisation with zero-wastage and actual consumption profile examples

2.3. Ventilation network

The second requirement to prove that a link exists is to evaluate the ventilation network using an existing assessment method: examination, surveys, and physical inspection. This assessment method is best described by the term 'auditing'. Auditing is an effective method to evaluate the compliance of a ventilation network compared with pre-defined objectives. The objective of the ventilation audit will be to identify ventilation shortfalls.

The ventilation shortfall will be primarily based on the dry- and wet-bulb temperatures, as these temperatures have a direct impact on the thermal comfort of mine personnel and on their health and safety. 'Dry-bulb temperature' refers to the true ambient temperature, which is usually measured by a regular thermometer [23], while 'wet-bulb' is the temperature of the adiabatic saturation, and is the lowest temperature at which water evaporates [24]. The literature indicated that a wet-bulb temperature exceeding 27.1 °C in South African deep-level mines is deemed hot and uncomfortable, and requires that safety measures be implemented to protect underground mining personnel [25][26]. This study will consider a wet-bulb temperature exceeding 27.1 °C as a ventilation shortfall.

In order to evaluate the ventilation network, the objective of the auditing process will be to measure the dry- and wet-bulb temperatures throughout the eight identified areas. This will be done during the drilling shift, as the greatest number of compressed air end users are present during this period. This is also the period during which the ventilation and compressed air networks are under the most strain. After the audit, the temperature data will be cross-referenced with the excessive compressed air wastage areas. This will enable a comparison between high and low compressed air wastage areas and their corresponding temperatures in order to evaluate the link between compressed air wastage and ventilation shortfalls and the viability of using compressed air wastage as a metric to identify areas with ventilation shortfalls.

3. IMPLEMENTATION AND RESULTS

The above method was applied to a case study on a deep-level mine to prove that a link exists between compressed air wastage and ventilation shortfalls. The results acquired through the implementation of the proposed methodology will be analysed to verify and validate the methodology and to determine the validity of the hypothesis.

The validation process will consist of the following three aspects:

A. Compressed air investigation

   A.1. Assess compressed air consumption using the zero-wastage model to identify high compressed air wastage sections in the mine.

   A.2. Compressed air crosscut audits in the identified section with the objective of identifying crosscut(s) with high compressed air consumption.

B. Ventilation evaluation

   B.1. Ventilation audit of the identified section with the objective of evaluating the ventilation network in the haulage and in identified crosscut(s).

C. Comparison assessment

The proposed method was implemented on a compressed air and ventilation network of a deep-level platinum mine. For confidentiality purposes, the mine is referred to as 'mine A' throughout the rest of this case study.

3.1. Compressed air investigation

3.1.1. Zero-wastage model

For this case study, the zero-wastage model was used to identify a specific level in mine A with high compressed air wastage. Weekends often had reduced operations in mine A, and therefore only weekdays were considered, as this was when mining operations were most active and consistent. To monitor the consumption, this study monitored the total daily consumption for five consecutive weekdays. A conservative 25% wastage factor was considered for the zero-wastage consumption, calculated using Equation (2) from section 2.2.4. Figure 6 shows the total daily consumption of all the levels in the case study mine.

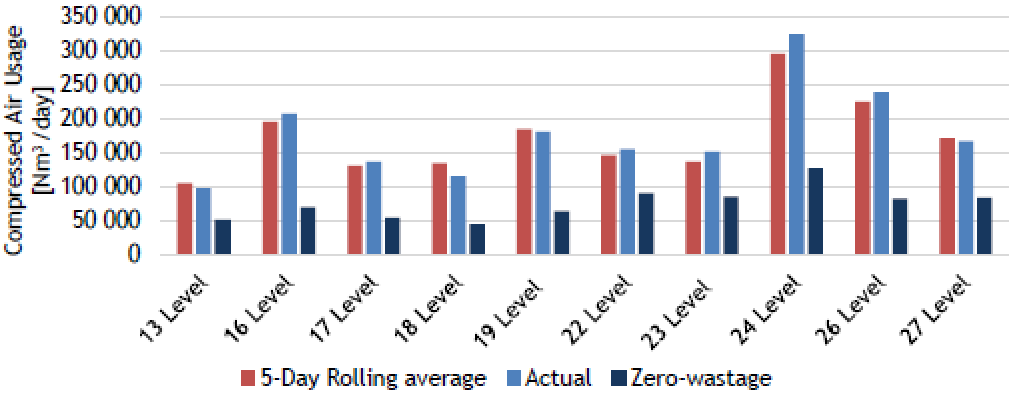

Figure 6: Daily shaft performance summary with a five-day rolling average

From Figure 6 it is evident that there was a big discrepancy between the zero-wastage and actual compressed air consumption at all of the levels at mine A. A more in-depth analysis followed to monitor a 24-hour period of consumption. Figure 7 shows the results over the shifts on level 24 of mine A, which was identified as a problematic level by evaluating Figure 6.

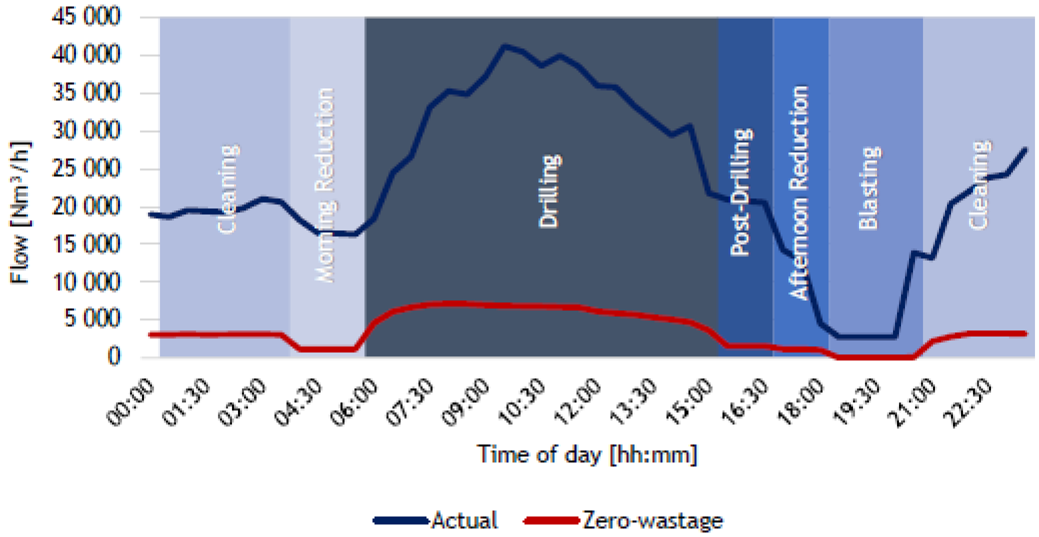

Figure 7: 24-hour actual compressed air consumption and zero-wastage profile

The data was further summarised into drilling and non-drilling shifts to compute the total wastage in these two shifts. The compressed air wastage during the drilling shift was compared with the equivalent number of rockdrills, while a baseload percentage was determined for the duration of the non-drilling shifts. The baseload percentage represented the amount of compressed air wasted during the non-drilling shift. Table 3 shows the compressed air wastage during the drilling and non-drilling shifts.

Table 3: Equivalent compressed air wastage during drilling and non-drilling shifts

Description	Drilling (06:30 - 15:00)	Non-drilling
Total zero-wastage consumption [Nm³]	48 993	36 598
Total actual consumption [Nm³]	263 389	287 395
Wastage [Nm³]	214 395	250 797
Baseload percentage	81%	87%

It is evident from Table 3 that there was a significant discrepancy between the zero-wastage and the total actual consumption during the drilling shift, indicating the likely presence of class 2 compressed air users during this period to account for the 81% baseload. In addition, 87% of the compressed air usage was wasted during the non-drilling shift.

After the level with the highest compressed air consumption had been identified, the specific crosscuts that consumed an excessive amount of compressed air had to be further identified and ranked. The approach was to audit the level with the objective of evaluating compressed air usage per active crosscut in the level.

3.1.2. Compressed air audit

Crosscut consumption audits were performed to determine which crosscuts consumed the most compressed air. This was achieved by simply closing each crosscut sequentially during the cleaning shift while monitoring the change in total consumption for that level. This allowed the baseload consumption of each crosscut to be determined. Figure 8 to Figure 10 depict the crosscuts with the highest compressed air wastage obtained during the crosscut audits.

