Improved ventilation control of an integrated deep-level gold mine using simulation

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the North-West University

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Graduation: April 2024

ABSTRACT

Title: Improved ventilation control of an integrated deep-level gold mine using simulation

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Keywords: Ventilation improvement, ventilation control, simulation, deep-level gold mine

The gold mining industry in South Africa has experienced a decline in productivity, primarily due to rising operational costs, including high electricity tariffs. In addition, ventilation and refrigeration systems, responsible for significant electricity usage in gold mines, contribute to operational inefficiencies, necessitating new initiatives to improve ventilation systems and reduce operational costs.

Simulation software enables accurate representation and understanding of complex deep-level ventilation systems, aiding in assessing airflow distribution and ventilation networks. In addition, such simulations facilitate the identification of energy-saving opportunities and the evaluation of their feasibility.

Integrated ventilation networks add new branches and ventilation control devices to an increasingly complex system, thus increasing the difficulty of managing the ventilation networks and creating the need for simulation software to evaluate the system.

Minimal literature was found on improving integrated ventilation networks using simulation software and ventilation control. Thus, this study aimed to develop, using existing research, and implement a new method to improve integrated deep-level gold mine ventilation systems using ventilation control methods and simulation software to reduce operational costs.

A four-phase method was developed from existing literature to improve integrated ventilation networks using simulation software and ventilation control methods in deep-level

gold mines. The phases are 1) system investigation, 2) simulation development, 3) strategy development, and 4) implementation and evaluation.

The proposed method was applied to improve the ventilation network of a gold mining complex consisting of three integrated shafts (A, B, and C). In the first case study, a simulation was developed to address a pending labour strike, requiring a reduction in ventilation electricity demand. Based on the simulation results, it was decided to switch off one surface fan on Shaft A and increase the frequency output of the remaining fans. This implementation lead to a demand reduction of 1.8 MW, resulting in cost savings of R 3.48 million over a three-month period.

In the second case study, it was identified that the fan cowling of surface fan two was broken, leading to increased frequency outputs across all fans to compensate for the reduced airflow. With the aid of the simulation, a lower-frequency output was chosen and implemented after the fan cowling was repaired. Consequently, the electricity demand decreased by 0.74 MW, leading to annual savings of R 7.16 million.

The findings highlighted the new method’s effectiveness in improving integrated ventilation networks and achieving substantial energy and cost savings in gold mines using ventilation control methods and simulation software. The study emphasised the significance of implementing energy-saving initiatives to reduce operational expenses in the gold mining industry while maintaining safe working conditions.

ACKNOWLEDGEMENTS

As the author, I would like to express my sincere gratitude to the following contributors that were critical to the success of this study:

- ETA Operations (Pty) Ltd for funding the project and supplying the data to complete this study.
- Dr Franco Jansen van Rensburg and Dr Johan Marais, my supervisors, for their input and guidance in completing this dissertation.
- My parents, Hein and Mariette Louw, for always believing in me and supporting me in my decisions.
- I would like to thank my colleagues who supported and motivated me throughout this venture. I am truly blessed and honoured to have had experienced this with all of you. I wish you the best of luck with the rest of your endeavours.

All information portrayed in this dissertation was done by acknowledging sources and referencing published work.

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NOMENCLATURE

Symbol	Unit	Description
A	m^2	Cross-sectional area
AP	kW	Air power
F	-	Correction factor
η	-	Fan efficiency
N	rpm	Fan speed
$\dot{m}$	kg/s	Mass flow
P_T	kPa	Total pressure
P_0	kPa	Barometric pressure
P_s	kPa	Static pressure
P_v	kPa	Dynamic pressure
P_ω	kW	Electrical power due to the fan shaft
Q	m^3/s	Volumetric flow
T	$°C$	Temperature
T_{DB}	$°C$	Dry-bulb temperature
T_{WB}	$°C$	Wet-bulb temperature
v	m/s	Velocity
$v_{adjusted}$	m/s	Adjusted velocity
$Error$ %	%	Percentage error
K	-	Number of total data points
k	-	Specific data point
A_k	-	Actual data point
S_k	-	Simulated data point

ABBREVIATIONS

3D	Three dimensional
DXF	Drawing eXchange Format
X/C	Crosscut
Eskom	Electricity supply commission
FOG	Fall of ground
GSC	Geographic coordinate system
KPI	Key performance indicators
MAE	Mean absolute error
PTB 3D	Process Toolbox
RAW	Return airway
SCADA	Supervisory Control and Data Acquisition Network
TOU	Time of use
VOD	Ventilation on demand
VRT	Virgin rock temperatures
VSD	Variable speed drive
VUMA	Ventilation of Underground Mine Atmospheres

Chapter 1: Introduction

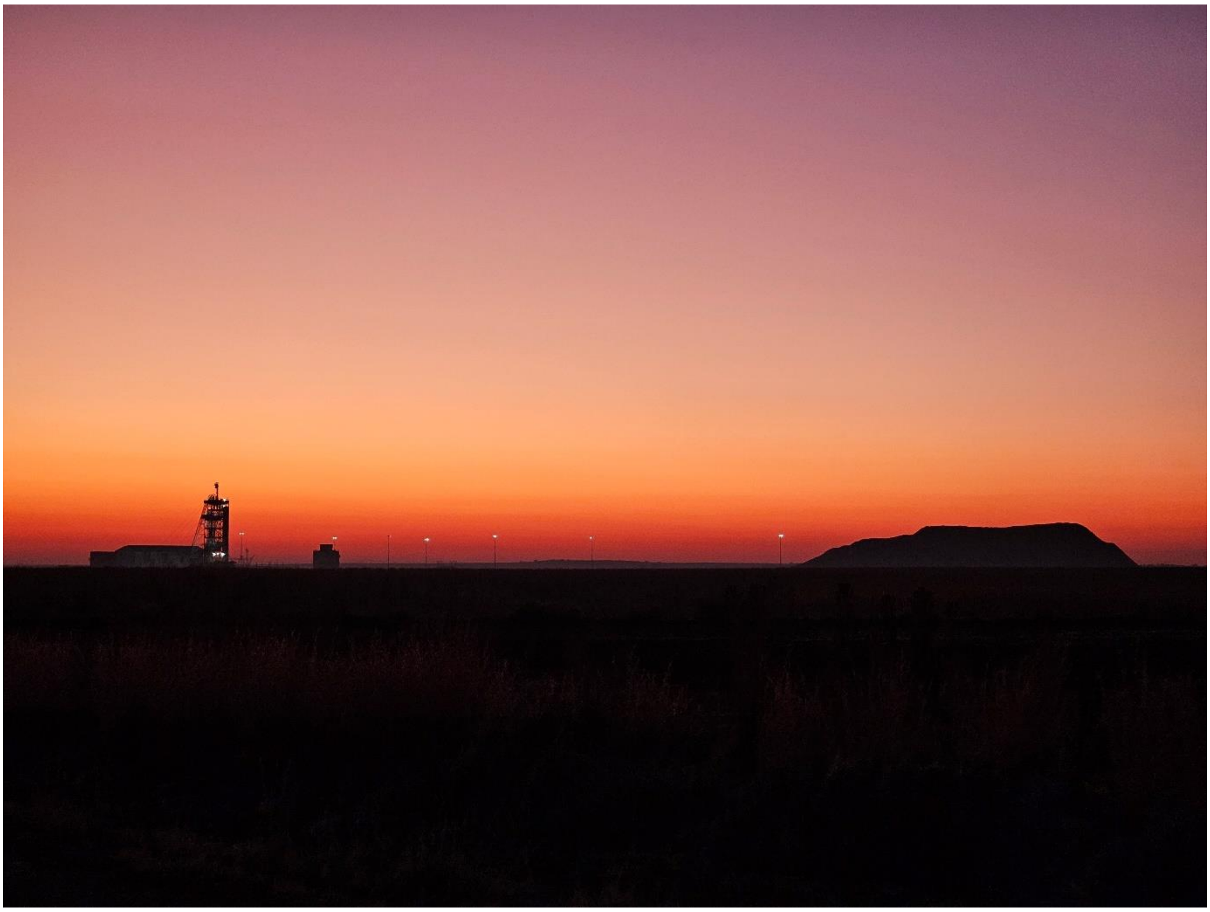


Figure: Typical South African mining complex[1]

"Success is not final; failure is not fatal: it is the courage to continue that counts." – Winston Churchill

[1] S Louw, Personal photograph, South Africa, 2023

1. INTRODUCTION

1.1. Preamble

The background for this study is discussed, followed by an introduction to mine ventilation systems. Next, a critical review of similar studies is presented where the shortcomings and contributions to this study are discussed. A state-of-the-art table is compiled from the literature review, and the need for the study is identified. The problem statement and objectives are derived from the need for the study and then discussed. The chapter concludes with a brief description of the outline of this document.

1.2. Background

Mining precious minerals, such as gold, is essential to human civilisation. Gold has had an economic impact on most ordinary people since ancient Egypt. It is estimated that over time, over 175 000 tonnes have been mined [1]. As technology changed over the years, the methods of extracting gold ore have drastically improved, making it dependent on electrical energy [2].

1.2.1. Gold mining in South Africa

Gold mining in South Africa has a long history of shaping the country and has been a driving force behind the development of the economy [3, 4]. South Africa is rich in natural minerals such as gold. Thus, the mining industry in South Africa has always been a backbone of the South African economy [3, 5].

Gold deposits in South Africa are mainly found in Gauteng, though gold mines can also be found in Limpopo, North-West and the Free State, as illustrated in Figure 1 [3]. The discovery of gold in an area attracts economic investment in local municipalities and the country. Towns and cities such as Johannesburg owe their development to the discovery of gold in the region [3, 6, 7]. Towns near large-scale mining operations are usually wholly dependent on the mines [7].

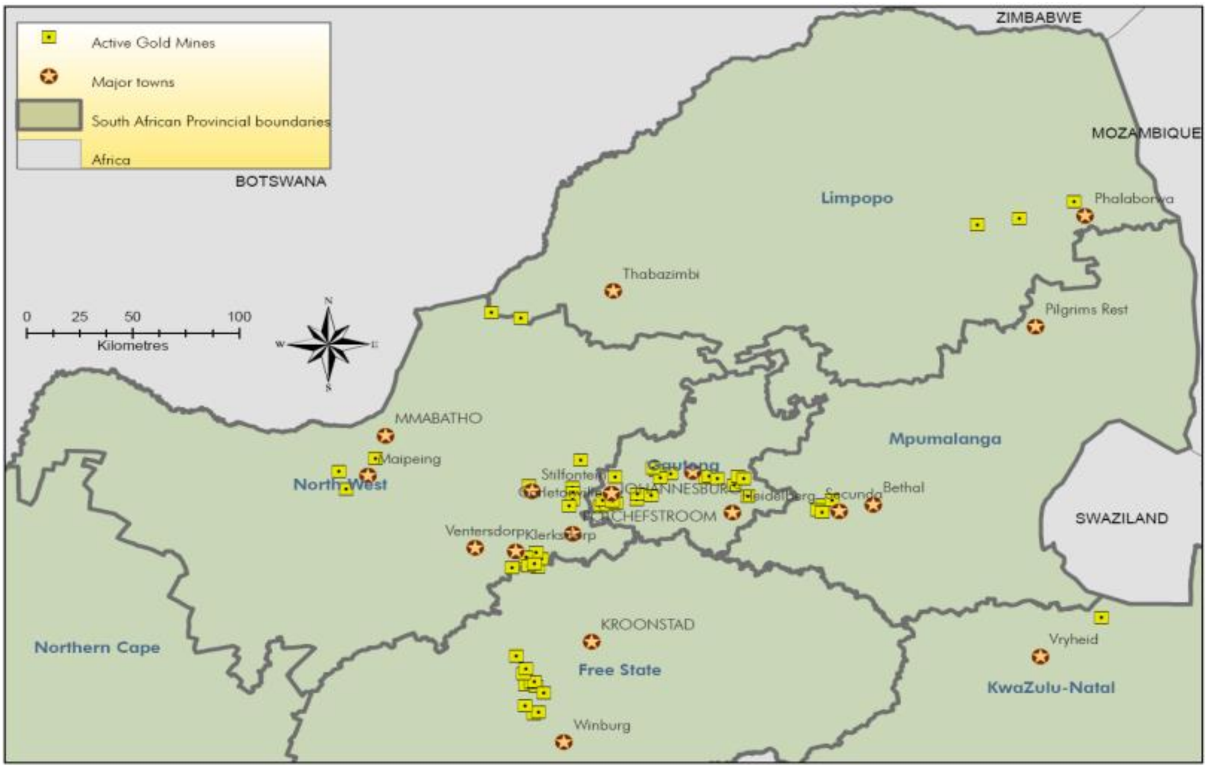


Figure 1: Active gold mine locations in South Africa [3]

Like most sectors, the mining sector depends on electricity for operation. Mining is the second largest electricity consumer in South Africa, with approximately 14.3 TWh, as illustrated in Figure 2 [8].

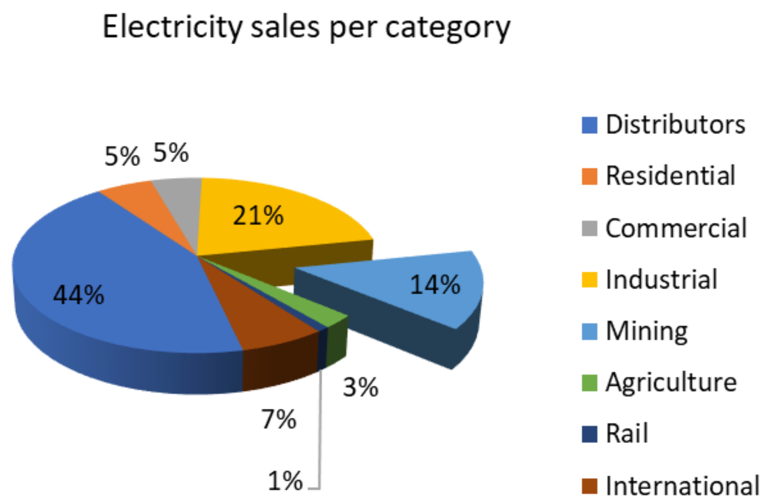


Figure 2: Top electricity consumers per category in South Africa [8]

South Africa has some of the world's deepest gold mines, with six out of the ten deepest mines in the world. The shallow ore reserves are being depleted, forcing mining industries to extract the ore at ever-increasing depths. Extracting ore at these depths are extremely difficult and thus increases the cost [9].

Due to the nature of gold mining, especially in the deep-level mines in South Africa, workers are exposed to harsh working conditions [10]. As a result, South Africa has some of the strictest labour laws, which affect the productivity and profitability of the mines [11]. According to Statistics South Africa, the number of gold mine employees was 101 993 in 2019. This corresponds to around 19.8% of the total employees employed by the mining industries [12].