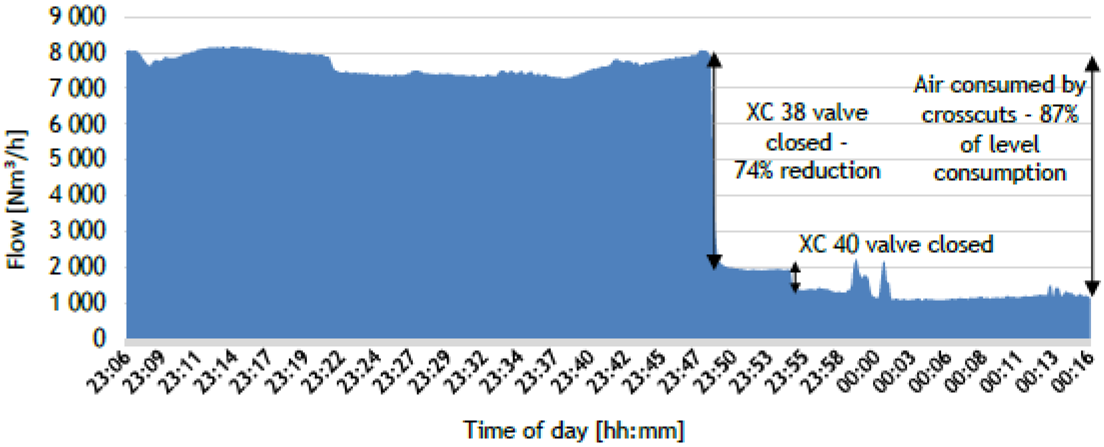

Figure 8: 24L half-level crosscut flow consumption audit

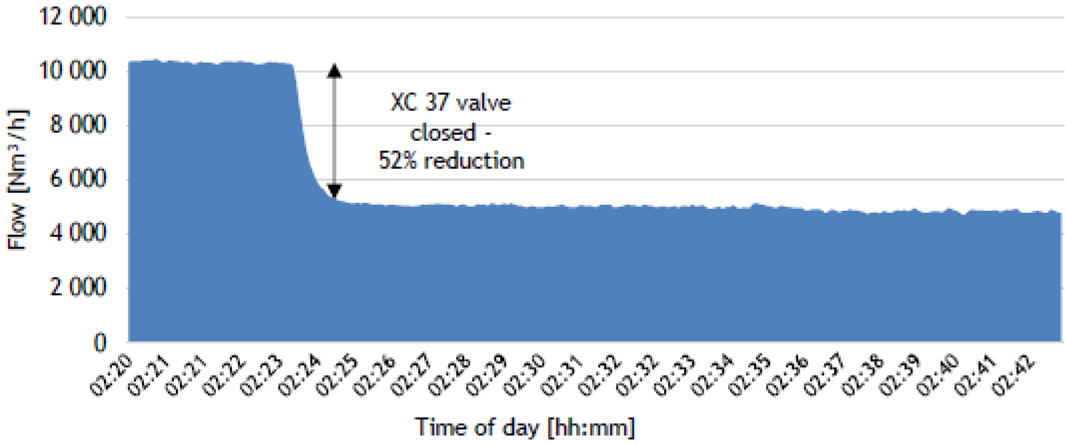

Figure 9: 25L south half-level crosscut flow consumption audit

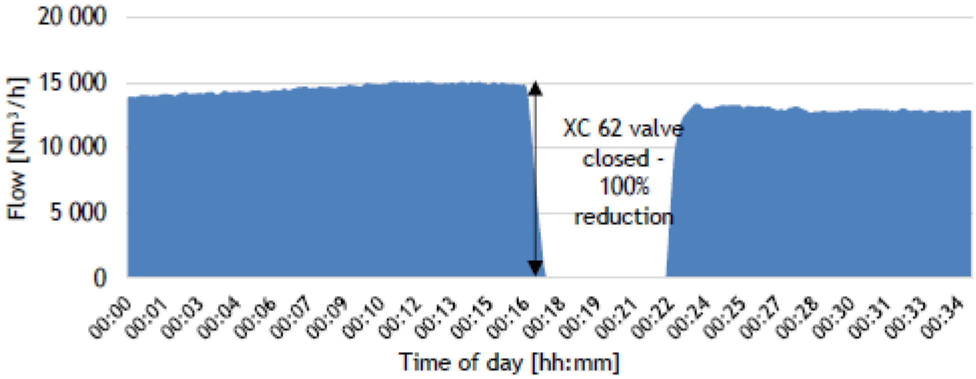

Figure 10: 25L north half-level crosscut flow consumption audit

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The audit indicated that the level had a few leaks and numerous open-ended pipes inside the crosscuts. In certain instances, the compressed air network was also intentionally damaged, and pipelines were punctured with holes to supply cooled air to the working area. Both the open-ended pipes and the punctured pipelines fall under class 2 end users, as listed in Table 1, and are considered compressed air wastage.

In summary, the zero-wastage model was used to evaluate the compressed air network and to investigate wastage in mine A. First, a five-day (weekday) rolling average was calculated for each level. This made it possible to identify the worst-performing level (i.e., the highest compressed air wastage).

After the worst performing level had been identified, it was monitored for a 24-hour period to determine which shift had the largest discrepancy between actual and zero-wastage consumption. Second, crosscut consumption audits were conducted to determine the worst-performing crosscuts. The final step was to evaluate the corresponding ventilation network through auditing.

3.2. Ventilation evaluation audit

The wet-bulb and dry-bulb temperatures were measured during the drilling shift (6:30 to 15:00 for mine A) to assess the ventilation network and to identify any shortcomings. Temperatures were recorded across the whole level and in the crosscuts. Table 4 below lists each crosscut with its corresponding temperatures recorded inside the crosscuts (collected during the ventilation evaluation audits). In addition, each crosscut is ranked according to the recorded wet-bulb temperature. Table 4 is only a sample of the data set that was collected. A total of 78 crosscuts were evaluated to ensure that the sample was representative of a typical platinum mine.

Table 4: Sample crosscut ventilation audit data at mine A

Rank	Crosscut [XC]	Temperature [°C]		Ventilation shortfall
		Wet-bulb	Dry-bulb	
1.	XC62	34.7	37.2	Yes
2.	XC38	31	34.8	Yes
3.	XC105	30.5	33.2	Yes
4.	XC123	30.1	30.5	Yes
5.	XC106	29.5	30.5	Yes
6.	XC37	28.5	30	Yes
7.	XC122	24	27	No
8.	XC106CA	23.5	28.5	No
9.	XC39	22.5	29.5	No

3.3. Comparison

To prove that there was a link between compressed air wastage and ventilation shortfalls, the compressed air wastage of each crosscut was compared with its corresponding wet-bulb temperature. During the ventilation audit, it was found that an increased occurrence of prohibited compressed air use (class 2 end users) was associated with higher wet-bulb temperatures. This led to a significant increase in consumption (i.e., wastage).

Figure 11 below is a summarised comparison (of the 78 crosscuts evaluated) between the wet-bulb temperatures and the corresponding compressed air wastage percentage collected from multiple mines (including, but not limited to, Mine A). It is divided into four quadrants, based on two categories: a wastage percentage and the ventilation shortfall line (27.1 °C). Each quadrant shows the percentage of the total crosscuts found in that quadrant's specifications. This study will consider a wastage percentage above 25% as excessive wastage.

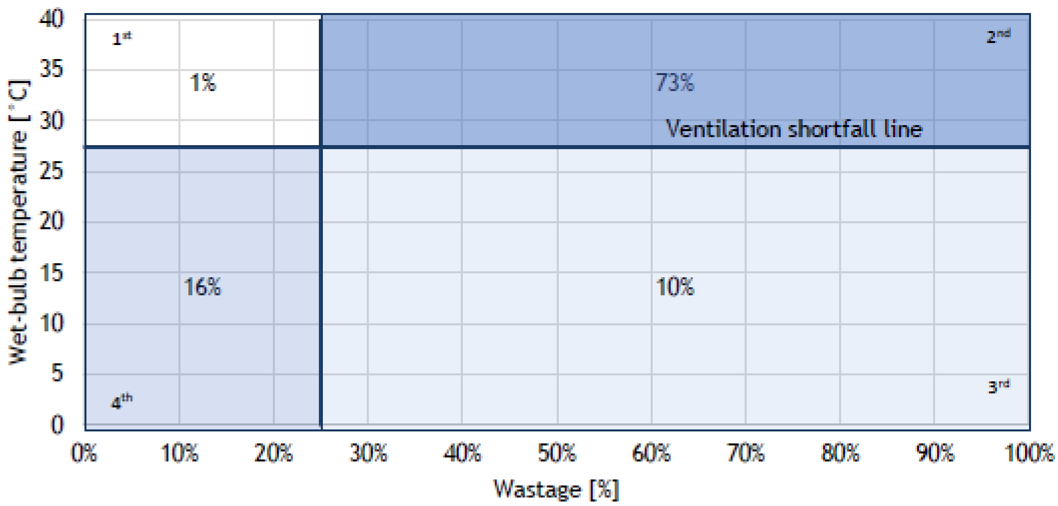

Figure 11: Wet-bulb temperature versus compressed air wastage across multiple mines

Figure 11 indicates that 73% of the crosscuts that had a temperature above the ventilation shortfall line (the thermally uncomfortable temperature of 27.1 °C) also had excessive wastage. Only 10% of the crosscuts that were under the ventilation shortfall line had excessive wastage. The majority of these crosscuts were also very close to the thermally uncomfortable temperature. Overall, the majority of crosscuts that had an excessive compressed air wastage also exceeded the thermally uncomfortable limit, which is indicative of a ventilation shortfall (as noted in Table 4 and seen in Figure 11).

This confirms that, based on the crosscuts considered at the specific mines, there is likely to be a link between compressed air wastage and ventilation shortfalls. It is expected that, if more results had been obtained, most of the cases would have lain in the second and fourth quadrants, which was the case for 89% of the samples tested.

4. RECOMMENDATIONS

The hypothesis was tested using a case study of a platinum mine. It is recommended that this hypothesis be tested on other mines to strengthen the argument of the link between compressed air and ventilation shortfalls. This includes different types of mine (gold, PGM, coal, etc.). The biggest limitation of this approach is its dependency on equipment to measure the actual flow and pressure. It is thus recommended that additional equipment, such as flowmeters, be installed to reduce the total size of the areas to be considered. This would enable better monitoring of the actual flow, as well as fewer errors and assumptions in the mathematically calculated zero-wastage flow.

The limitations of this study also include the assumption(s) of the operational time of the different equipment. Identifying and quantifying the actual end users of compressed air can be time-consuming. An improved and more accurate model could be developed to reduce the quantification time and the assumptions about the operational time. Another limitation is the resources expended to measure the temperatures throughout the mine. It is recommended that the advantages of an improved (less time-consuming) method be explored to collect the temperature data accurately.

It is recommended that the link between compressed air wastage and ventilation shortfalls be further used to improve ventilation and to reduce compressed air wastage. A less resource-intensive methodology could be developed to use the link and to identify ventilation shortfalls quickly. This methodology would have to benchmark the compressed air system to identify and rank ventilation shortfalls reliably. It would also have to aim to minimise investigation periods while moving away from multivariable data inputs - i.e., the current common ventilation assessment methods.

5. CONCLUSION

The background of this study highlighted that production is the primary objective of mine planning and design, causing mines to expand rapidly and constantly. This often causes ventilation to be neglected, which results in compressed air being misappropriated for underground self-ventilation.

The literature highlighted that ventilation networks are vast and complex, making it increasingly difficult to identify shortfalls. Instrumentation, simulations, and physical examinations are the three commonly used methods for ventilation assessment to identify possible shortfalls. However, these methods are time-consuming and resource-intensive. Thus, a need was identified for an alternative and simplified methodology to identify ventilation shortfalls.

The novelty of this study is that it investigated compressed air wastage as a metric to identify ventilation shortfalls. To use compressed air wastage as a metric, it first needed to be proven that a link existed between compressed air wastage and ventilation shortfalls. As a result, the primary objective of this study was to prove the hypothesis to be true.

The hypothesis was supported through a case study on a platinum mine. Objective 1 was achieved through a zero-wastage compressed air model that highlighted a substantial discrepancy between actual and zero-wastage consumption. In addition, compressed air crosscut audits were performed on the problematic levels to identify crosscut(s) with a high compressed air consumption and to rank them. Objective 2 was achieved by evaluating the corresponding ventilation network to determine whether there were any shortfalls.

Objective 3 was achieved by analysing the results, which revealed that a relationship existed between compressed air wastage and ventilation shortfalls. A greater occurrence of open-ended pipes and prohibited compressed air usage was associated with high wet-bulb temperatures (which is regarded as a ventilation shortfall). It was therefore concluded that a link does exist between compressed air wastage and ventilation shortfalls, proving the hypothesis to be true.

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Appendix B Deep-level mine compressed air

Compressed air a preferred energy choice

Compressed air has been utilised in the mining sector since the beginning of the industrial revolution [3]. With the historically low cost of electricity (until the late 2000's), energy as an operational expense was not a major concern for most mining companies [50]. This meant that the mining industry was less concerned with the efficiency of compressed air. In addition, the susceptibility to misuse and misappropriation of compressed air was overlooked due to its numerous advantageous properties, such as: 1) safety (in terms of energy transfer and storage), 2) reliability, 3) scalability, 4) proven resilience, 5) lightweight tools, and 6) user-friendliness [34].

Electrically driven equipment was considered as an alternative to compressed air driven equipment during the early stages of mechanisation of the mining industry. This is because electricity is the most efficient energy carrying medium [4]. However, it was discovered that electrically driven equipment had two major drawbacks that rendered it unsuitable for use in the South African mining industry at the time. Firstly, the weight of handheld electrical equipment was much higher than that of compressed air equipment, resulting in fatigue and ultimately reducing worker productivity.

Secondly, the potential safety risks were of greater importance. Combining water, electricity, and an ill-educated workforce increased the risk of electrocution, while combining electricity and flammable gases increased the chance of explosions. Owing to the severity of these safety risks, the mining sector was unable to pursue greater operational efficiency by means of electrically powered equipment. Hence, compressed air systems are still utilised today, in the South African mining sector.

Compressed air alternatives

It is well documented that compressed air is a very inefficient energy carrying medium, when compared with other energy carrying mediums on deep-level mines. Therefore, it has been suggested that mining companies step away from compressed air as their primary energy carrying medium [42], [51]. Recent advances in modern technology have led to the re-evaluation of electrically driven equipment as a possible alternative to compressed air systems.

With the combination of lightweight materials and shifting of load onto power packs, weight issues that made electrically driven equipment unsuitable in the past have been resolved. Furthermore, the use of seals has lowered the risks of water and flammable gases, making electrical equipment safer to use [21]. In addition, new advances in technology have also enabled the early detection of flammable gases underground and mining personnel are better educated than in the past. The above-mentioned factors have enabled the mining industry to re-evaluate its dependency on compressed air systems.

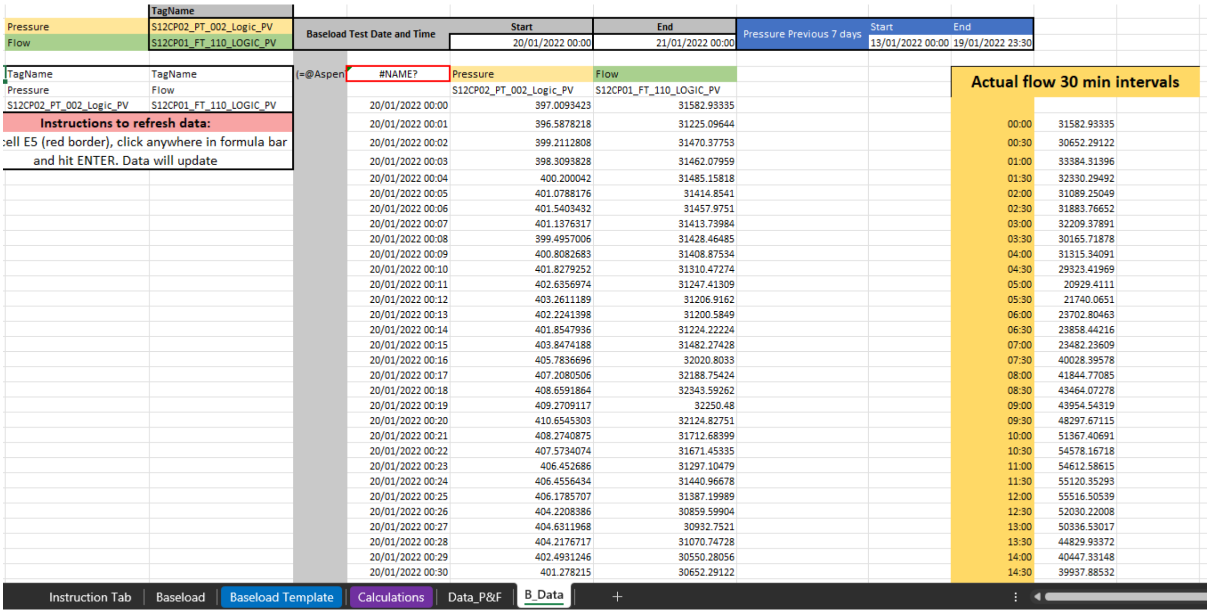
There are several alternative technologies to compressed air, but the most notable technologies that outperform compressed air (with regards to energy efficiency) are electro-hydraulic and hydroelectric. However, adoption of these new technologies has been slow, with only a few mines in South Africa that have replaced compressed air as their primary source of mechanical power [21].

Literature has indicated that mining companies are reluctant to adopt new technologies for several reasons, including the extensive nature and complexity of existing compressed air networks – replacing these will be labour-intensive and time-consuming, large capital requirements to convert the whole system, and insufficient infrastructure to accommodate the additional electrical and water requirements. Additionally, the new technologies pose several risks, including a lack of a proven track record, susceptibility to misuse and mismanagement, and resistance to change (by unions and mine workers) [50]. Owing to these previous challenges, mining companies are more likely to extend their current compressed air network and improve their energy efficiency than to convert to new technologies Therefore, it is crucial to pursue compressed air optimisation strategies, of current systems, as far as possible [29].

Appendix C Benchmark method 1

The full model developed in Section 4.2.1.2 is described below with figures as reference to each phase.

ADP.1: Extract the pressure and flow data and capture it into the model.



	TagName
Pressure	S12CP02_PT_002_Logic_PV
Flow	S12CP01_FT_110_LOGIC_PV

Baseload Test Date and Time	Start	End
	20/01/2022 00:00	21/01/2022 00:00

Pressure Previous 7 days	Start	End
	13/01/2022 00:00	19/01/2022 23:30

TagName	TagName
Pressure	Flow
S12CP02_PT_002_Logic_PV	S12CP01_FT_110_LOGIC_PV

Instructions to refresh data:
:ell E5 (red border), click anywhere in formula bar and hit ENTER. Data will update

(=@Aspen	#NAME?	Pressure	Flow	Actual flow 30 min intervals	
		S12CP02_PT_002_Logic_PV	S12CP01_FT_110_LOGIC_PV		
	20/01/2022 00:00	397.0093423	31582.93335		
	20/01/2022 00:01	396.5878218	31225.09644	00:00	31582.93335
	20/01/2022 00:02	399.2112808	31470.37753	00:30	30652.29122
	20/01/2022 00:03	398.3093828	31462.07959	01:00	33384.31396
	20/01/2022 00:04	400.200042	31485.15818	01:30	32330.29492
	20/01/2022 00:05	401.0788176	31414.8541	02:00	31089.25049
	20/01/2022 00:06	401.5403432	31457.9751	02:30	31883.76652
	20/01/2022 00:07	401.1376317	31413.73984	03:00	32209.37891
	20/01/2022 00:08	399.4957006	31428.46485	03:30	30165.71878
	20/01/2022 00:09	400.8082683	31408.87534	04:00	31315.34091
	20/01/2022 00:10	401.8279252	31310.47274	04:30	29323.41969
	20/01/2022 00:11	402.6356974	31247.41309	05:00	20929.4111
	20/01/2022 00:12	403.2611189	31206.9162	05:30	21740.0651
	20/01/2022 00:13	402.2241398	31200.5849	06:00	23702.80463
	20/01/2022 00:14	401.8547936	31224.22224	06:30	23858.44216
	20/01/2022 00:15	403.8474188	31482.27428	07:00	23482.23609
	20/01/2022 00:16	405.7836696	32020.8033	07:30	40028.39578
	20/01/2022 00:17	407.2080506	32188.75424	08:00	41844.77085
	20/01/2022 00:18	408.6591864	32343.59262	08:30	43464.07278
	20/01/2022 00:19	409.2709117	32250.48	09:00	43954.54319
	20/01/2022 00:20	410.6545303	32124.82751	09:30	48297.67115
	20/01/2022 00:21	408.2740875	31712.68399	10:00	51367.40691
	20/01/2022 00:22	407.5734074	31671.45335	10:30	54578.16718
	20/01/2022 00:23	406.452686	31297.10479	11:00	54612.58615
	20/01/2022 00:24	406.4556434	31440.96678	11:30	55120.35293
	20/01/2022 00:25	406.1785707	31387.19989	12:00	55516.50539
	20/01/2022 00:26	404.2208386	30859.59904	12:30	52030.22008
	20/01/2022 00:27	404.6311968	30932.7521	13:00	50336.53017
	20/01/2022 00:28	404.2176717	31070.74728	13:30	44829.93372
	20/01/2022 00:29	402.4931246	30550.28056	14:00	40447.33148
	20/01/2022 00:30	401.278215	30652.29122	14:30	39937.88532

Instruction Tab | Baseload | Baseload Template | Calculations | Data_P&F | B_Data

ADP.2: Insert the times when the isolation valves were closed into the table.