South Africa dominated world gold production until 2007 when China became the largest producer. In 2021 South Africa was ranked tenth globally in gold production [13]. However, it is estimated that South Africa still has 6 000 tonnes of extractable ore, making it the largest verified ore deposit in the world [3].

The gold production trend for South Africa has seen a steady decline from 189 tonnes in 2010 to 96 tonnes in 2020, with a slight increase to 100 tonnes in 2021, as illustrated in Figure 3 [14]. The steady decline can be attributed to several reasons, which will be discussed later.

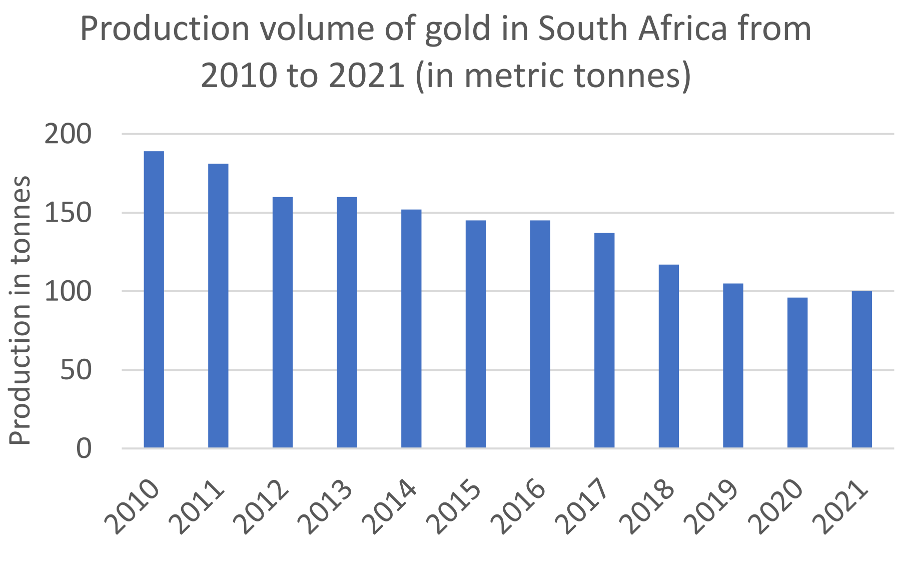


Figure 3: Gold production decline in South Africa [14]

Gold mining in South Africa has a unique history and remains vital to the country's mining industry. Unfortunately, gold industries in South Africa have been experiencing a steady decline in productivity over the last few years. Thus, now more than ever, it is crucial to find new innovative means to improve the profitability of gold mining.

1.2.2. Problems facing South African gold mines

As mentioned, the gold mining industry must improve its productivity and profitability to ensure its continuation in South Africa. Firstly, the problems facing gold mines in South Africa is investigated.

Deep-level mines

Extending gold mining operations to greater depths creates new challenges for mining engineers. These challenges can be summarised as safety, productivity, and profitability [15].

Mining at 3 000 m plus depths increases the risk of injuries. Risks include fall of ground, warm working conditions, and exposure to mining gasses, to name a few [9, 16]. Therefore, some procedures must be in place to ensure the safety of the miners working at these extreme depths [17]. These procedures must comply with the Mine Health and Safety Act of 1996 [18].

Productivity is affected in numerous ways due to depth. Much time is lost as the time needed for the workers and equipment to arrive at the working place and start mining is increased [19]. Constant maintenance is also needed on all the equipment used to ensure it is in working order, as underground conditions typically are not ideal for most equipment [19].

The operating cost of most large engineering systems, such as cooling, dewatering, ventilation, and winders, which are all crucial in the daily operation of gold mines, increases. The electrical energy demand increases as the systems need to overcome the challenges that come with operating at these depths, such as [20] :

- higher virgin rock temperatures (VRTs),
- an increase in fissure water (groundwater seeping into the mine),
- increased pumping distance (to pump water back to surface),

- increased distance for ore, equipment, and workers to be transported to the surface and working levels, and
- ventilation demand increase.

Labour law in the mining sector

Labour issues have plagued the mining industry in the last decade by protest actions bringing production to a standstill. The protest by the mine employees can quickly turn violent as not all employees usually participate [10]. Nevertheless, the mine tries to keep production going, as seen in recent strike actions in South Africa. These actions are mainly for increased wages and better living and working conditions [21].

Rising operation costs

The main contributors to rising operating costs are labour and electricity costs. Rising electricity cost in South Africa is severely impacting the mining industry, especially the gold mining industry, as up to 47% of total mining electricity usage is from the gold sector [22].

South Africa's electricity tariffs are of the highest in the world and, subsequently, cause one of the highest operational costs compared to similar operations elsewhere. The high electricity tariffs are due to the significant annual tariff increases by the power utility company, Electricity Supply Commission (Eskom) [21].

Electricity tariffs increased by 15.63% in 2021 compared to the annual consumer price inflation of 5.5% for the same year [22, 23]. The electricity tariff increase of 753% between 2007 and 2021 is more than five times greater than the total inflation increase for the same period, shown in Figure 4, due to mismanagement and increasing debt by Eskom, the producer of 95% of South Africa's electricity [24].

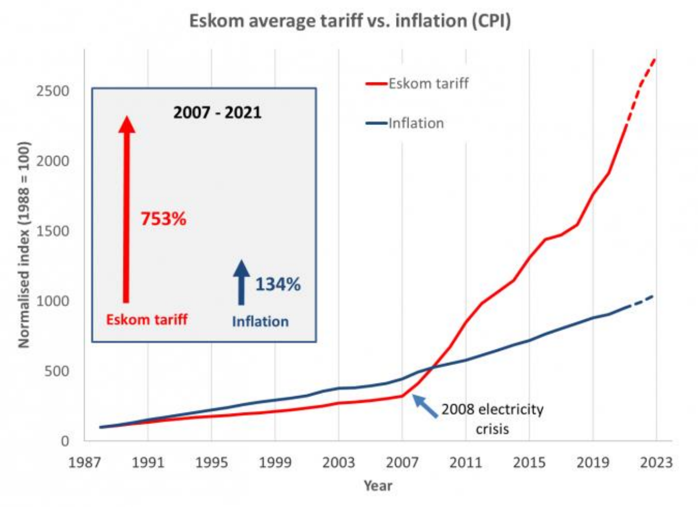


Figure 4: Average electricity tariff increase vs inflation increase in South Africa [24]

Further, the mega flex pricing initiative implemented by Eskom and used by most mining operations, consists of different electricity tariffs for various stages. The stages are determined due to the demand throughout the day and week, and use peak, standard and off-peak tariffs, with the peak being the highest tariff and off-peak the lowest tariff. The stages, also known as Time-of-Use (TOU), are illustrated in Figure 5 [8].

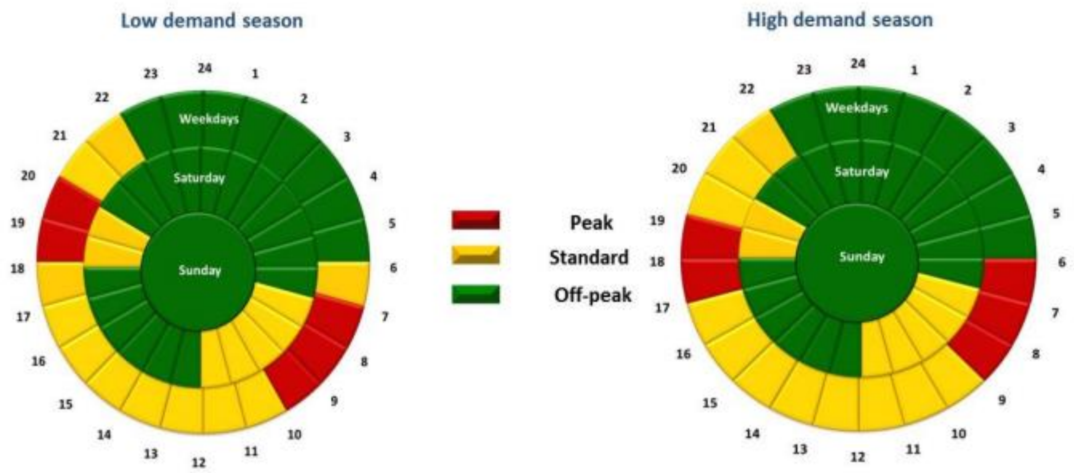


Figure 5: Eskom time-of-use stages [8]

As most South African gold mines were designed when Eskom was considered a cheap electricity producer, most mines did not consider electrical energy costs when they were designed. This further increases the operational costs as most equipment is energy inefficient

[25]. Nevertheless, it also creates the best opportunities to improve the mines to improve their profitability.

Gold mining in South Africa is in decline due to the increasing difficulty of obtaining high-grade ore and the rising operational costs [26]. The operational costs needed to extract gold must be decreased for the gold sector to flourish again in South Africa. Thus, it has become essential to find innovative ways to reduce the electricity demand in gold mines to reduce operating costs [21].

1.2.3. Energy-intensive gold mining sectors

Energy, mainly electrical energy, is the driving force in gold mining. Electrical energy contributes up to 90% of the total energy consumed by the gold mining industry in South Africa [27]. Other energy consumed may include diesel fuel, natural gas and coal.

Gold mining is an extensive operation consisting of numerous departments to operate. It can be summarised in three main categories, namely underground operations (all activities and services needed to extract the gold ore), metallurgical plants (everything needed to refine the gold ore), and business (offices, lighting, and hostels), all dependent on energy. Underground operations are the leading energy consumer, responsible for around 80% of the total energy consumed on a typical gold mine (Illustrated in Figure 6) [27].

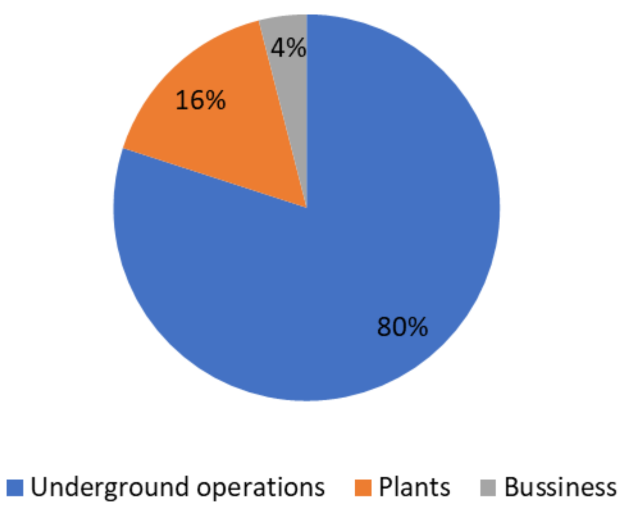


Figure 6: Energy distribution on a typical gold mine [27]

Primary engineering services for extracting gold ore include winding and loading, compressed air, pumping, ventilation, and refrigeration. These services are the primary consumers of electricity in the industry. Figure 7 shows the electricity distribution on a typical gold mine [28].

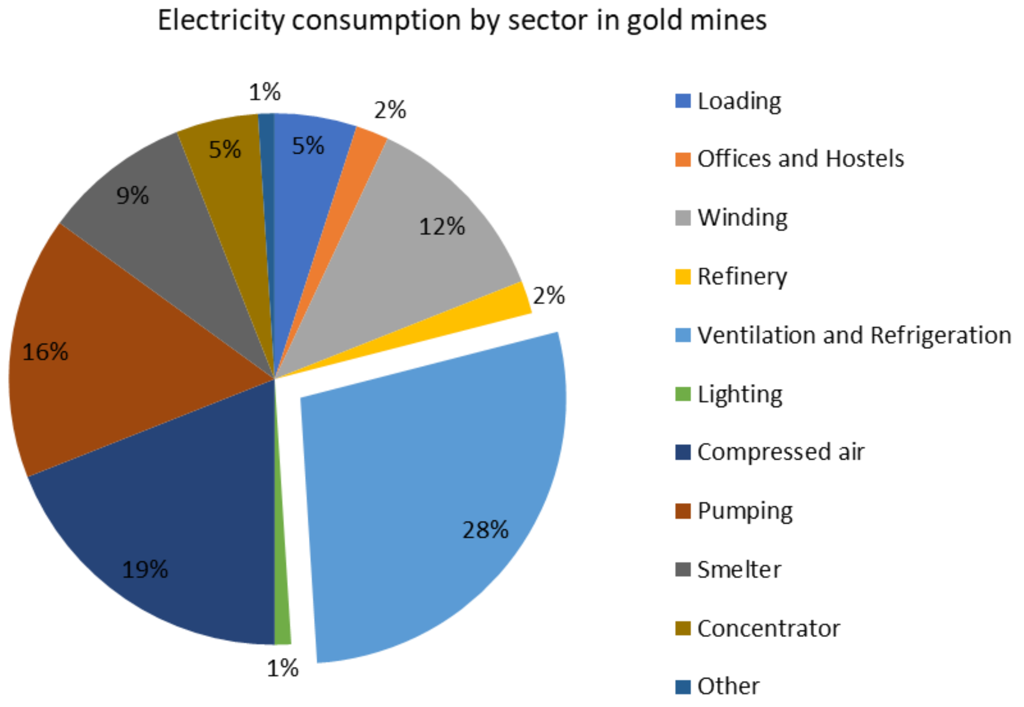


Figure 7: Benchmarked electricity distribution of South African gold mines [28]

As shown in Figure 7, ventilation and refrigeration systems use up to 28% of the total electricity of a typical deep-level gold mine [28]. In addition, ventilation networks are inefficient due to the system's management, the complexity of the system, and the dynamic and integrated nature thereof [29, 30]. Therefore, a large scope exists for initiatives to improve and reduce operation costs on gold mine ventilation systems [31–37].

1.3. Ventilation systems

Ventilation systems are essential to mining operations as they supply fresh air to the working areas and dilute fumes and toxic gasses [38, 39]. Harmful gasses such as methane has to be diluted to protect the workers from explosions and fires [40, 41]. The primary goal of a ventilation system is to supply air to ensure safe working conditions for the miners [42–44].

To ensure the safety of the workers, ventilation conditions and limits have been set [45]. Ventilation regulations given by the Mine Health and Safety Act of South Africa are listed in Table 1 [30, 32, 33, 46, 47].

Table 1: Ventilation regulations [30, 32, 33, 46, 47]

Parameter	Standards
Wet-bulb temperature	≤ 32.5 $°C$
Dry-bulb temperature	≤ 37 $°C$
Pollutants in air	≤1 mg/m^3
Working area air velocities	0.5−1 m/s
Developing area air velocities	0.3−0.5 $m/s\ per\ m^2\ of\ face$

Mining operations cease where the regulations stipulated in Table 1 are not met. Thus, mines use different ventilation control components to ensure the required air reaches the working areas.

1.3.1. Typical mine ventilation networks

Ventilation networks consist of energy-intensive surface fans that create a suction pressure on the surface, inducing airflow down the downcast shaft and allowing fresh air to be supplied to various working places [48]. Finally, the surface fans extract the air through the upcast shaft [49]. A simplified ventilation network is shown in Figure 8 [30].