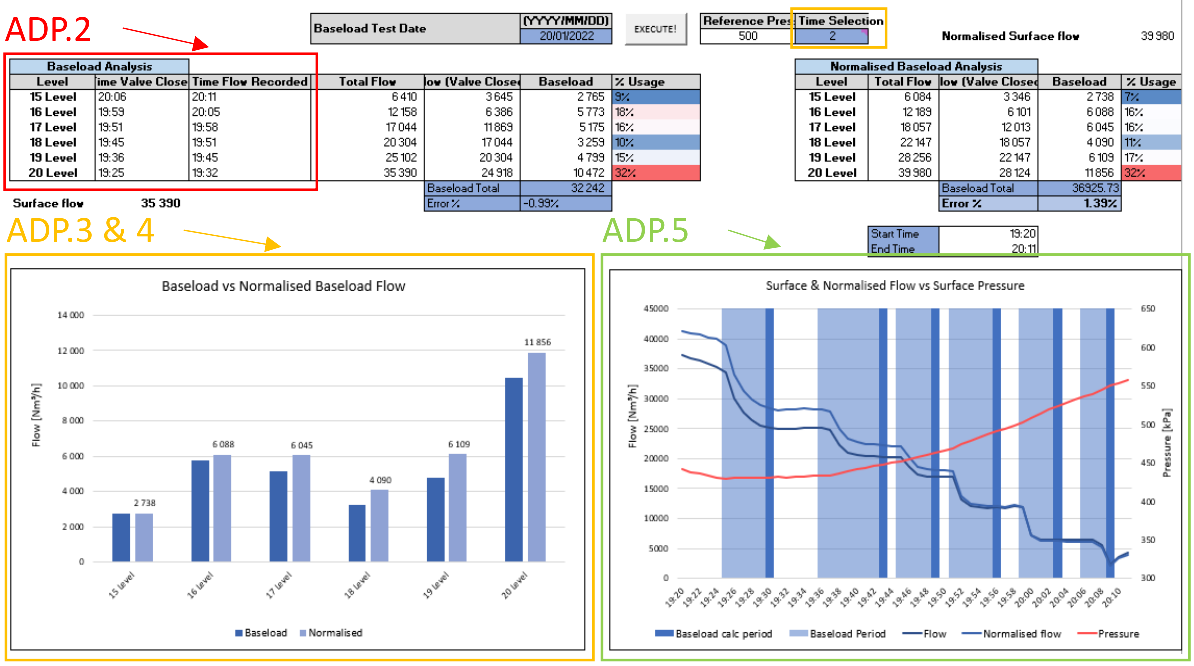
ADP.3: The model computes the compressed air distribution and error percentage.

ADP.4: Normalise the consumption of each level using ideal gas law.

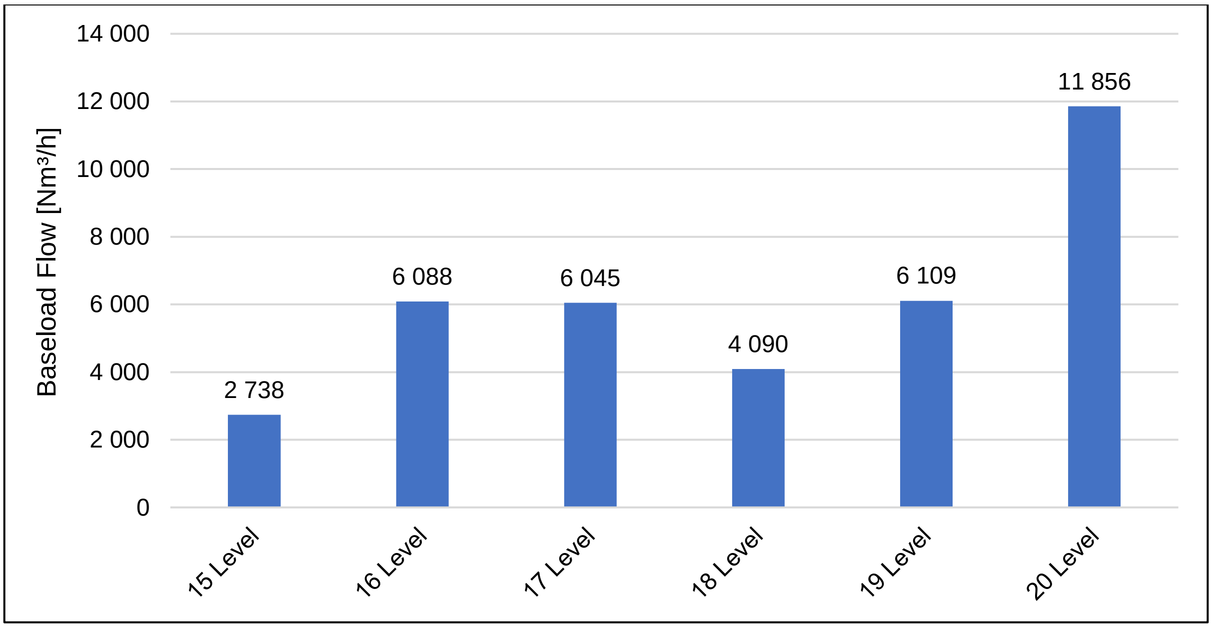
ADP.5: The surface flow- and normalised consumption, surface pressure, baseload - and baseload calculation period are illustrated through a graph.

ADP.2 to ADP.5 is depicted in the figure below to illustrate the model input and output.

Appendix A - Detailed Processing



ADP.6: The normalised consumption of each level is illustrated with the distribution of each level depicted as a percentage of the total consumption.



Appendix D Benchmark method 2

ACM.1: Extract the pressure and flow data and capture it into the model.

										20L	19L	18L	17L	16L	15L
									Paste here:	Downstream Pressure	Downstream Pressure	Downstream Pressure	Downstream Pressure	Downstream Pressure	Downstrea
Date	DateValue	Time	TimeValue	Year	Month	WeekOfYea	DayOfWeel	Weekday/Weeken	Column1	S12BI_PT_170A_VAL	S12BI_PT_169A_VAL	S12BI_PT_168A_VAL	S12BI_PT_167A_VAL	S12BI_PT_166A_VAL	S12BI_PT_1
2022/09/11	11/09/2022	00:00	00:00:00	2022	9	37	7	Sunday	11/09/2022 00:00	0	0	0	1.065609641	0.811023479	
2022/09/11	11/09/2022	00:30	00:30:00	2022	9	37	7	Sunday	11/09/2022 00:30	0	0	0	1.066673228	0.805242289	
2022/09/11	11/09/2022	01:00	01:00:00	2022	9	37	7	Sunday	11/09/2022 01:00	0	0	0	1.080450495	0.808907488	
2022/09/11	11/09/2022	01:30	01:30:00	2022	9	37	7	Sunday	11/09/2022 01:30	0	0	0	1.088240097	0.79836776	
2022/09/11	11/09/2022	02:00	02:00:00	2022	9	37	7	Sunday	11/09/2022 02:00	0	0	0	1.112719377	0.812681074	
2022/09/11	11/09/2022	02:30	02:30:00	2022	9	37	7	Sunday	11/09/2022 02:30	0	0	0	1.114546809	0.777979635	
2022/09/11	11/09/2022	03:00	03:00:00	2022	9	37	7	Sunday	11/09/2022 03:00	0	0	0	1.084230311	0.773397071	
2022/09/11	11/09/2022	03:30	03:30:00	2022	9	37	7	Sunday	11/09/2022 03:30	0	0	0	1.113605318	0.782477641	
2022/09/11	11/09/2022	04:00	04:00:00	2022	9	37	7	Sunday	11/09/2022 04:00	0	0	0	1.098359473	0.772396908	
2022/09/11	11/09/2022	04:30	04:30:00	2022	9	37	7	Sunday	11/09/2022 04:30	0	0	0	1.096555723	0.752775235	
2022/09/11	11/09/2022	05:00	05:00:00	2022	9	37	7	Sunday	11/09/2022 05:00	0	0	0	1.135370228	0.798577162	
2022/09/11	11/09/2022	05:30	05:30:00	2022	9	37	7	Sunday	11/09/2022 05:30	0	0	0	1.121598	0.7723015	
2022/09/11	11/09/2022	06:00	06:00:00	2022	9	37	7	Sunday	11/09/2022 06:00	0	0	0	1.139392692	0.810354179	
2022/09/11	11/09/2022	06:30	06:30:00	2022	9	37	7	Sunday	11/09/2022 06:30	0	0	0	1.175362045	0.796511017	
2022/09/11	11/09/2022	07:00	07:00:00	2022	9	37	7	Sunday	11/09/2022 07:00	0	0	0	1.188950013	0.787238502	
2022/09/11	11/09/2022	07:30	07:30:00	2022	9	37	7	Sunday	11/09/2022 07:30	0	0	0	1.282718997	0.896976524	
2022/09/11	11/09/2022	08:00	08:00:00	2022	9	37	7	Sunday	11/09/2022 08:00	0	0	0	1.058613542	0.727557895	
2022/09/11	11/09/2022	08:30	08:30:00	2022	9	37	7	Sunday	11/09/2022 08:30						
2022/09/11	11/09/2022	09:00	09:00:00	2022	9	37	7	Sunday	11/09/2022 09:00						
2022/09/11	11/09/2022	09:30	09:30:00	2022	9	37	7	Sunday	11/09/2022 09:30						
2022/09/11	11/09/2022	10:00	10:00:00	2022	9	37	7	Sunday	11/09/2022 10:00						
2022/09/11	11/09/2022	10:30	10:30:00	2022	9	37	7	Sunday	11/09/2022 10:30	0	0	0	1.351560421	5.66419E-19	
2022/09/11	11/09/2022	11:00	11:00:00	2022	9	37	7	Sunday	11/09/2022 11:00	0	0	0	1.66811368	1.215922921	
2022/09/11	11/09/2022	11:30	11:30:00	2022	9	37	7	Sunday	11/09/2022 11:30	0	0	0	1.534546125	1.233423817	
2022/09/11	11/09/2022	12:00	12:00:00	2022	9	37	7	Sunday	11/09/2022 12:00	0	0	0	1.55205489	1.203554291	
2022/09/11	11/09/2022	12:30	12:30:00	2022	9	37	7	Sunday	11/09/2022 12:30	0	0	0	1.479532884	1.140367176	
2022/09/11	11/09/2022	13:00	13:00:00	2022	9	37	7	Sunday	11/09/2022 13:00	0	0	0	1.379904136	1.097042233	
2022/09/11	11/09/2022	13:30	13:30:00	2022	9	37	7	Sunday	11/09/2022 13:30	0	0	0	1.313340989	1.042529367	
2022/09/11	11/09/2022	14:00	14:00:00	2022	9	37	7	Sunday	11/09/2022 14:00	0	0	0	1.262624568	1.003041724	