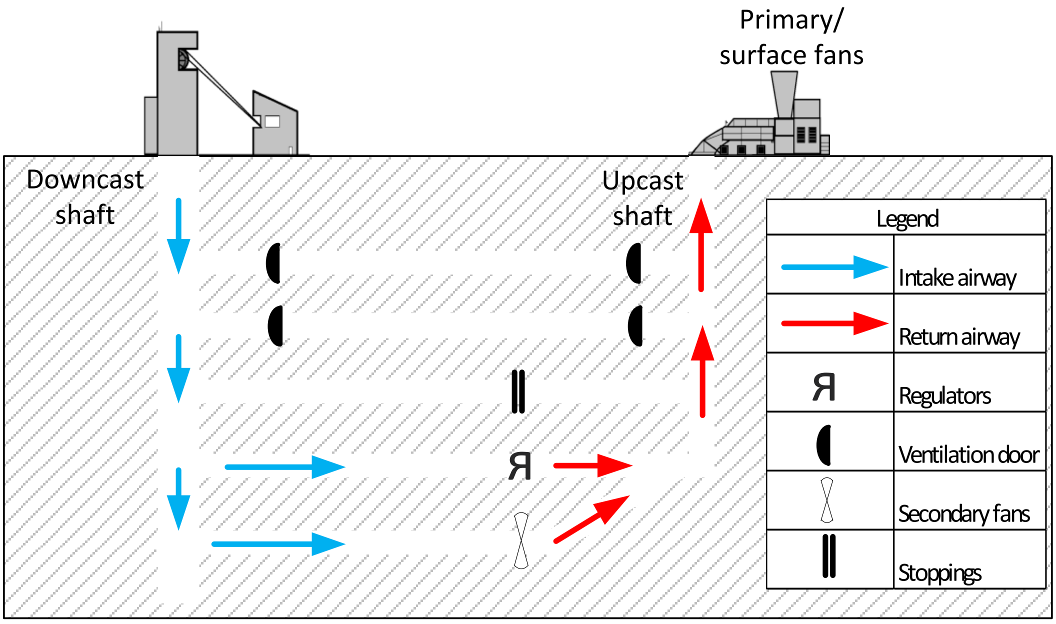


Figure 8: Simplified ventilation network [30]

A typical ventilation network, shown in Figure 8, consists of a complex system of airways and branches. All ventilation networks are ventilated by manipulating the airflow through numerous ventilation components [19]. Ventilation networks in mines are developed for specific mine areas and conditions [50]. As the mine progresses, new sections must be opened, and old sections closed, all while maintaining safe working conditions, making managing these networks extremely difficult [51]. Due to mismanagement, complexity, and the dynamic and integrated nature of deep-level ventilation systems, most systems are inefficient [29, 30].

Ventilation components

Air will always follow the path with the least resistance; thus, ventilation systems have different components to overcome the flow resistance and manipulate the airflow [52]. Some of these components are listed and described in Table 2 [53, 54].

Table 2: Description of mine ventilation components [53, 54]

Component	Description
Primary or surface fans	Primary fans are the driving force behind the entire ventilation network. Primary fans are placed on the surface, extracting all the air through the mine by creating a significant pressure difference to overcome the resistance.
Booster fans	Booster fans are used with the primary fans to assist if the system resistance is too great for the surface fans.
Auxiliary fans	Auxiliary fans ventilate certain areas underground like development ends and stopes.
Ventilation doors	Ventilation doors prevent air from flowing to certain areas by creating an airlock. Usually found in places with significant pressure differences. Ventilation doors can be opened to transport equipment and workers to pass through.
Stoppings	Stoppings or seals can be classified into two categories: permanent and temporary. Permanent stoppings, usually concrete block walls, stop airflow into specific areas. Temporary stoppings have the same purpose but are typically easy to disassemble.
Regulators	Opening or hole in a stopping, regulating the quantity of air flowing through.
Brattices	Conveyor belts and strips are hung in travelling ways and centre gullies to ensure the working face is ventilated, allowing workers to travel unhindered.

It is essential to understand the purpose of each ventilation component and how it works when analysing ventilation systems. These components can work separately or combined to achieve the goal.

1.3.2. Primary fans

The main surface or primary fans are the main ventilation component that supplies the mine with fresh air [55]. Fans are mechanical devices used to generate a movement of air by inducing a pressure difference [56]. Usually, the primary fans extract all the air flowing through the ventilation system, making it the most energy-intensive ventilation component. Electric motors drive primary fans as a rule, but internal combustion engines can be used in emergencies [57].

Mining engineers usually take excellent care with designing the primary fan assemblage. The location, configuration and type of fans substantially impact the system's total performance [58]. Primary fans can be found underground, but due to accessibility for maintenance and emergencies, it is usually installed on the surface. Similarly, primary fans can be installed on the downcast (intake) airshaft, the upcast (return) airshaft or both, with the installation only on the upcast shaft being the most common. Thus, primary fans are mainly installed on the upcast airshaft, but can differ due to the location and requirements of the mine [59].

Primary fans usually consist of two or three fans working together in parallel, in series, or a combination. The parallel configuration increases the airflow without increasing the system pressure, and fans connected in series increase the pressure without significantly influencing the airflow. Depending on the mine requirements, any of these configurations can be used [57, 59].

The types of primary fans consist typically of axial fans, centrifugal fans, or a combination, usually an emergency fan, depending on the needs of the ventilation network [55]. The main performance difference being that axial fans deliver higher flow rates at lower pressures, while centrifugal fans deliver large air quantities at high pressures [60].

Fan performance

The characteristics listed below must be assessed to evaluate the performance of a fan in a ventilation system [59].

- Static or total pressure
- Power
- Volumetric flow

Other characteristics that could influence the fan performance:

- System resistance
- Guide vane angle
- Operating speed
- Efficiency

As the total air extracted by the fan is the primary goal, the characteristics will be assessed concerning the total volumetric flow (Q) extracted by the fan [59].

Static or total pressure

Static pressure (P_s) is pressure in the system regardless of air movement, like ambient pressure, and is used to determine the pressure drop between two points. The dynamic pressure (P_v) is the pressure in the system due to the movement of air. Total pressure (P_T) of the system is the sum of the static and dynamic pressure, as shown in Equation (1) [60].

$$P_T = P_s + P_v \tag{1}$$

System resistance

Due to friction, many factors such as wall roughness of the haulage, impeding structures and fall of ground (FOG) influence airflow resistance in a ventilation network [60, 61]. Higher resistance increases the static pressure and lowers the volume flow. Conversely, lower resistance decreases static pressure and increases airflow [62].

Power

The output power of the fan, or airpower (AP), is defined as the product between the volumetric flow (Q) and air pressure (P_T), illustrated in Equation (2) [60]:

$$AP = P_T \cdot Q \tag{2}$$

Electrical power, or shaft power (P_ω), is the total electric power consumed to drive the fan. Air power and shaft power are used to determine the total efficiency of the mine ventilation system and is a crucial characteristic in evaluating the performance of the fans [63].

Guide vane angle

Guide vanes are stationary blades usually installed on a fan's inlet and are used to deliver a pre-swirl to the air, which lowers the static pressure and airflow and ultimately reduces the electrical power [64, 65].

Operating speed

The fan's operating speed can be changed using a Variable Speed Drive (VSD) [66]. By controlling the frequency supplied to the electric motor, the fan's operating speed is changed [32]. Fan Laws or Affinity laws enable us to understand the effects of changing the operating speeds on the system's flow rate, pressure, and power. The laws are given below in Equations (3), (4) and (5) [32, 36, 66].

Flow rate (Q):

$$Q = Q_0 \frac{N}{N_0} \tag{3}$$

Pressure (P):

$$P = \left(P_0 \frac{N}{N_0}\right)^2 \tag{4}$$

Power (P_w):

$$P_{\omega} = \left(P_{\omega_0}\frac{N}{N_0}\right)^3 \tag{5}$$

Figure 9 illustrates the characteristic changes in the operating point by lowering the fan speed from 1 000 RPM to 250 RPM [32]. The fan speed (N) changes from N_0 = 1000 RPM to N = 250 RPM.

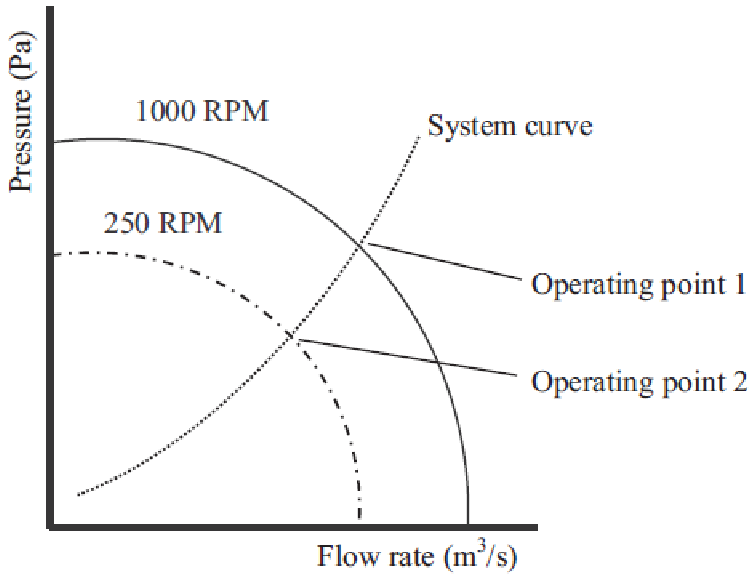


Figure 9: Fan curve at different operational speeds [32]

Literature provides evidence that using VSDs to reduce energy costs by lowering the operational speeds of the fans has proven effective, as illustrated in Figure 10 [67, 68]. Lowering the volumetric flow can result in decreasing energy losses in the system [69].

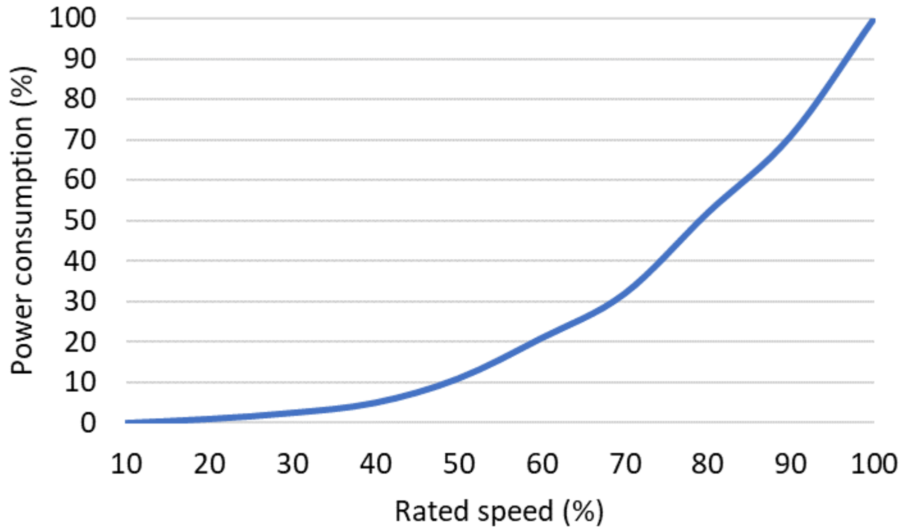


Figure 10: Impact of VSDs on power consumption of a motor [67]

Efficiency

The overall efficiency of the fan is an essential characteristic used to evaluate the system's performance [38]. Overall efficiency (η) is calculated by dividing air power (AP) by electrical power P_ω, illustrated in Equation (6) [38]. The energy-saving initiatives can be evaluated by comparing the air power and electrical power.

$$\eta = \frac{AP}{P_\omega} \tag{6}$$

A fan curve can characterise the performance indicators of an individual fan as described above [38]. A typical fan curve illustrates the relationship between the fan's characteristics and can be obtained by the fan supplier. Some parameters must be measured to determine the remaining characteristics of the fan curve. These measurements form part of the ventilation surveys and are discussed in the following section. The parameters needed are listed below:

- Static pressure in the fan (P_s) $[kPa]$
- Volumetric flow through the fan (Q) [m^3/s]

1.3.3. Ventilation surveys

A ventilation survey is a method to obtain data to establish the temperature, air quality, air quantity and pressure within a ventilation network [43]. Due to the dynamic nature of the systems, surveys must be done regularly to ensure that [19, 70]

- working areas are sufficiently ventilated,
- ventilation records are up to date, and
- air quantity and distribution through the mine are verified.

Surveys are also used in developing and verifying ventilation simulations, as numerous data points are needed to calibrate such a simulation. In addition, by conducting regular surveys, the ventilation personnel better understand the system's performance [19].

The required data gathered and the quality depend on the survey's reason, but primarily consist of the parameters listed in Table 3 [30].

Table 3: Ventilation survey measuring inputs [30]

Parameter	Unit
T_{DB} (Dry-bulb temperature)	$°C$
T_{WB} (Wet-bulb temperature)	$°C$
P_0 (Barometric pressure)	kPa
v (Airflow velocity)	m/s
A (Cross-sectional area)	m^2

The data gathered in Table 3 are needed to derive the performance of the ventilation network at the measuring point in the network. Multiple measurements must be taken at distinct locations to characterise the entire ventilation network. Before conducting a ventilation survey, the measurement locations must be determined. This is done by understanding the current air distribution and identifying key locations using existing data [19].

The instrumentation needed and the ventilation survey methods are described in Appendix A. Ventilation surveys are an excellent method to characterise the ventilation networks and identify potential energy-saving initiatives [29]. However, studies have shown that simulation software can assist in managing and improving ventilation networks [49, 71].

1.4. Ventilation simulation

Due to their complexity and ever-changing nature, deep-level ventilation systems are difficult to manage and design [72]. Mine ventilation simulations are designed to predict airflow distribution through the system accurately [73]. Therefore, simulation software is best suited to process the vast amounts of data obtained in large ventilation networks [71].

Studies show that mine ventilation simulations proved helpful in design, management, and improvement of ventilation networks [74]. Simulations are designed to represent the ventilation network accurately and can assist in identifying inefficiencies in the network. In addition, the same simulation can be altered to evaluate possible operational changes without capital expenditure and implementation [75].

Simulation software significantly eases the management and future planning of underground ventilation networks for ventilation engineers. In addition, since it eliminates the need for tedious and time-consuming hand calculations, larger, more complex systems can be solved using computing technologies [49].

The following ventilation simulation software are available and will be compared in order to choose the software best suited for this study:

- Ventsim
- VUMA
- PTB 3D
- Environ

VentSim

VentSim was designed primarily to simulate complex three-dimensional (3D) ventilation models. Drawing eXchange Format (DXF) mine layouts can be imported to represent the system accurately and simulate changes made to the ventilation network. The software can accommodate different systems, such as auxiliary ventilation systems. However, it struggles to accurately simulate complicated networks [30]. In addition, simulations of different services cannot be integrated [76].

Ventilation of Underground Mine Atmospheres (VUMA)

VUMA simulates underground ventilation and refrigeration systems and is widely used in mining [77]. The software simultaneously simulates the thermodynamic behaviour of the underground ventilation system's gas, dust emissions and airflow [78]. However, a substantial amount of input data is needed to deliver accurate simulation, and experienced personnel is needed to operate the software [79].

Process Toolbox (PTB 3D)

PTB is a thermal-hydraulic dynamic simulation software capable of simultaneously simulating multiple mine operations and services [80]. In addition, the software allows importing mining DXF layouts, and the three-dimensional interface gives the user an accurate representation of the simulation model [72].

The software has various capabilities, including the optimal operation of equipment, and can determine the total electrical demand of the equipment. In addition, PTB simulations are used to optimise, analyse, design, and accurately represent different mining systems. Assorted studies prove the accuracy of the simulations. However, a substantial amount of input data is required [81, 82].

Environ

Environ is used to simulate, design and solve ventilation problems of mine ventilation networks [79]. However, the software is not dynamic and can only simulate ventilation networks. Nevertheless, Environ is widely used in the mining industry, focusing on designing networks [83].

Comparison of software

The advantages and disadvantages of the different simulation software are listed in TB ## below.

Table 4: Comparison of simulation software

Simulation software	**Advantages**	**Disadvantages**
VentSim	• Auxiliary systems can be simulated. • Changes to the ventilation network can be simulated.	• Difficult to accurately simulate complicated networks.
VUMA	• Thermodynamic behaviour of the underground ventilation system's gas, dust emissions and airflow can be simulated. • Accurate simulations.	• Requires large amount of data to reach accurate results. • Experienced personnel is needed to operate the software.
PTB 3D	• Capable of simultaneously simulating multiple mine operations and services. • Cost savings can be calculated. • Accurate	• Requires large amount of data to reach accurate results.
Environ	• Auxiliary systems can be simulated. • Changes to the ventilation network can be simulated.	• Not dynamic and can only simulate ventilation networks

Accuracy of simulations

To determine the accuracy of the simulation, the simulation baseline should be compared to the actual measured values at various preselected points. Studies suggest that the mean absolute error (MAE) is one of the most effective methods of determining the accuracy of the entire ventilation simulation [38, 49, 71]. The MAE can be calculated using Equation (7) [38, 49].

$$Error\ \% = \frac{1}{K}\sum_{k=1}^{K}\left|\frac{A_k - S_k}{A_k}\right|(100\%) \qquad (7)$$

Where:

Error % = Percentage error [%]

K = number of total data points

k = Specific data point

A_k = Actual data point

S_k = Simulated data point

Conclusion on ventilation simulation

Due to the complexity and sheer size of ventilation systems, many data points and variables must be considered. Therefore, simulation technology has become increasingly essential for ventilation engineers to manage, design, and accurately represent an underground ventilation network.

Simulation software makes it possible to represent complex deep-level ventilation systems accurately. In addition, ventilation simulations give a better visual representation and understanding of the airflow distribution and ventilation network. Accordingly, ventilation simulations can identify potential energy-saving initiatives and evaluate whether initiatives are feasible to implement.

1.5. Mining complexes with integrated ventilation networks

Most South African gold mines, as illustrated in Figure 1, are centralised around a few locations in the country [3]. Thus, mines are usually near each other, and it is typical for a few mining complexes, especially those belonging to the same mining company, to be connected underground [38]. The ventilation networks of these separate complexes are thus integrated, and any significant changes made to one system will affect the other. Figure 11 illustrates a simplified representation of an integrated ventilation network in South Africa [49].

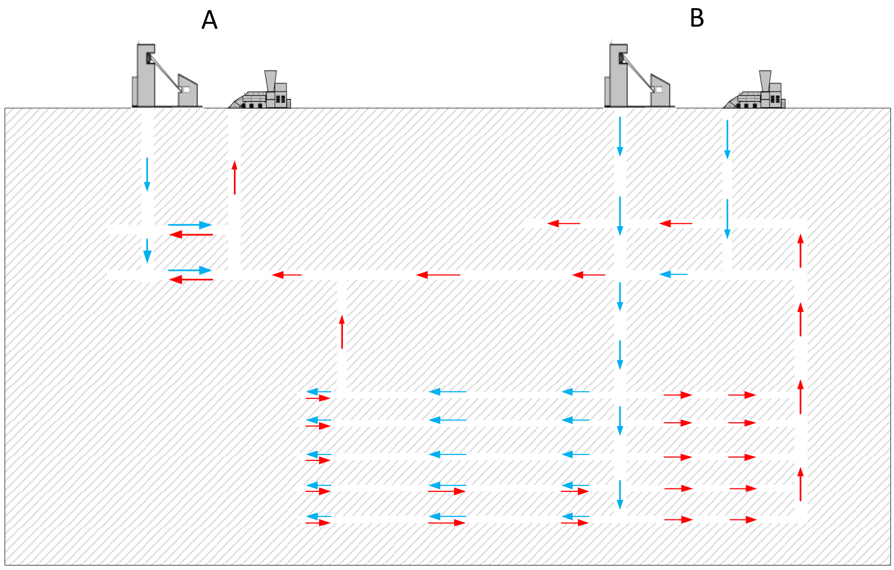


Figure 11: Adapted integrated mining complexes [38]

Integrated ventilation networks add new branches and equipment to a complex system. This increases the difficulty of managing the ventilation networks and emphasises the need for simulation software to evaluate the system [29, 49].

1.6. Methods of improving ventilation networks

Studies show numerous methods of improving ventilation networks. The methods can be summarised as

- reducing the system resistance,
- reducing air losses in the system,
- improving the main fan configuration, and
- airflow control strategies.

Reducing the system resistance and pressure losses

Eliminating pressure losses in the system as far as possible will reduce power the fan needs to overcome the system resistance [84, 85]. Eliminating pressure losses is done by removing or minimising any restriction of airflow, such as by [86]:

- clearing fall of ground,
- removing any unnecessary obstacles,

- avoiding any sudden changes in the airway area,
- avoiding any sudden changes in the airflow direction,
- avoiding using regulators as far as possible, and
- improving the roughness of the airway to reduce the friction factor.

Reduce air losses in the system

Comparing the cost of ventilation system equipment and the amount of air reaching the required areas is another way to evaluate the system's efficiency. Reducing air losses in the system can improve the overall efficiency of the ventilation system [87]. Air losses are minimised by improving flow control. Methods to improve flow control include [57]:

- splitting air flows to improve airflow, and
- improving the use of ventilation control components.

Improving the main fan configuration

The primary fans are responsible for all the airflow through the system, and improving the configuration will drastically improve the system's efficiency [88]. Some improvements of the primary fans include [60]:

- a new fan blade design,
- improved fan ducting, and
- proper fan selection and configuration according to the requirements of the mine.

Improving the surface fan configuration is usually an extensive capital procedure, and proper investigations should be done before implementing the methods [60].

Airflow control strategies

Implementing flow control strategies improves the power used by the primary fans. Information regarding methods used to control the flow are discussed in the subsections of section 1.3.2 that deals with guide vane angle and operating speed [60]."

Control of the operating speeds using VSDs and the guide vane angles improves the system's overall efficiency [89]. However, it also introduces new philosophies that can be used. These philosophies include ventilation on demand (VOD), time-of-use, and peak-clipping strategies. The strategies require airflow control according to a schedule. The schedule will differ between the strategies but will further reduce the operating cost of the mine [32].

VOD

Ventilation on demand is used to distribute air to specific areas according to the current demand, or to the ventilation network according to the demand at a specific time [90, 91].

TOU

Schedule based on Eskom's time-of-use tariffs. TOU reduces demand during the peak tariffs to reduce electricity costs [32]. Peak-clipping and load-shifting are control philosophies based on TOU. Where peak-clipping reduces the demand in peak periods, and load-shifting shifts the demand from peak periods to off-peak or standard periods [32].

1.6.1. Conclusion on ventilation systems

The ventilation network of a gold mine is an energy-intensive system. Managing mine ventilation systems can be extremely difficult due to the network's integrated nature and complexity. The complexity is increased by multiple integrated shafts as more branches and flow control equipment need to be evaluated. Simulation software can evaluate, identify problems, and improve ventilation networks. Air flow control can increase the ventilation networks' overall efficiency and reduce the mine's operational costs.

1.7. Improving ventilation networks to reduce operational cost

1.7.1. Review of previous studies

Relevant studies focusing on optimising mine ventilation systems with the aim of electricity cost reduction were investigated. Twenty-four studies were identified that focused on improving mining ventilation networks. The aim of the researched studies, their contribution to this study, and the shortcomings of these relevant studies are summarised below.

Study 1: The Use of 3D Simulation System in Mine Ventilation Management [75]

Wei et al. [75] used 3D simulation software to evaluate the effects of ventilation network optimisation in a coal mine. By using VentSim, it was established that the network experienced significant system resistance in specific working areas. Different solutions to lower the underground resistance were simulated to determine the most feasible solution before implementation. However, the study focused on coal mines and VentSim was used. The study proved that simulation software can be used to improve ventilation networks. The use of simulation software to identify problems and evaluate proposed ventilation network changes to be made could be implemented in the current study.

Study 2: Heat Treatment and Ventilation Optimisation in a Deep Mine [92]

Nie *et al*. [92] focused on reducing high underground temperatures and damages caused by elevated temperatures by optimising the ventilation and refrigeration systems. The ventilation network was optimised by clearing critical airways. However, the operating cost was lowered, and the study focused on improving the air delivered to the working areas. To maintain the working conditions, the methods used to reduce the system resistance could be used in this study. Simulation software could identify problem areas and develop solutions to reduce the resistance, especially in an integrated ventilation network.

Study 3: The integration of mine simulation and ventilation simulation to develop a 'Life Cycle' mine ventilation system [71]

Kocsis *et al*. [71] focused on integrating underground mine and ventilation simulations to determine the "life cycle" of the mine. The use of mine and ventilation simulations to determine the best solution for ventilation on demand may further be investigated in future studies. However, the study was purely theoretical and was not implemented on an industrial scale.

Study 4: Optimisation of mine ventilation fan speeds according to ventilation on demand and time-of-use tariff [32]

Chatterjee *et al*. [32] focused on optimising fan speeds according to TOU and VOD. Mathematical models were built to determine the optimal fan speed for dynamic ventilation system control. No simulation was used to verify and manage the ventilation network.

Study 5: Methods to improve mine ventilation system efficiency [29]

Pritchard [29] evaluated different methods to improve ventilation networks. These methods included:

- VOD,
- utilisation of Return airways (RAW),
- use of booster fans,
- day-to-day examinations, and
- replacement of fan blades.

These methods can be considered as methods to improve the ventilation system. However, no simulation software was used to evaluate the effects of the different methods. Simulation software will help evaluate complex problems such as multiple integrated shaft ventilation networks.

Study 6: Reducing electrical costs for a mine ventilation system with the aid of simulation software [93]

Smit [93] used simulation software to evaluate the effects of implementing a TOU strategy on auxiliary fans in a platinum mine. The fan operating speed control could be implemented on a main surface fan. Simulation software can evaluate the operational change, which is essential in a complex integrated ventilation network.

Study 7: Optimising the operation of underground mine refrigeration plants and ventilation fans for minimum electricity cost [33]

The study by Chatterjee *et al. [33]* aimed to determine an optimum working point for a ventilation network by developing a simulation and optimisation model. VOD was used as the method to improve the ventilation network. A mathematical model simulation was developed to evaluate the changes. This could be challenging when considering a more complex system. The use of VSDs to improve the network could be implemented in the current study.

Study 8: Research on reducing costs of underground ventilation networks in South African mines [31]

The study's objective, by Kukard [31], was to develop a control method for the primary fans to reduce energy costs while maintaining underground conditions. Implementing a control method on the primary fan could be used in the current study. However, simulation software can evaluate the operational changes to the underground network and the working conditions.

Study 9: An integrated approach towards the optimisation of ventilation, air cooling and pumping requirements for hot mines [94]

Webber-Youngman [94] used an integrated approach towards optimising ventilation for underground mines. Simulations were used to predict the changes in the ventilation network by dynamically controlling the operating speeds of the surface fans. However, the study did not focus on an integrated ventilation system with multiple shafts.

Study 10: Analysis of Mine Ventilation Systems Using Operations Research Methods [95]

Wu *et al.* [95] focused on the location and sizing of ventilation control equipment to reduce operational costs. The current study could use these methods to supply the correct airflow to the working areas. However, simulation can be used to evaluate the effects before implementation, particularly in an integrated deep-level mine.

Study 11: Mine ventilation characterisation through simulations [72]

The study, by Nel *et al.* [72], focused on developing a methodology to evaluate the effects of various operational changes to a mine ventilation system. The case study evaluated nine operational changes to an integrated ventilation network using VUMA and key performance indicators (KPIs). The operational changes included the relocation of fans, airway enlargement and changing the airflow direction. The intensive methodology developed could be used to evaluate the operational changes in the current study.

Study 12: Study of Coal Mine Ventilation System Optimization based on Ventsim [96]

Using VentSim as a simulation software, Zhang Jing *et al*. [96] analysed methods to improve the ventilation network of an underground coal mine. Key locations where the system resistance could be improved were identified using the simulation. The suggested tunnel renovations were simulated to determine the best suitable solution. The study proved that simulation software can be used in the decision-making process of improving ventilation networks. However, the study did not focus on an integrated deep-level mine. Therefore, the use of simulation software could be implemented in the current study.

Study 13: Improving the ventilation system at Rosh Pinah zinc mine [52]

Using VentSim as a simulation software, Develo [52] analysed methods to improve the ventilation network of an underground zinc mine. Different solutions were simulated to determine the best suited. It was determined to be the relocation of the surface fans to redirect airflow to reach critical working areas. Thus, simulation software can evaluate operational changes to an integrated deep-level ventilation network.

Study 14: Improving the operational efficiency of deep-level mine ventilation systems [19]

Hancock [19] developed a generic solution strategy to identify network inefficiencies, find suitable solutions using simulation, and implement the solution. The generic solution was developed to improve the operational efficiency of deep-level ventilation systems. The generic solution was used to reroute air from inactive working areas to active working areas.

Hancock's study used simulation software to improve the operational efficiency of the mining complex, but failed to include integrated ventilation networks and ventilation control methods.

Study 15: Evaluating localised ventilation improvements on deep-level mines using simulation models [30]

Oosthuizen [30] focused on developing a methodology to identify ventilation problems on localised ventilation networks and mitigating the problems using simulation software. According to Oosthuizen [30], the localised network made it less time consuming to investigate and implement ventilation improvements. The study thus did not focus on an integrated ventilation network. The study also focused on improving secondary ventilation systems and did not use ventilation control methods to improve the system.