ACM.2: Insert shift period for each level.

Drilling shift time schedule for all levels:								
>=06:30:00	>=06:30:00	>=06:00:00	>=06:30:00	>=06:30:00	>=06:30:00	>=07:00:00	>=08:30:00	>=08:30:00
<16:00:00	<16:00:00	<16:30:00	<17:00:00	<16:00:00	<16:30:00	<15:00:00	<16:30:00	<16:30:00

ACM.3: Model computes PI and identifies lowest PI per level for specified times.

Lowest KPI during drilling shift					
L19 KPI_L	L18 KPI_L	L17 KPI_L	L16 KPI_L	L15 KPI_L	L20 KPI_L
13.64	10.98	12.21	8.82	9.47	13.56
14.83	11.81	14.78	6.39	7.89	21.99
14.37	9.36	11.20	11.02	8.05	23.03
13.04	11.21	14.40	10.57	11.61	17.30
12.95	9.56	14.45	13.79	12.86	14.49
15.30	10.02	14.13	8.59	12.03	15.82
12.84	9.43	15.08	11.07	11.68	15.37
15.08	11.74	12.69	11.84	12.22	14.47
13.15	9.64	14.08	11.59	11.23	14.30
12.58	12.77	12.82	10.27	9.87	13.75
12.64	10.97	16.25	10.86	12.04	14.35
11.72	12.35	12.97	10.51	12.30	13.73
9.46	12.16	13.60	10.64	13.44	12.13
11.33	13.52	13.32	10.13	12.76	15.33
15.72	12.09	13.52	10.55	12.64	17.40
16.49	11.83	15.27	11.10	14.43	15.32
13.79	9.19	15.68	10.25	11.75	17.03
18.03	12.23	15.18	11.87	14.57	16.74
16.41	12.28	15.13	14.04	12.30	17.09
17.06	13.40	18.36	11.06	11.99	18.10
16.79	8.76	20.17	9.87	10.35	21.61
14.42	11.00	16.26	10.63	11.30	19.40
14.04	12.27	14.73	4.35	10.89	18.49

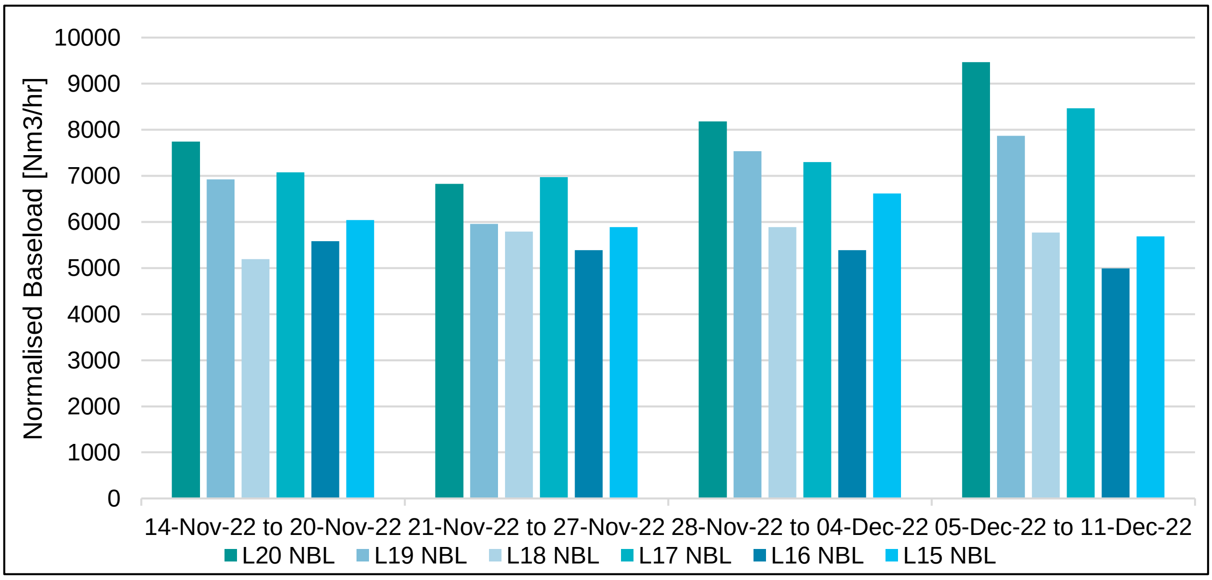
ACM.4: Correlate PI timestamp with specific flow and pressure.

Pressure at lowest KPI						Baseload flowrate					
L19 Pressure_	L18 Pressure_	L17 Pressure_	L16 Pressure_	L15 Pressure_E	L20 Pressure_	L19 Flowra	L18 Flowra	L17 Flowra	L16 Flowrat	L15 Flowrate	L20 Flowra
563.08	431.60	565.47	560.39	567.41	563.08	7678.74	4739.02	6904.58	4941.48	5373.14	7634.28
551.16	365.55	387.96	478.85	524.47	384.18	8173.65	4317.89	5732.49	3062.22	4136.98	8447.78
493.37	428.98	493.11	489.27	560.32	388.20	7089.55	4017.02	5520.85	5390.35	4508.73	8940.53
491.62	369.76	484.44	481.03	515.44	386.05	6410.72	4144.37	6975.82	5083.64	5984.69	6677.82
518.53	449.95	391.51	387.98	518.42	388.40	6715.72	4303.58	5658.90	5351.93	6669.14	5627.26
489.46	370.52	501.67	384.63	500.70	383.21	7489.99	3711.89	7087.92	3302.36	6021.16	6061.88
490.89	443.43	393.77	390.68	504.50	389.90	6302.42	4182.76	5937.21	4323.32	5890.09	5991.61
551.51	421.26	520.71	520.87	539.45	387.20	8316.48	4944.24	6607.52	6168.72	6593.14	5603.96
549.62	418.88	373.33	387.35	543.89	511.27	7227.99	4038.43	5255.92	4488.19	6106.88	7311.35
549.12	424.37	563.23	397.54	577.79	397.55	6906.60	5418.37	7220.83	4082.58	5700.57	5465.84
566.79	420.37	553.18	548.89	567.19	481.73	7166.61	4609.95	8991.98	5959.04	6828.39	6914.37
571.65	414.46	510.51	506.34	586.98	376.19	6702.48	5119.74	6618.99	5321.34	7222.47	5166.87
491.45	435.95	501.27	497.30	567.54	394.71	4646.81	5299.69	6816.87	5291.72	7629.40	4786.92
513.79	453.28	588.37	583.68	517.18	513.79	5820.39	6127.58	7839.61	5912.21	6599.72	7878.63
511.82	435.26	469.76	504.10	540.21	378.16	8047.34	5261.22	6350.95	5319.68	6829.65	6579.81
532.30	405.78	515.25	494.01	559.00	379.13	8779.43	4798.52	7867.36	5485.49	8065.98	5810.13
558.89	427.98	549.96	555.27	547.41	378.06	7709.23	3933.53	8622.58	5692.97	6430.55	6438.09
551.38	421.74	555.47	377.80	555.68	375.89	9938.94	5158.70	8434.78	4485.55	8097.28	6293.29
502.45	342.02	369.55	463.62	539.33	468.08	8245.36	4201.14	5592.25	6507.68	6633.02	7997.41
517.87	406.50	539.95	325.46	540.49	452.88	8835.41	5446.15	9915.08	3600.59	6483.02	8198.78
518.40	378.75	377.76	376.17	522.57	374.57	8701.92	3317.08	7620.60	3713.22	5411.20	8096.16
527.47	398.21	555.99	552.85	562.28	384.06	7603.65	4382.23	9040.13	5877.90	6354.71	7451.37
531.24	408.66	541.34	355.04	564.00	389.81	7459.32	5015.67	7971.51	1543.09	6143.57	7209.05

ACM.5: Normalise the consumption of each level.