Study 16: Improving the ventilation of deep-level gold mines by simulating inactive sections [38]

Rouan [38] developed a methodology to accurately model a mine ventilation network and develop a reconditioning plan using simulation software. The results of the case study proved that simulation software can be used to evaluate and improve ventilation in inactive sections. However, Rouan [38] concluded that the study focused on inactive deep-level gold mining units, but the methodology can be used on other mining configurations such as integrated networks. The study focused on a sealing plan to improve the ventilation network and did not consider ventilation control methods.

Study 17: Improving air distribution in deep-level mine ventilation systems [46]

Mulder [46] created a feasible method for improving air distribution of a deep-level mine ventilation system. The study used simulation to evaluate solution strategies on an integrated ventilation system. However, the study focused on improving distribution by implementing small changes to the ventilation network and not by implementing control methods.

Study 18: Evaluating complex mine ventilation operational changes through simulations [49]

Nel *et al*. [49] developed, analysed and implemented a method to evaluate operational changes to a complex ventilation system using simulation. The method was not implemented on an integrated network, however, but the methodology could be adapted to improve integrated ventilation systems. The operational changes also did not focus on ventilation control methods.

Study 19: A review of primary mine ventilation systems optimisation [55]

Acuña *et al*. [55] developed algorithms to minimise the fan power costs in primary mine ventilation systems by identifying the number, location and duty of fans and regulators to distribute the required air flow and minimise costs. The study used computational design instead of simulation software to improve the network. By using simulation, integrated networks could be better represented and ventilation control methods could be added.

Study 20: Evaluating the impact of auxiliary fan practices on localised subsurface ventilation [58]

De Villiers *et al*. [58] evaluated the performance of underground auxiliary fans using simulation software. The study showed that the fans deviated from their design operating points. Simulation software could be used to evaluate the performance of auxiliary fans and main surface fans.

Study 21: Increasing energy efficiency of mine ventilation systems [64]

The study focused on a "system approach" to improve the energy efficiency of mine ventilation systems. The energy savings were achieved by properly sizing and streamlining the fan systems, as well as control strategies using speed control where possible. The study, however, did not use simulation software to aid in the improvement process when considering integrated ventilation networks.

Study 22: Increasing energy efficiency of a mine ventilation system via multipurpose control of a main fan adjustable speed electric drive [66]

The paper focused on multipurpose ventilation control for a fan frequency variable drive to provide the required fresh air while reducing energy losses. By using control strategies, the operational efficiency of the mines could be improved. The study, however, did not use simulation software that would aid in understanding more complex integrated ventilation networks.

Study 23: Ventilation-on-demand: Quantity or Quality – A pilot trial at Barrick gold's Bousquet mine [91]

The research paper, by Hardcastle *et al.* [91], centred on the implementation of a versatile ventilation-on-demand control system for a fan frequency variable drive, aiming to deliver the necessary fresh air while minimising energy wastage. The focus was on employing effective control strategies to enhance the operational efficiency of mining operations. However, it is worth noting that the study did not utilise simulation software, which could have facilitated the analysis of intricate integrated ventilation networks and their corresponding dynamics.

Study 24: Optimisation of mine secondary fan systems [97]

Fair [97] explores various aspects related to secondary fan systems, including fan selection, fan placement, control mechanisms, and operational parameters. Key findings of the study highlighted the significance of proper fan selection based on site-specific requirements and operational conditions.

The research highlighted the benefits of adopting optimisation strategies, including reduced energy consumption, improved ventilation effectiveness, and enhanced worker safety. It emphasised the potential for significant cost savings and environmental impact reduction through efficient secondary fan operations. The study, however, did not consider integrated ventilation systems or ventilation control strategies.

1.7.2. State of the Art

The above-mentioned studies were evaluated on six categories derived from the introduction. These categories include:

- improvement of ventilation systems,
- deep-level gold mine ventilation networks,
- integrated ventilation networks,
- using simulation software to aid in the improvement of the network, and
- implementation of ventilation control method.

The relevant studies are summarised in a state-of-the-art matrix in Table 5, evaluating whether they included the categories mentioned above in their scope. Minimal research focussed on the highlighted categories. Few studies considered ventilation control on an integrated ventilation network.

Table 5: State of the Art index on mine ventilation

Study	Optimisation	U/G deep-level mine	Integrated ventilation network	Simulation	Ventilation control	Implemented
1	Within scope	Not within scope	Not within scope	Within scope	Not within scope	Within scope
2	Within scope	Within scope	Not within scope	Not within scope	Not within scope	Within scope
3	Within scope	Not within scope	Within scope	Within scope	Within scope	Not within scope
4	Within scope	Not within scope	Not within scope	Not within scope	Within scope	Within scope
5	Within scope	Not within scope	Not within scope	Not within scope	Within scope	Not within scope
6	Within scope	Within scope	Not within scope	Within scope	Within scope	Within scope
7	Within scope	Within scope	Not within scope	Within scope	Within scope	Not within scope
8	Within scope	Within scope	Not within scope	Not within scope	Within scope	Within scope
9	Within scope	Within scope	Not within scope	Within scope	Within scope	Within scope
10	Within scope	Not within scope	Not within scope	Not within scope	Not within scope	Within scope
11	Within scope	Within scope	Within scope	Within scope	Not within scope	Not within scope
12	Within scope	Not within scope	Not within scope	Within scope	Not within scope	Within scope
13	Within scope	Not within scope	Not within scope	Within scope	Not within scope	Within scope
14	Within scope	Within scope	Not within scope	Within scope	Not within scope	Within scope
15	Within scope	Within scope	Not within scope	Within scope	Not within scope	Within scope
16	Within scope	Within scope	Not within scope	Within scope	Not within scope	Within scope
17	Within scope	Within scope	Within scope	Within scope	Not within scope	Within scope
18	Within scope	Within scope	Within scope	Within scope	Not within scope	Not within scope
19	Within scope	Within scope	Not within scope	Not within scope	Not within scope	Within scope
20	Within scope	Within scope	Not within scope	Within scope	Not within scope	Within scope
21	Within scope	Within scope	Not within scope	Not within scope	Within scope	Not within scope
22	Within scope	Within scope	Not within scope	Not within scope	Within scope	Within scope
23	Within scope	Within scope	Not within scope	Not within scope	Within scope	Within scope
24	Within scope	Within scope	Not within scope	Within scope	Not within scope	Within scope

	Within scope
	Not within scope

1.7.3. Critical review of previous studies

From Table 5, Studies 3, 6 and 11 were identified for a critical review as they contain various aspects that could be implemented in the current study. These studies will be further investigated in the following sections. The critical review focuses on the following parameters:

- objective,
- method,
- results & conclusion,
- contribution to this study to optimising mine ventilation systems with the aim of electricity cost reduction, and
- shortcomings

Study 3

Title:

The integration of mine simulation and ventilation simulation to develop a 'Life Cycle' mine ventilation system [71]

Objective:

Integrate ventilation modelling with event simulation to predict the ventilation requirements based on the life of mine and auxiliary VOD (ventilation on demand).

Method:

The prediction model integrated with a ventilation simulation was built using existing ventilation data, current airflow and requirements, future mining operations, and locations. The auxiliary ventilation network was then evaluated by gathering the airflow distribution and vehicle tracking & identification data. Then, using VOD, the auxiliary network was automated to distribute airflow to the working areas and the control was added to the simulation.

Based on the simulation, it was determined whether the current ventilation networks satisfied the airflow distribution requirements. If not, the ventilation network and the VOD control had to be modified until the updated network satisfied the requirements.

Next, the ventilation network was evaluated to determine whether the system needed optimisation. Evaluating entailed determining if the current ventilation equipment was sufficient and could be improved to lower the operating cost. Different optimisation scenarios were simulated using all stages in the life of a mining cycle until it was determined that the ventilation network was sufficiently optimised for the life cycle of the mine.

The resulting ventilation network was then processed and presented to the ventilation engineers to evaluate and implement the changes if needed. If any changes were made to the life cycle of the mine, the method was repeated.

<u>Results:</u>

The model indicated that the total intake airflow could be reduced by implementing the method in an underground mine. This was achieved by improving the underground airflow management. The simulation determined that the total airflow could be reduced by 19%, resulting in a potential ventilation operating cost reduction of 50%.

<u>Contribution to this study:</u>

The study, by Kocsis *et al. [71]*, used ventilation simulation to optimise a ventilation network and reduce operating costs. The ventilation simulation model was based not only on the current ventilation network and requirements, but also on the entire life of mine. The study's methodology provides a greater understanding of the methods used to optimise ventilation systems while ensuring the ventilation requirements are met.

<u>Shortcomings:</u>

As the primary fans are the biggest energy consumer of a typical mine ventilation system, more significant savings may be obtained by implementing flow control methods on the main fans when considering more extensive deep-level integrated ventilation networks. Implementing and simulating VOD on the auxiliary equipment could be increasingly challenging due to the increased complexity of the system.

Study 6

Title:

Reducing electrical costs for a mine ventilation system with the aid of simulation software [93].

Objective:

Determining the validity of using VUMA to analyse the ventilation network of a platinum mine. Using the simulation software to determine the effects of configuration changes on a platinum mine ventilation network. To evaluate potential energy savings initiatives using time of use on the system.

Method:

The ventilation network was simulated to determine the simulation software's validity. The simulated results were compared to actual ventilation measurements taken, and thus the accuracy and validity of the simulation were determined.

Potential saving initiatives focused on a specific section of a mine with the highest temperature. The cost-saving initiatives were simulated to evaluate the energy savings and the working conditions.

Results:

According to the TOU, a cost savings of R 500h was obtainable by switching off secondary fans during peak tariff hours. Furthermore, the cost savings could be obtained while maintaining safe working conditions.

Contribution to this study:

The study, by Nie *et al*. [93], used ventilation software to evaluate energy-saving initiatives while maintaining safe working conditions. The simulation accuracy was verified before it was used to evaluate cost-saving predictions. When determining the accuracy of the simulation, the results could be compared to measured data in specific critical locations.

The study concluded that reducing airflow to achieve lower operational costs could be implemented if simulation software was used to prove that safe working conditions would be maintained.

Shortcomings:

Cost savings could be increased by focusing on the primary fan configuration and control, particularly when considering the increased complexity of an integrated ventilation network with multiple shafts.

Study 11

Title:

Mine ventilation characterisation through simulations [72]

Objective:

The study focused on evaluating operational changes to a complex mine ventilation network through simulation.

Method:

The operational change had to be identified and defined to evaluate the system's operational change. In addition, the operational change was compared to the current ventilation network; thus, the system had to be benchmarked and verified using manual measurements.

Key performance indicators (KPIs) were established based on the operational change. First, the simulation software to be used was determined according to the simulation requirements and the software's capabilities. Simulation boundaries could then be defined accordingly.

A ventilation model was then simulated, and the result was analysed based on the operational efficiency. Finally, the operational change could be evaluated by using the KPIs.

Results:

Different operational changes were evaluated on an integrated ventilation mining complex. Using the method, the most feasible method was determined and implemented, resulting in energy savings of 13.32 GWh.

Contribution to this study:

The study, by Nel *et al.* [72], developed a scalable method to evaluate operational changes to a complex ventilation system. The method focused on creating and verifying a benchmark system that could be compared. Determining KPIs beforehand simplified the evaluation process as the changes were only measured according to these parameters.

Shortcomings:

The changes evaluated in the study were primarily to reduce the underground resistance. Evaluating the changes due to control on the primary fans could lead to increased savings as the system resistance could be lowered in the entire system.

1.7.4. Conclusion

Given the above, it can be concluded that integrated ventilation systems and ventilation control by implementing flow control on the primary fans have not been widely investigated. Therefore, further research should be conducted on ventilation control methods to improve the ventilation system on an integrated ventilation network using simulation.

1.8. Problem statement and objectives

This study's problem statement, aim and objectives are derived from this chapter's background and literature review.

1.8.1. Problem statement

Energy savings initiatives on ventilation systems are widely investigated to reduce the operational cost of a gold mine. However, inefficient ventilation systems on gold mines can increase electricity consumption. In addition, integrated deep-level mine ventilation systems can be difficult to manage and optimise. Minimal research was found on improving an integrated deep-level gold mine ventilation system using ventilation control methods and simulations.

1.8.2. Aim

The aim of the study was to develop, using existing research, and implement a new method to improve integrated deep-level gold mine ventilation systems using ventilation control methods and simulation software to reduce operational costs.

1.8.3. Objectives

The objectives of this study were as follows:

1. Develop a method to improve integrated ventilation networks using simulation software and ventilation control.
2. Evaluate the feasibility of the method by implementing it on a case study.

The following points will be used to determine the feasibility of developed method:

a. Develop a ventilation model of an integrated ventilation system using simulation software by
    i. calibrating the ventilation simulation, and
    ii. verifying the accuracy of the simulations within a 5% MAE.
b. Investigate the effects of implementing ventilation control methods using the simulation.
c. Evaluate the different methods using identified KPIs.
d. Implement the ventilation control method on an integrated ventilation network.
e. Validate the effects of the control method on the system.

1.9. Summary

Gold mines in South Africa are forced to reduce operational costs. Ventilation networks are inefficient due to the system's mismanagement, complexity, dynamic and integrated nature. A scope exists for initiatives to improve and reduce gold mine ventilation system operating costs.

A literature review of previous studies was performed and then summarised in a state-of-the-art table to identify gaps in the literature. Three studies were identified to perform a critical review to better understand different improvement methodologies. The critical review focused on the shortcomings and contributions to further studies. Finally, this study's problem statement, aim and objectives were derived using this chapter's contents.

1.10. Research approach

A case study methodology was used in this study, where Chapter 1 consists of the research on the topic. The method development is described in Chapter 2 and the implementation in a case study in Chapter 3. The effect of the developed method on the case study is also discussed in Chapter 3, and Chapter 4 gives a small summary indicating whether the new method to improve integrated ventilation networks using ventilation control and simulation software was successfully used to improve the ventilation network of the case studies.

Chapter 1: Introduction – The chapter contains the background relevant to this study, followed by an introduction to ventilation systems. A literature review is given on similar studies and used to formulate the problem statement, aim and objectives of this study.

Chapter 2: Method – The chapter contains the method of implementing a ventilation control philosophy on the ventilation network of an integrated mining complex using simulation software. The four phases in the methodology are thoroughly discussed.

Chapter 3: Implementation and Results – The methodology implemented to improve the ventilation network of integrated mining complex A in two case studies is explained. Firstly, the mining complex's system investigation and the simulation process are discussed. Afterwards, the strategy development and implementation are elaborated on.

Chapter 4: Conclusion – The chapter summarises the study overview, encompassing the study background, problem statement, methodology, solution and results. This is followed by examining the shortcomings and limitations encountered during the research process. Lastly, concluding remarks for the study are discussed.