Normalised Baseload Flowrate					
L19 NBL	L18 NBL	L17 NBL	L16 NBL	L15 NBL	L20 NBL
6818.47	5490.07	6105.22	4408.94	4734.84	6779.00
7415.01	5906.01	7388.03	3197.45	3943.95	10994.54
7184.88	4682.09	5597.95	5508.59	4023.37	11515.47
6519.99	5604.09	7199.88	5284.16	5805.38	8648.87
6475.77	4782.29	7227.08	6897.18	6432.14	7244.16
7651.28	5009.08	7064.31	4292.89	6012.73	7909.29
6419.44	4716.36	7539.02	5533.08	5837.50	7683.43
7539.77	5868.39	6344.74	5921.58	6111.00	7236.57
6575.47	4820.49	7039.28	5793.40	5614.11	7150.22
6288.84	6384.09	6410.16	5134.79	4933.06	6874.43
6322.11	5483.25	8127.49	5428.27	6019.50	7176.61
5862.40	6176.36	6482.69	5254.75	6152.27	6867.35
4727.61	6078.33	6799.66	5320.45	6721.43	6063.83
5664.14	6759.21	6662.13	5064.61	6380.44	7667.12
7861.48	6043.72	6759.71	5276.37	6321.26	8699.85
8246.74	5912.72	7634.57	5551.95	7214.60	7662.35
6896.92	4595.47	7839.30	5126.33	5873.60	8514.71
9012.73	6116.04	7592.47	5936.47	7285.89	8371.08
8205.09	6141.58	7566.25	7018.31	6149.31	8542.83
8530.49	6698.85	9181.45	5531.61	5997.31	9051.90
8393.08	4379.01	10086.58	4935.62	5177.49	10807.26
7207.63	5502.43	8129.71	5316.00	5650.80	9700.74
7020.71	6136.78	7362.82	2173.12	5446.45	9246.81

ACM.6: The normalised consumption of each level is illustrated graphically.



Appendix E Case study 1

List of active and inactive crosscuts on 25 Level, Mine Y.

Table E-1: List of active and inactive crosscuts on 25 Level - Mine Y

Half-level	Crosscut number	Active/Inactive
MS	42	Inactive
MS	41	Active
MS	38	Active
MS	37	Active
MS	36	Active
MN	56	Inactive
MN	57	Inactive
MN	58	Active
MN	60	Active
MN	61	Active
MN	62	Active

Full audit results of 25LMN, crosscut 62 with photos of all the leaks identified during the audit.

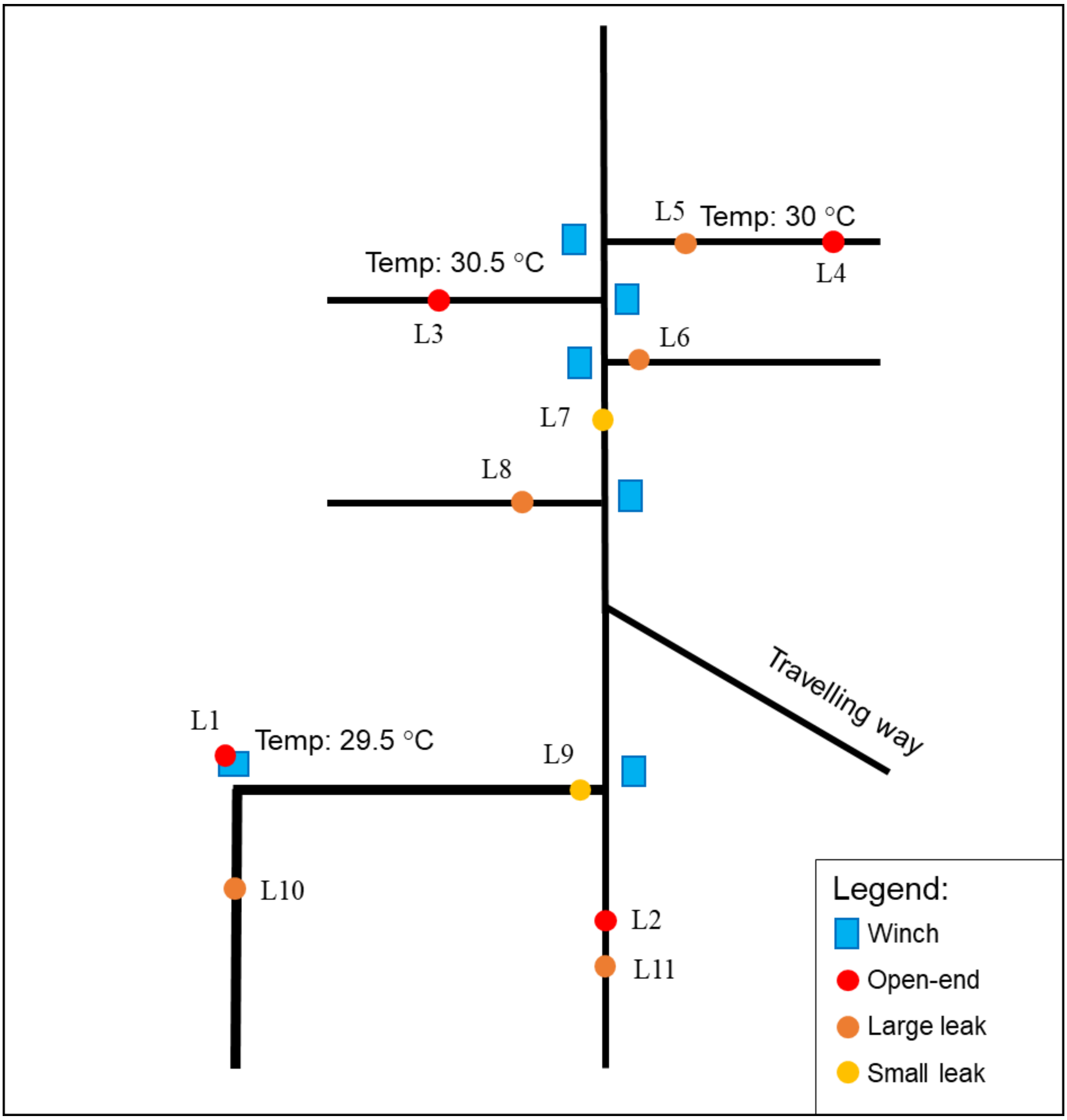


Figure E-1: 25LMN, crosscut 62 layout - Mine Y

L1

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L8

L9

L10

Full audit results of 25LMS, crosscut 37 with photos of all the leaks identified during the audit.

Figure E-2: 25LMN, crosscut 37 layout - Mine Y

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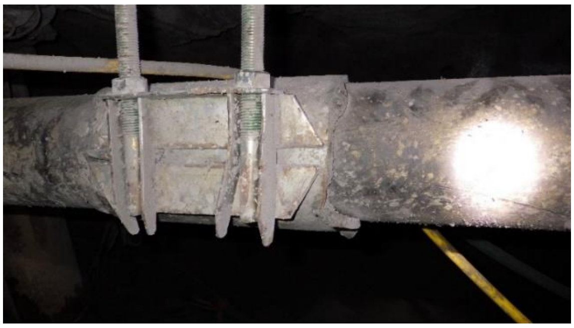


P7

Appendix F Case study 2

Lowest PI computed for each level on Mine Z from 10/11/2022 to 09/12/2022 is summarised in the Table F-1 below.

Table F-1: Lowest PI per level over a period of 4 weeks - Mine Z

Date	L20 PI_L	L19 PI_L	L18 PI_L	L17 PI_L	L16 PI_L
10/11/2022	7.89	14.83	11.81	14.78	6.39
11/11/2022	8.05	14.37	9.36	11.20	11.02
14/11/2022	11.61	13.04	11.21	14.40	10.57
15/11/2022	12.86	12.95	9.56	14.45	13.79
16/11/2022	12.03	15.30	10.02	14.13	8.59
17/11/2022	11.68	12.84	9.43	15.08	11.07
18/11/2022	12.22	15.08	11.74	12.69	11.84
21/11/2022	11.23	13.15	9.64	14.08	11.59
22/11/2022	9.87	12.58	12.77	12.82	10.27
23/11/2022	12.04	12.64	10.97	16.25	10.86
24/11/2022	12.30	11.72	12.35	12.97	10.51
25/11/2022	13.44	9.46	12.16	13.60	10.64
28/11/2022	12.76	11.33	13.52	13.32	10.13
29/11/2022	12.64	15.72	12.09	13.52	10.55
30/11/2022	14.43	16.49	11.83	15.27	11.10
01/12/2022	11.75	13.79	9.19	15.68	10.25
02/12/2022	14.57	18.03	12.23	15.18	11.87
05/12/2022	12.30	16.41	12.28	15.13	14.04
06/12/2022	11.99	17.06	13.40	18.36	11.06
07/12/2022	10.35	16.79	8.76	20.17	9.87
08/12/2022	11.30	14.42	11.00	16.26	10.63
09/12/2022	10.89	14.04	12.27	14.73	4.35