Chapter 2: Method

Figure: Three centrifugal main surface fans[2]

"There's no shortage of remarkable ideas, what's missing is the will to execute them."

– Seth Godin

[2] S Louw, Personal photograph, Welkom, 2023

2. DEVELOPMENT OF A METHOD FOR IMPROVING INTEGRATED VENTILATION NETWORKS

2.1. Preamble

Chapter 2 explains the development of the method of implementing a control philosophy on the ventilation network of an integrated mining complex. As discussed in Study 11, Nel *et al.* developed a method to evaluate operational changes to a complex mine ventilation system. The method derived in this chapter will be adapted from Nel *et al.* , all changes made to the Nel *et al.* method are discussed.

The method comprises four phases: system investigation, simulation, strategy development, and implementation and evaluation. These phases are thoroughly discussed in this chapter.

2.2. Phase 1: System investigation

A complete system investigation has to be done on the current system to evaluate the effects of changes made to the network. The investigation included establishing KPIs, benchmarking the current ventilation system and verifying the system with manual readings. The phase's purpose is to better understand the ventilation network, which is crucial to building an accurate simulation and establishing the KPIs, as it forms the basis of the simulation and strategies [72].

2.2.1. Establish KPIs

Identifying and choosing the correct KPIs is crucial to the success of the study as much of the latter steps rely on the KPIs chosen. The KPIs will be used to evaluate the effects of the changes made to the ventilation network. Furthermore, it provides parameters to be compared before and after implementing the changes.

The KPIs is chosen based on the requirements of the study and network. Typical KPIs include [72] :

- operational KPIs:
    - energy,
    - efficiency, and
    - total airflow of the system;
- service delivery KPIs:
    - wet-bulb temperature,
    - dry-bulb temperature,
    - pressure, and
    - airflow;
- technical KPIs; and
- airflow per kilotonnes mined.

Nel *et al.* [72] showed the importance of establishing KPIs to evaluate the effects of changes made to a ventilation system. However, by defining the KPIs before the extensive investigation and benchmarking, the KPIs can be used to identify inefficiencies unlike in Nel et al. [72].

Once the KPIs have been established, further investigation is needed to benchmark the current ventilation system and build a simulation to identify inefficiencies. While benchmarking the current system, the KPIs could be used to identify problem areas where the KPIs were not met.

2.2.2. Benchmark the current ventilation system and identify inefficiencies

Data acquisition is the primary purpose of this step. The accuracy of the simulation is dependent on the data available. Thus, acquiring relevant and accurate data was crucial to the study. This step can be further separated into five sub-steps, illustrated in Figure 12 and adapted from [72]. While acquiring the data, the data can be compared to the KPIs to identify problematic areas and inefficiencies.

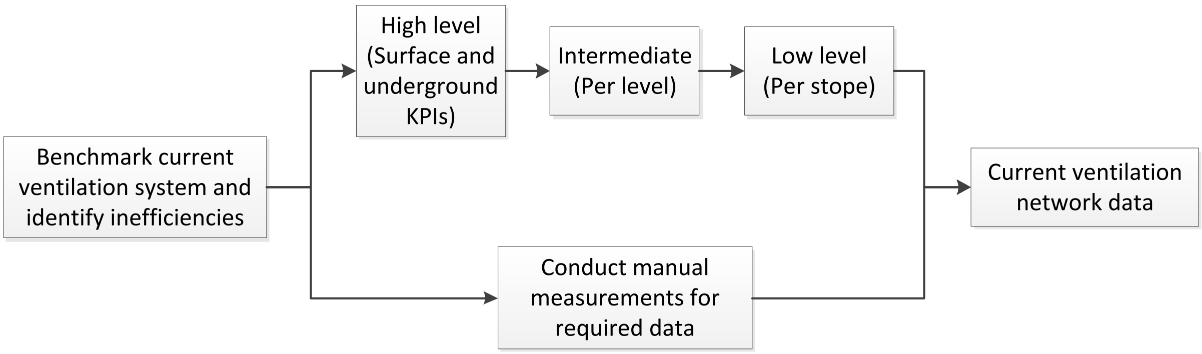


Figure 12: Steps in benchmarking the current ventilation system

The following three steps focuses on obtaining existing data directly from mine personnel or the Supervisory Control and Data Acquisition Network (SCADA). SCADA is a network system that stores data to view operating conditions and mining trends [98]. The data gathered from SCADA depends on the instrumentation available on the specific mine [39, 99].

High-level data

High-level data acquisition pertains to the overall parameters of the ventilation system and can be used to evaluate the operational efficiencies of the system. High-level data contains data from the surface and underground. The parameters include main fan assemblies, VRT, fan power, shaft diameters, average stope temperature, average stope airflow and average face velocity [38].

The data gathered will consist of the KPIs of the ventilation network and will be used to establish the benchmark for the system.

Intermediate data

Data gathered in this step will be used in constructing a mass balance of the mine. The data mainly consist of airflow, temperature and barometric pressures for the main intake and return airways for each level on the mine [72]. With the ventilation data gathered, efforts should be made to obtain the DXF mine layouts if available. Figure 13 depicts a two-dimensional DXF mine layout of a single level.

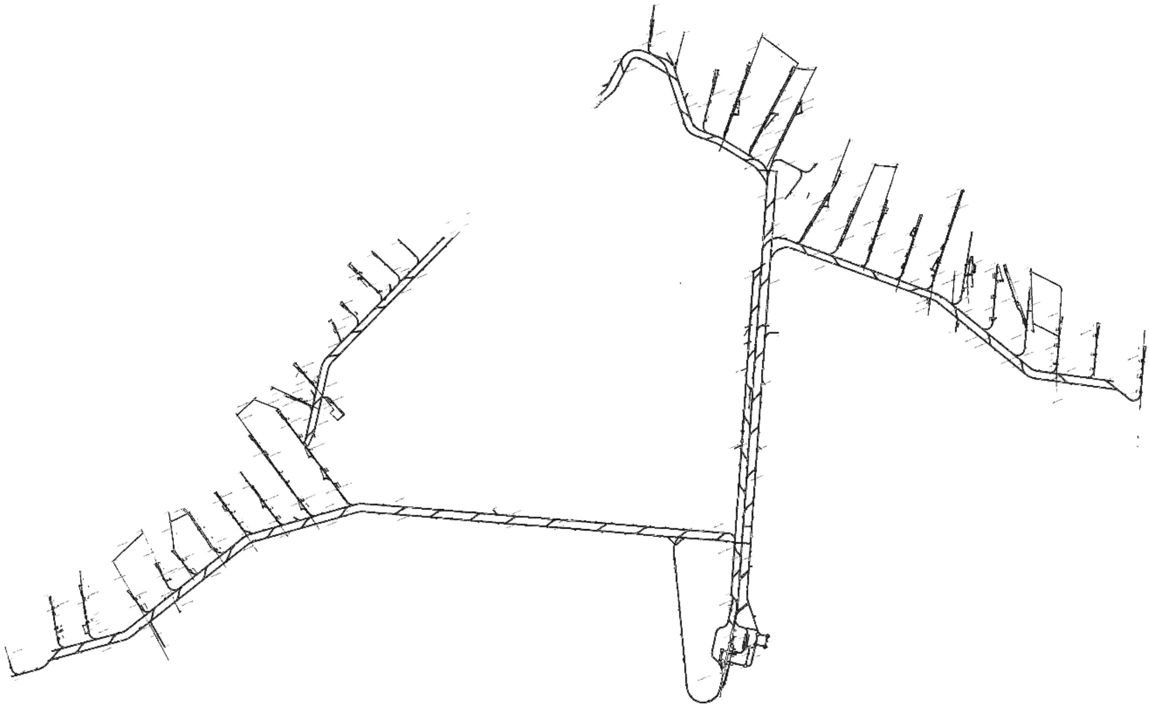


Figure 13: DXF layout of a single level of an underground gold mine

Obtaining the layouts assists in the construction of the simulation. Usually, the layouts are drawn using a geographic coordinate system (GSC). The levels' longitude, latitude, and depth will be obtained with the GSC system. Three-dimensional layouts also depict raised lines, as illustrated in Figure 14 below.

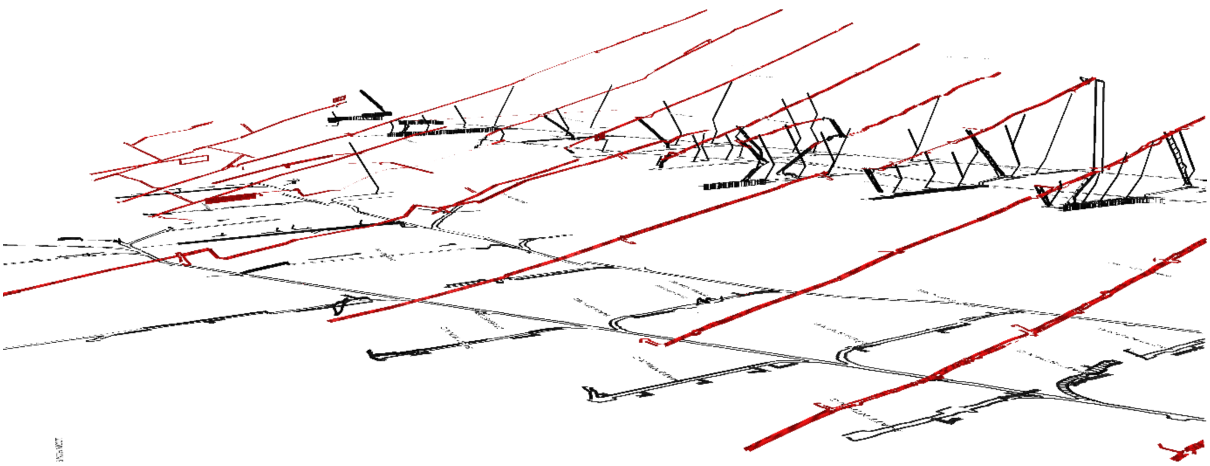


Figure 14: Three-dimensional DXF mine layout of 25 and 26 level

Locations and specifications of all ventilation control equipment needs to be obtained for the levels. The data will be used to better understand the airflow directions and quantities per level [38].

Low-level data

Low-level data are the most detailed data available for a ventilation system. Therefore, using this data to construct the simulation model leads to the most accurate simulation. The data that needs to be gathered consists of the airflow, temperature, and barometric pressure on various points in the ventilation network [38].

Conduct manual measurements for required data

The ventilation department can acquire data not available on SCADA on the mine. In addition, the ventilation departments are required to conduct ventilation audits regularly. The data received from the audits are of immense value if the audits are done according to the regulations [19].

Any data unavailable from either SCADA or the ventilation department needs to be obtained by manual measurements, as discussed in Appendix A. Manual measurements are necessary when more accurate data are required.

Current ventilation network data

The data gathered need to be processed by creating simplified ventilation layouts. Detailed layouts will be used to visibly represent the ventilation network to understand the system better and identify inefficiencies. Figure 15 shows a ventilation layout used by Nel *et al.* [72] and depicts the complete overview of the ventilation system.

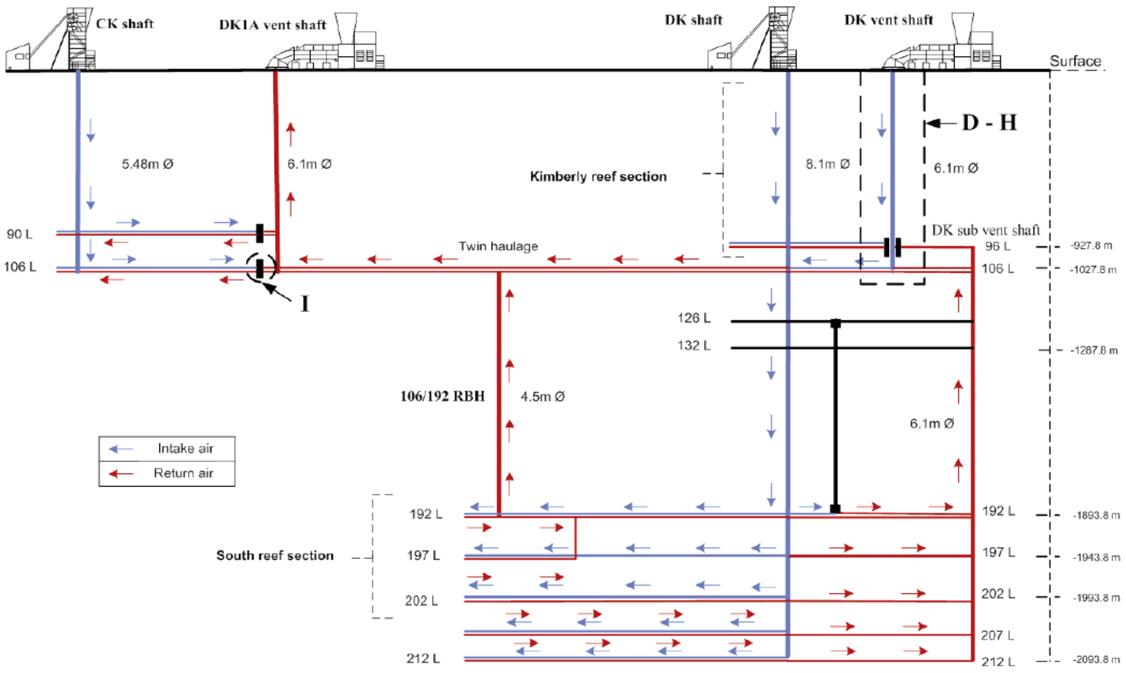


Figure 15: Simplified ventilation layout of a typical mine [72]

Data represented in the layout in Figure 15 have intake airways, return airways, depths, and shaft diameters. The detailed level ventilation layouts in Figure 16 illustrates the airflow volume and direction per level.