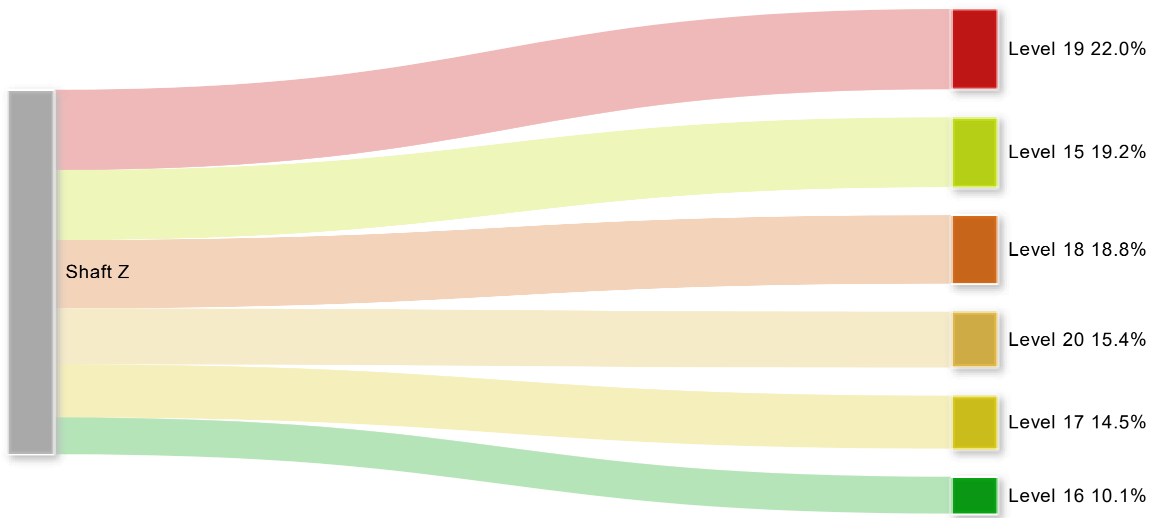
The corresponding pressure of the lowest PI per day on Mine Z is summarised in the table below.

Table F-2: Pressure at correspond lowest PI - Mine Z

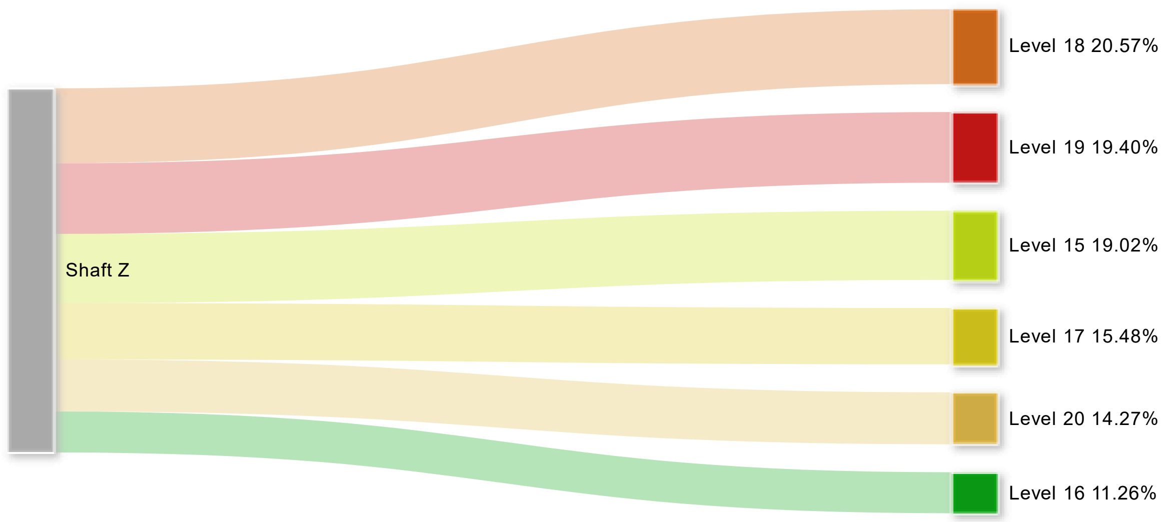
Date	L19 Pressure	L18 Pressure	L17 Pressure	L16 Pressure	L15 Pressure	L20 Pressure
10/11/2022	563.08	431.60	565.47	560.39	567.41	563.08
11/11/2022	551.16	365.55	387.96	478.85	524.47	384.18
14/11/2022	493.37	428.98	493.11	489.27	560.32	388.20
15/11/2022	491.62	369.76	484.44	481.03	515.44	386.05
16/11/2022	518.53	449.95	391.51	387.98	518.42	388.40
17/11/2022	489.46	370.52	501.67	384.63	500.70	383.21
18/11/2022	490.89	443.43	393.77	390.68	504.50	389.90

Date	L19 Pressure	L18 Pressure	L17 Pressure	L16 Pressure	L15 Pressure	L20 Pressure
21/11/2022	551.51	421.26	520.71	520.87	539.45	387.20
22/11/2022	549.62	418.88	373.33	387.35	543.89	511.27
23/11/2022	549.12	424.37	563.23	397.54	577.79	397.55
24/11/2022	566.79	420.37	553.18	548.89	567.19	481.73
25/11/2022	571.65	414.46	510.51	506.34	586.98	376.19
28/11/2022	491.45	435.95	501.27	497.30	567.54	394.71
29/11/2022	513.79	453.28	588.37	583.68	517.18	513.79
30/11/2022	511.82	435.26	469.76	504.10	540.21	378.16
01/12/2022	532.30	405.78	515.25	494.01	559.00	379.13
02/12/2022	558.89	427.98	549.96	555.27	547.41	378.06
05/12/2022	551.38	421.74	555.47	377.80	555.68	375.89
06/12/2022	502.45	342.02	369.55	463.62	539.33	468.08
07/12/2022	517.87	406.50	539.95	325.46	540.49	452.88
08/12/2022	518.40	378.75	377.76	376.17	522.57	374.57
09/12/2022	527.47	398.21	555.99	552.85	562.28	384.06
10/11/2022	531.24	408.66	541.34	355.04	564.00	389.81

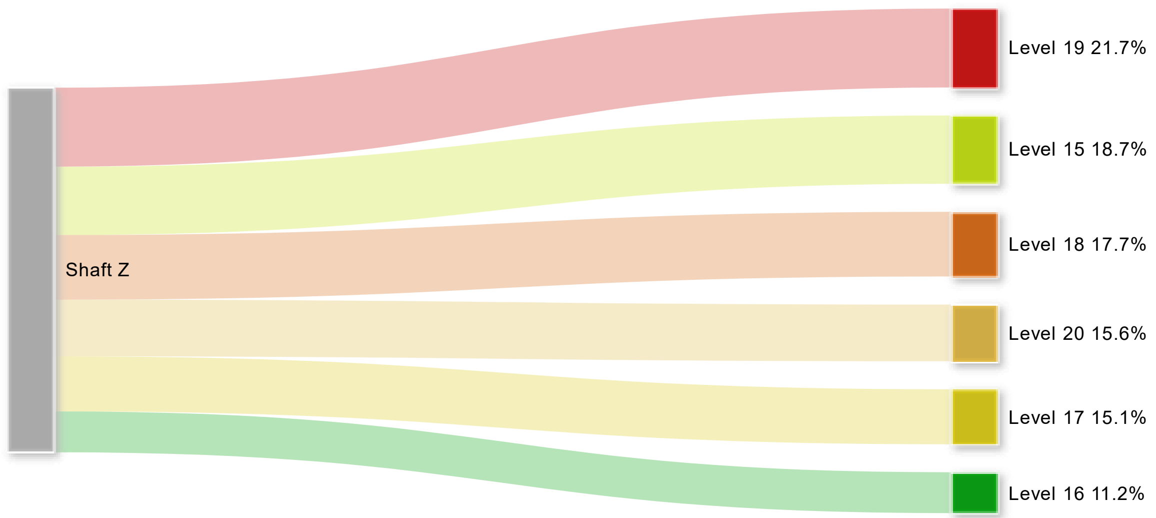
Mine Z, Sankey chart level distribution for 28-Nov-22 to 04-Dec-22:



Mine Z, Sankey chart level distribution for 14-Nov-22 to 20-Nov-22:



Mine Z, Sankey chart level distribution for 21-Nov-22 to 27-Nov-22:



List of active and inactive crosscuts on 19 Level, Mine Z, as per Table F-3.

Table F-3: List of active and inactive crosscuts on 19 Level - Mine Z

Half-level	Crosscut number	Active/Inactive
UN	123B	Active
UN	123A	Active
UN	122	Active
UN	121	Active
UN	120	Active
UN	119	Active
UN	118	Inactive
UN	117	Inactive

Half-level	Crosscut number	Active/Inactive
UN	117A	Inactive
UN	116	Inactive
UN	115	Inactive
US	114	Inactive
US	113	Inactive
US	112	Inactive
US	110	Inactive
US	109	Inactive
US	108	Inactive
US	107	Inactive
US	106	Active
US	106A	Active
US	105	Active
US	105A	Active

Full audit results of 19LUN, crosscut 123B, with photos of all the leaks identified during the audit.

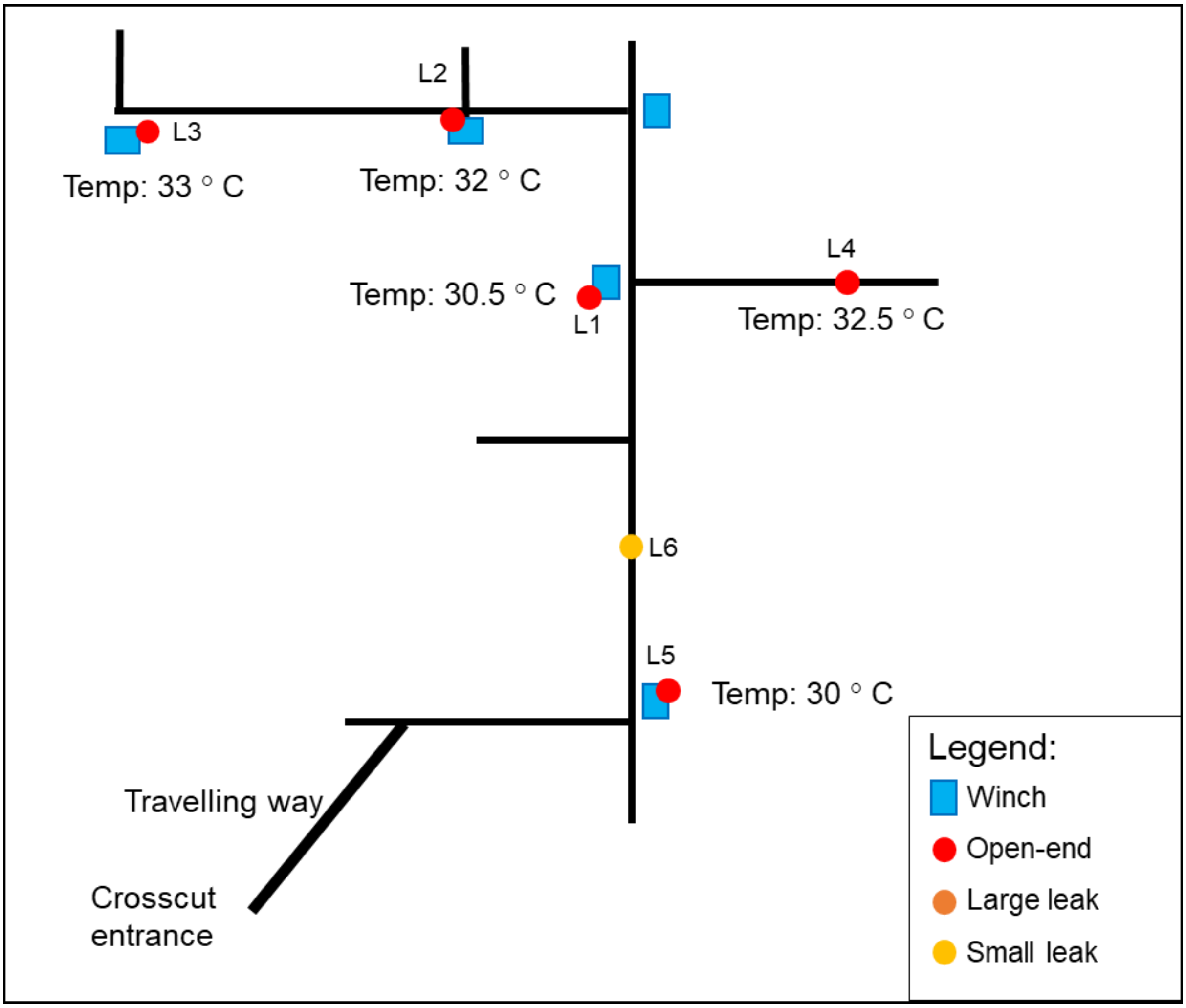


Figure F-1: 19L UN, crosscut 123B layout - Mine Z

Photos of corresponding leakages found in crosscut 123B:

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L4

L5

Crosscut 106A audit layout and photos

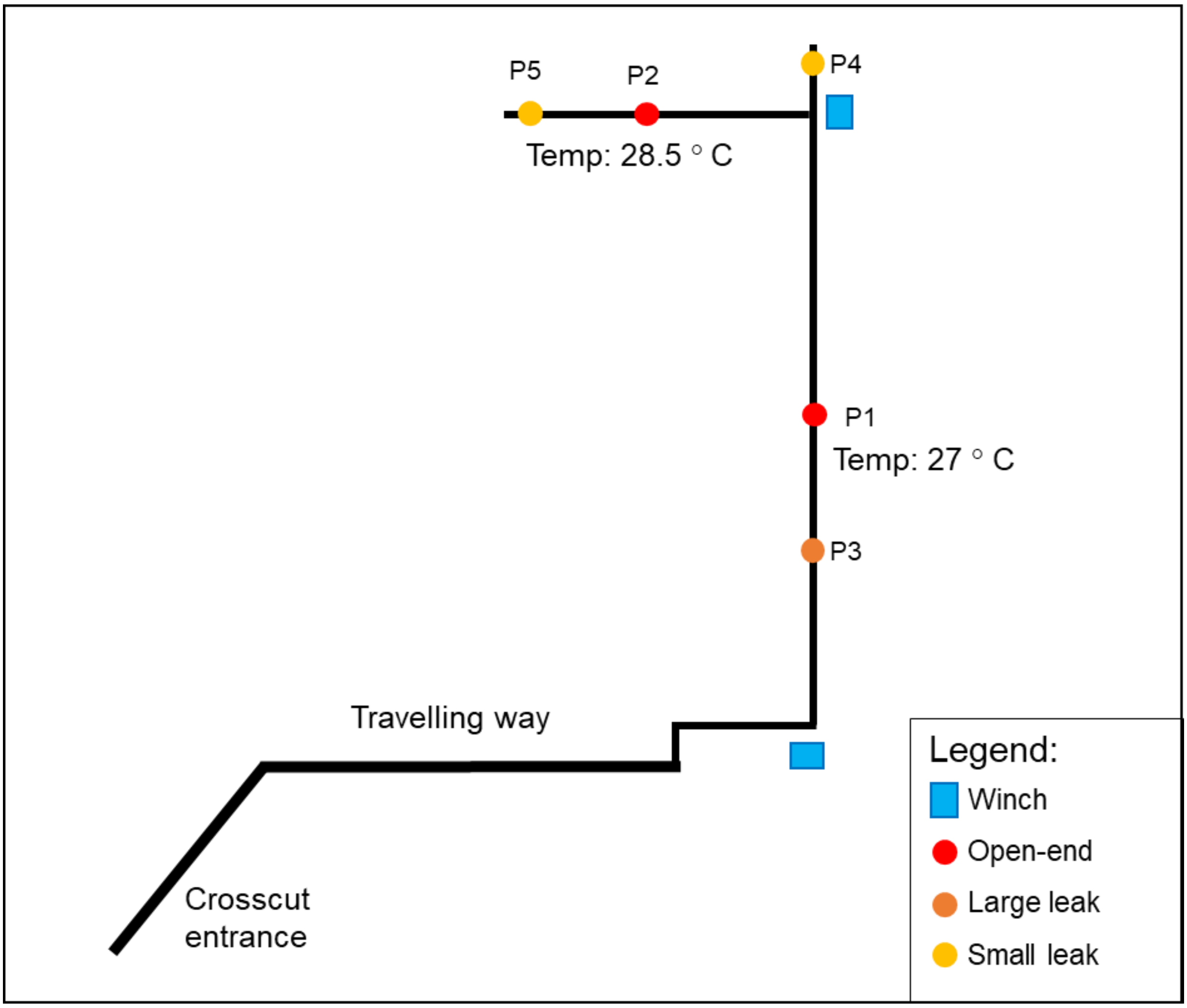

Figure F-2: 19L US, crosscut 106A layout - Mine Z

Photos of corresponding leakages found in crosscut 106A:

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P3

P4

P5

Appendix G Methodology summary

A brief summary of the methodology and whether each outcome was reached or not is depicted in the table below.

Table G-1: Methodology summary and outcome evaluation

Description	Outcome	Achieved	Discussion
Stage 1 – Data acquisition and verification	Different data (based on data availability) useable. Was the data collected, verified to minimise false information/results?	Yes	Incorporating data verification into the newly developed methodology ensures that the data is examined before proceeding with methodology. This stage assists in reducing redundant and inaccurate data, thereby increasing the accuracy of the data collected.
Stage 2 – Benchmark using new method 1	Validate operational baseload and verify if it is a suitable method to identify high CA wastage levels.	Yes	The operational baseload was verified and validated as a suitable method to identify high compressed air wastage levels. It was validated in case study 1.
Stage 2 – Benchmark using new method 2	Validate theoretical baseload and verify if it is a suitable method to identify high CA wastage levels.	Yes	Theoretical baseload identified the worst performing level(s) in case study 2, which verifies and validates this method as a suitable method to identify high CA wastage.
Stage 3 – Normalise results	Does the normalisation tailor the baseload results in Stage 3, to the level with the highest potential for ventilation shortfalls?	Yes	Case study 1 highlighted that the worst performing compressed air level did not have the highest compressed air usage per crew. The results highlighted that 24L (which could have been overlooked if only the highest compressed air consumption

Description	Outcome	Achieved	Discussion
			was investigated) had multiple ventilation shortfalls. This validates the normalisation.
Stage 4 – Crosscut baseload	Does the crosscut baseload narrow down the worst performing crosscut with the highest potential for ventilation shortfall on the worst performing level?	Yes	Crosscut baseload successfully narrowed down the worst performing crosscut with the highest possibility of ventilation shortfalls in both case studies. This thus validates the crosscut baseload.
Stage 5 – Crosscut audit	Did the crosscut ventilation audit identify ventilation shortfalls (based on the crosscuts highlighted in Stage 5)?	Yes	Multiple ventilation shortfalls were present in all of the worst performing crosscuts identified, confirming that the newly developed methods (benchmark methods, normalisation and crosscut baseload) within the newly developed methodology are suitable approaches to be used to successfully identify ventilation shortfalls.
Newly developed methodology	Did the new methodology successfully identify ventilation shortfalls in a less resource-intensive and time-consuming manner?	Yes	The methodology successfully narrowed down the worst performing level, followed by identifying the worst performing crosscut and successfully identifying the ventilation shortfalls within the crosscut. The total time taken to identify the ventilation shortfalls was much less compared with conventional methods. The number of resources required, compared

Description	Outcome	Achieved	Discussion
			with the control study was also less. This validates that the new methodology is a less resource- and time-consuming, and more versatile method to narrow down and identify ventilation shortfalls.