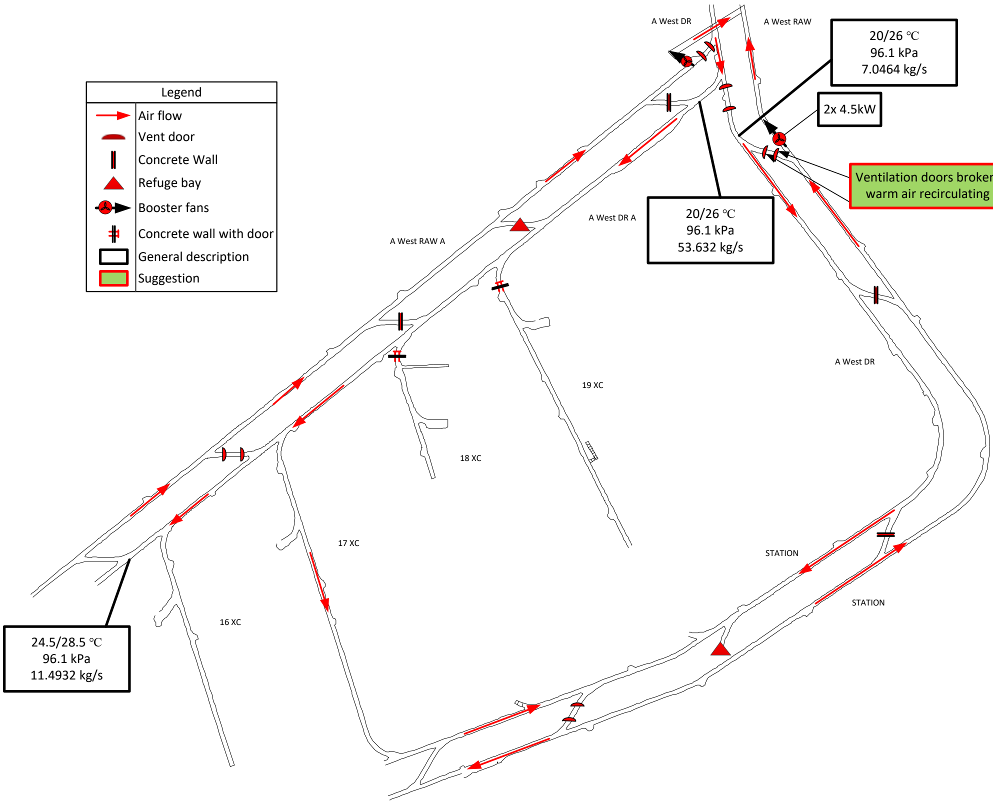


Figure 16: Detailed level ventilation layout of a typical mine level

The layouts will be made using DXF level layouts. The airflow quantities, temperature, barometric pressures, direction, and inefficiencies are depicted.

When considering an integrated ventilation network, the steps mentioned above must be done in all sections of the network. Increasing the data gathered, thus simplifying the network using layouts is essential [100].

2.2.3. Verify data with manual measurements

To ensure the accuracy of the simulation, the data gathered needs to be verified [38]. Several reasons may lead to inaccurate data, such as faulty instrumentation and measuring equipment [42]. Thus, ventilation audits of the entire integrated network must be conducted to verify the data with manual measurements using the procedures in Appendix A.

2.2.4. System investigation summary

A complete system investigation has to be done on the current system to evaluate the effects of changes made to the network. The steps included in the system investigation phase are visually illustrated in Figure 17.

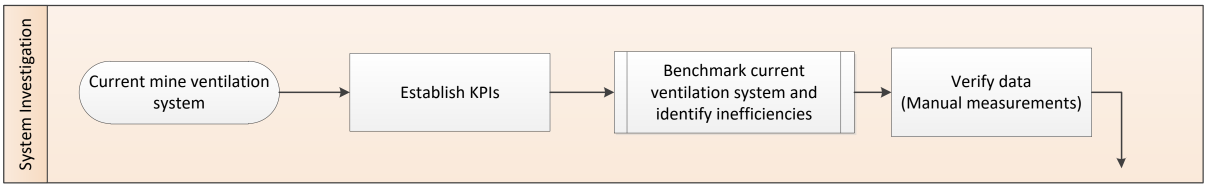


Figure 17: Phase 1: System investigation method

2.3. Phase 2: Simulation development

The next phase uses the data gathered from the system investigation to build an accurate ventilation simulation to identify further inefficiencies and strategy development. The following three phases differs from Nel *et al.* [72]. Nel *et al.* focussed on building a simulation for a specific operational change. The method derived in this Chapter will focus on using the simulation to identify inefficiencies as well as developing improvement strategies.

Selection of software

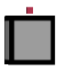
All the simulation software mentioned in Chapter 1 (p.19) is currently being used to assist ventilation engineers in improving and mapping ventilation systems. Therefore, the following deciding criteria were chosen to determine the software best suited for this study.

- Accuracy of the simulation
- Integrated software
- Calculate cost savings
- Familiarity
- User-friendliness

2.3.1. Build ventilation simulation

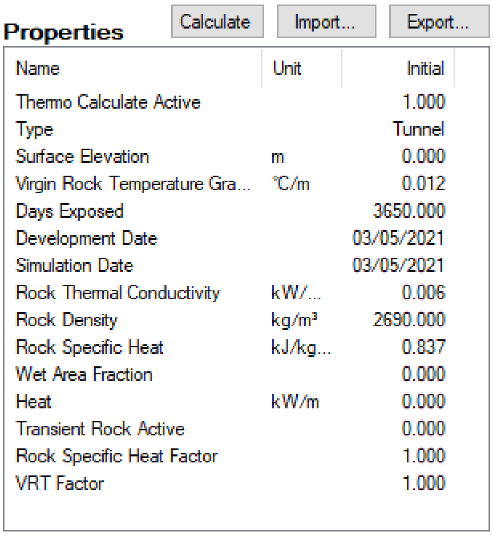
Data gathered will be used to build a simulation skeleton of the ventilation network. The simulation skeleton is an uncalibrated simulation representing the network. The data needed to build the skeleton are mine layouts, haulage sizes, shaft diameters, ventilation control equipment locations and sizes [97]. The network is represented in the simulation using the components in Table 6.

Table 6: PTB ventilation components

Component name	Component	Description
Air pressure boundary		Represents the ambient conditions used as the beginning and end of the simulation.
Air node		The air node is used between components and represents the air in the system.
Air tunnel		Represents the haulage or shaft in the network. The component can be altered to represent control equipment such as ventilation doors or walls.
Air fan		Represents any fan found in the network, such as main surface fans or development fans.
Air pipe		Air pipes are used with development fans. Illustrates the ducting used to force air into specific areas.

2.3.2. Calibrate the simulation

After the skeleton was built, the simulation needs to be calibrated. The measured data will be used to adjust the component parameters, illustrated in Figure 18. The parameters vital to the simulation are discussed below. The other parameters will be determined as constants within predefined ranges based on input provided by mining personnel. These parameters, including rock density, is not measured data but selected values obtained from mining personnel [30].



Name	Unit	Initial
Thermo Calculate Active		1.000
Type		Tunnel
Surface Elevation	m	0.000
Virgin Rock Temperature Gra...	°C/m	0.012
Days Exposed		3650.000
Development Date		03/05/2021
Simulation Date		03/05/2021
Rock Thermal Conductivity	kW/...	0.006
Rock Density	kg/m³	2690.000
Rock Specific Heat	kJ/kg...	0.837
Wet Area Fraction		0.000
Heat	kW/m	0.000
Transient Rock Active		0.000
Rock Specific Heat Factor		1.000
VRT Factor		1.000

Figure 18: Calibration of an underground tunnel

<u>Air mass flow [kg/s] and barometric pressure [kPa]</u>

Airflow is induced by a pressure difference between two points [52]. Thus, the parameters has to be calibrated simultaneously. The operating point of the main surface fans could be calibrated to provide the correct airflow through the mine. The air mass flow will be calibrated in specific areas by altering the airflow resistance. Lowering the resistance leads to higher airflow and contrariwise.

<u>Dry-bulb temperature [℃]</u>

Dry-bulb temperature is calibrated by adjusting the heat added by specific components. Heat is added to the system by VRT, workers and equipment [101]. The heat added needs to be adjusted for each component to calculate the temperature gain per section [97].

<u>Humidity [%]</u>

The humidity is calibrated by adjusting the moisture added by each component. The moisture added affects the wet-bulb temperature, and as humidity is the ratio between wet-bulb and dry-bulb temperature, adjusting the wet-bulb should suffice [97].

Calibration controllers

The parameters mentioned above can be calibrated using calibration controllers in PTB [102]. Calibration controllers calculate the parameters to achieve a setpoint, thus eliminating a manual iteration process. Calibration controllers is used to calibrate the fan to obtain its operating point.

2.3.3. Verify simulation

The accuracy of the simulation needs to be determined using Equation (7). Afterwards, the measured data will be compared to the simulation results at the exact locations. The accuracy error should be below 5% to be considered accurate [97]. Once the MAE is below 5%, the simulation can identify inefficiencies. Otherwise, all the steps from benchmarking onwards will be repeated until satisfactory.

2.3.4. Simulation development summary

The simulation development phase focused on developing an accurate ventilation simulation using the data gathered from the first phase. Figure 19 visually represents the simulation development phase.

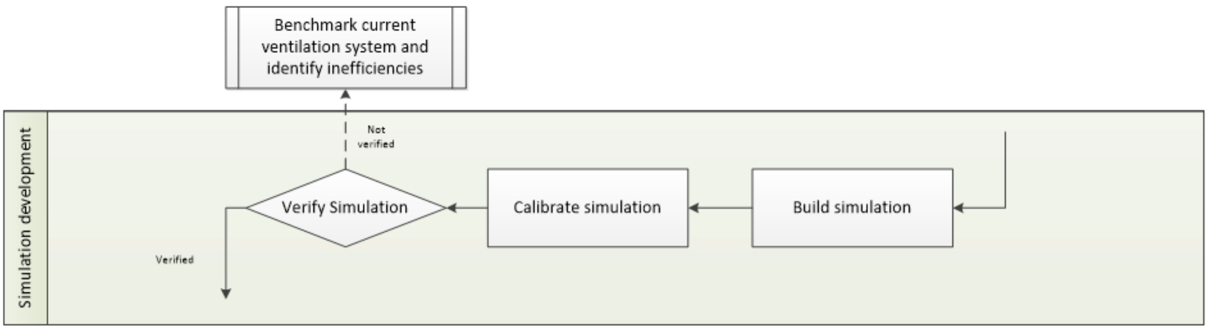


Figure 19: Phase 2: Simulation development

The following phase identified and investigated different strategies to improve the inefficiencies.

2.4. Phase 3: Strategy development

The following steps will be used to develop a strategy to improve the network's inefficiencies. Before implementation, the strategy needed to be simulated and the results thereof evaluated against the KPIs. The phase is an iterative process until the best strategy is chosen.

2.4.1. Identify inefficiencies

The following step identifies any inefficiencies in the network using the simulation developed. Simulation results will be compared to the KPIs identified. This is used to identify problematic areas. Using the simulation, the cause of the inefficiencies can be found. Causes of inefficiencies include fan control, configuration, pressure losses, system resistance and ineffective ventilation equipment.

2.4.2. Develop improvement strategy

The strategy focuses on ventilation control to reduce operational costs. The strategy options included:

- ventilation on demand,
- peak clipping,
- load shifting, and
- TOU strategies.

These strategies are mentioned and discussed in Chapter 1, but entail control using guide vane angles and VSDs. In some cases, changes to the system, such as reducing air resistance, clearing critical airways, and changing the airflow path will need to be implemented.

The following goals must be established and considered when developing an improvement strategy:

- cost of implementation,
- payback period,
- life of mine and lifespan of working areas, and
- safety concerns.

2.4.3. Simulate strategy

A verified simulation accurately predicts the strategy's effects on the system. All intended system changes need to be added to the simulation. By simulating the intended changes, the effects can be accurately predicted. From this, informed decisions can be made to select the best-suited strategy [93].

2.4.4. Evaluate strategy

The strategy must be evaluated to select the best suited to improve the network and eliminate inefficiency. The strategy can evaluated using the following criteria:

- operational KPIs:
    - the total power consumed by the system,
    - total airflow through the mine;
- service delivery KPIs:
    - working face velocity,
    - working area temperatures;
- payback period;
- waiting period; and
- safety concerns.

Using the abovementioned criteria to evaluate the strategies improves decision-making [97]. Thereafter, the best-suited strategy can be implemented.

2.4.5. Strategy development summary

Figure 20 shows the strategy development phase. Firstly, the inefficiency is identified, followed by developing an improvement strategy and simulating the strategy. After the strategy has been simulated, it is evaluated using the KPIs chosen in phase 1.

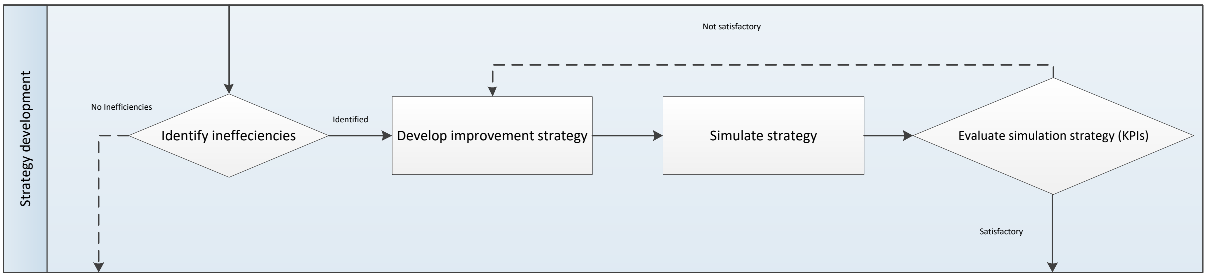


Figure 20: Phase 3: Strategy development

2.5. Phase 4: Implementation and evaluation

Following the steps mentioned above, the system was investigated, a simulation was built, inefficiencies were identified, different solution strategies were investigated, and finally, the best strategy was chosen. The final phase was to implement the chosen strategy and validate the effect of the strategy on the system.

2.5.1. Implement strategy

Throughout the method, the mine's ventilation department and any affected department must be included in the decision-making. Then, with mining personnel, the strategy can be implemented.

Depending on the strategy, some operational changes need to be made. These may include clearing airways or installing additional ventilation equipment. Any work must be thoroughly planned, and all the necessary documentation must be in order. As the process differs between mines, the mine personnel must assist in this step.

A detailed plan needs to be given to the mine to ensure correct implementation. The plan should entail all the proposed changes to the network, a timeline for when all changes need to be implemented, a list of all equipment needed and, if necessary, a list of external contractors capable of completing changes [38].

2.5.2. Evaluate the performance of the implemented strategy

After implementation, the effect of the strategy needs to be validated by evaluating the performance of the implemented strategy. The strategy was evaluated using the KPIs as criteria [72].

Depending on the instrumentation accessible and the KPIs chosen, ventilation audits are needed. The measurements have to be evaluated against the KPIs, showing if the current ventilation system is satisfactorily improved. If the strategy proves unsatisfactory, the steps from the identification of inefficiencies onwards must be repeated until satisfactory. Once the implemented strategy performance is deemed satisfactory, the current ventilation network with the additional changes becomes the new ventilation benchmark model of the mine.

2.5.3. Implementation and evaluation summary

The implementation and evaluation phase, shown in Figure 21, entails implementing and evaluating the proposed strategy. If the KPIs are not met, Phase 3 and Phase 4 are repeated until the KPIs are met.

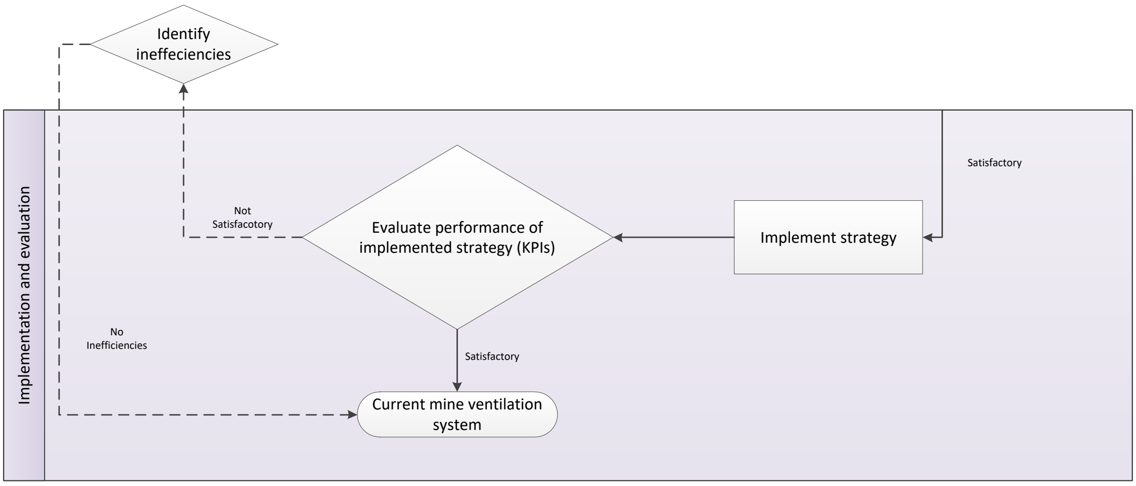


Figure 21: Phase 4: Implementation and evaluation

2.6. Conclusion

The developed method, shown in Figure 22, can improve integrated ventilation networks by using simulation and implementing ventilation control strategies. The newly-developed method addresses all the criteria chosen for the state of the art in Chapter 1:

1. improvement of ventilation systems,
2. deep-level gold mine ventilation networks,
3. integrated ventilation networks,
4. using simulation software to aid in the improvement of the network, and
5. implementation of ventilation control method.

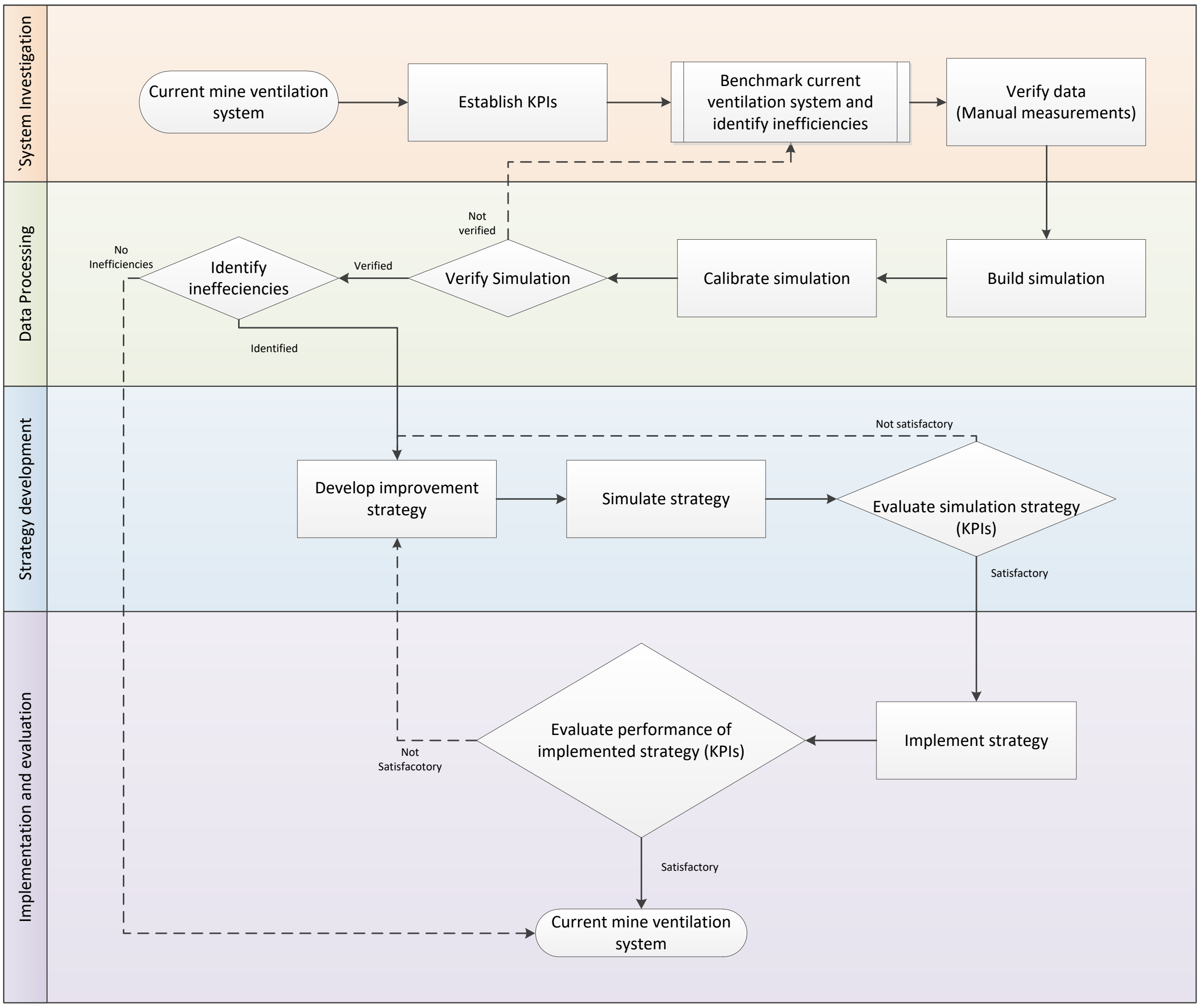


Figure 22: Summary of a new method for improving an integrated mine ventilation system

To improve the network, a whole system investigation is needed. The KPIs are chosen from the investigation, and the network is benchmarked.

Secondly, a simulation is built and calibrated using the data gathered from the system investigation. Once the simulation accuracy is verified, it can be used to identify further inefficiencies. With the inefficiencies identified, strategies to improve the network are developed using the simulation and the best solution is chosen using the KPIs chosen in the system investigation.

Lastly, the chosen strategy can be implemented and evaluated using the KPIs. The following chapter describes how the method was implemented in a case study to improve the ventilation network of an integrated mining complex.

Chapter 3: Implementation and Results

Figure: Emergency diesel-powered axial surface fan[3]

"There are no secrets to success. It is the result of preparation, hard work and learning from failure." – Colin Powell

[3] S Louw, Personal photograph, Welkom, 2023

3. IMPLEMENTATION OF NEW METHOD AND RESULTS

3.1. Preamble

The method developed as described in the previous chapter was implemented to improve the integrated mining complex A in two case studies. Firstly, the mining complex's system investigation and the simulation process are discussed. Afterwards, each case study's strategy development and implementation are discussed.

3.2. Mining complex A

The studies focus on a gold mining complex A, consisting of three integrated shafts as illustrated in Figure 23.

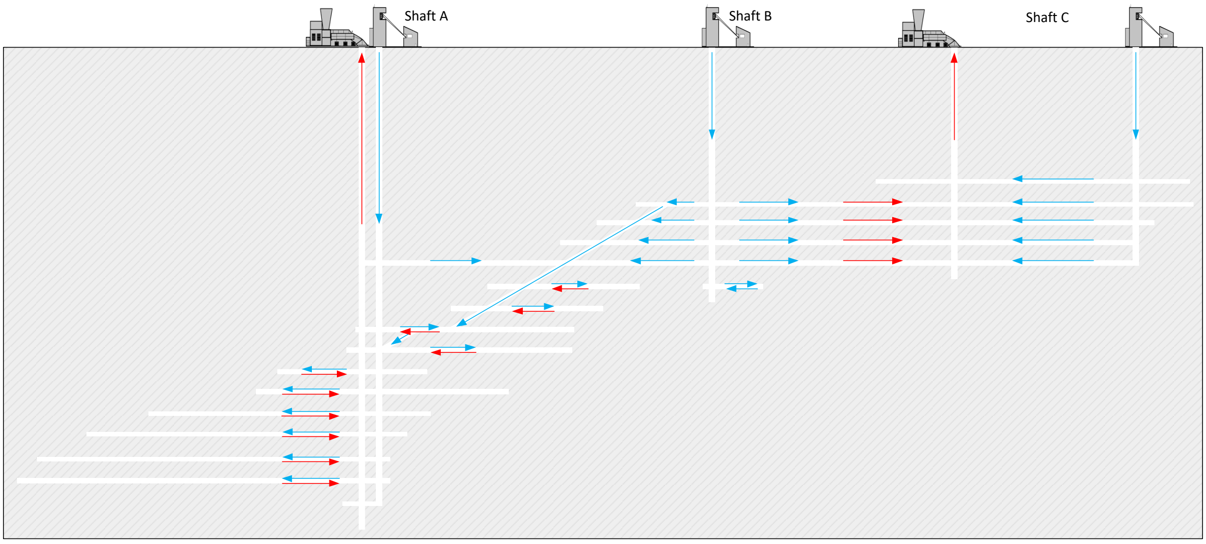


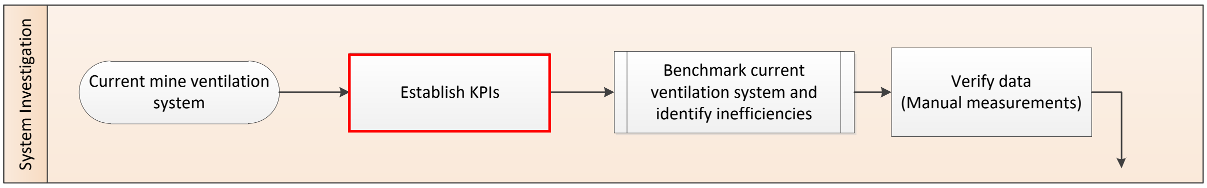
Figure 23: Representation of the mining complex A

Gold mining complex A consists of three integrated shafts: Shafts A, B, and C. Shafts A and B are active Shaft C is inactive, with Shaft A and C down- and upcasting air and Shaft B only downcasting. Shaft B also supplies Shaft A with fresh air through a decline shaft. Shafts A and C both have three surface fans, with a 2.6 MW and 1.2 MW per fan power rating, respectively. Shaft A currently uses all three surface fans and Shaft C uses only two of the three.

3.3. Phase 1: System investigation

A complete system investigation was done on Mining complex A. Firstly, the KPIs were chosen. After this, data were gathered to benchmark the system, and the data were later verified with manual measurements. The data gathered in the system investigation were used to understand the system better and were essential to build an accurate simulation in the following phase.

3.3.1. Establish KPIs

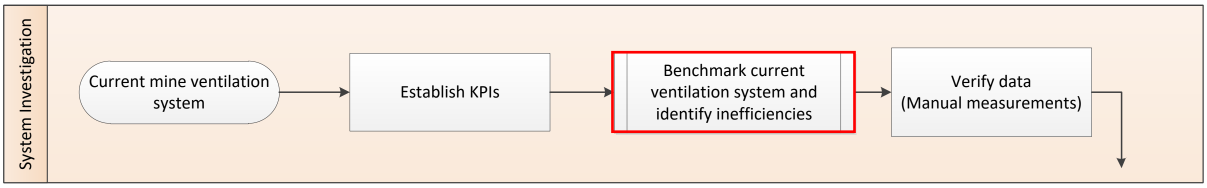


The KPIs chosen for the integrated mining complex A can be split into operational and service delivery indicators. The operational indicators illustrated the operational point at which the system runs, while the service delivery indicated if the ventilation supplied was sufficient.

The KPIs for mining complex A were:

- Operational KPIs – Operational cost of the ventilation system.
- Service delivery KPIs – Underground working conditions.

3.3.2. Benchmark the current ventilation system and identify inefficiencies



Data were gathered to gain a complete representation of the ventilation network. The data gathered in the following steps were gathered from SCADA data and mining personnel. First, high-level, intermediate, and low-level data were gathered, and manual measurements were needed. Once all the data were gathered, they were compiled for the following phases.

High-level data

The Shaft A surface fan assembly consisted of three electric centrifugal fans and two diesel-powered axial fans to be used in an emergency. At the same time, Shaft C had three electric centrifugal fans, two working and one on standby. The fan assemblies for shafts A and C are illustrated in Figure 24 below.

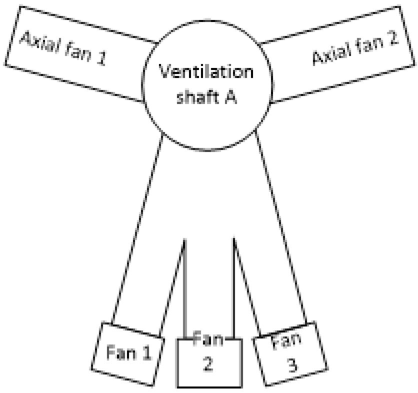


Figure 24: Representation of Shaft A and Shaft C fan assemblies

Both Shafts A and C main surface fans had fixed guide vane angles. However, Shaft A had VSDs which can control the volume flow through the mine. Figure 25 represents an average monthly 24-hour power profile for the surface fans for both shafts.

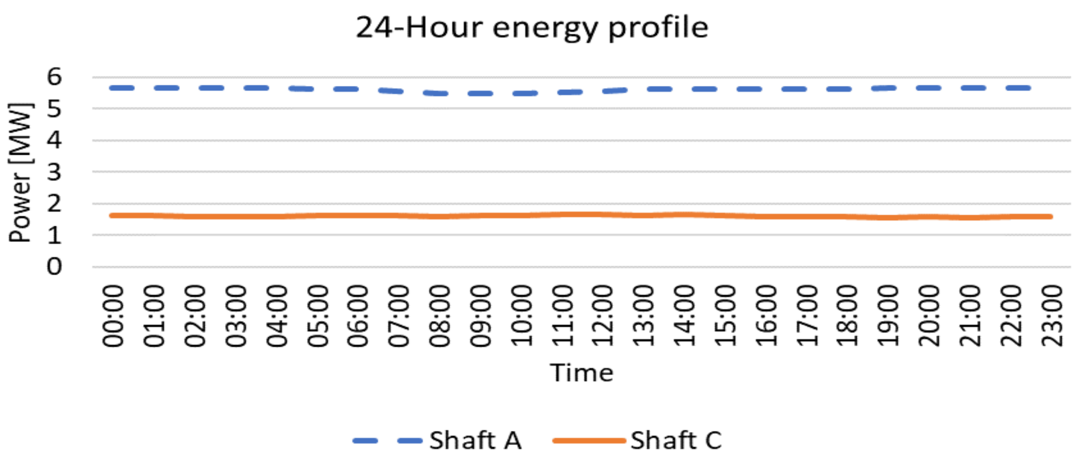


Figure 25: 24-hour surface fan power profile of Shafts A and C

The shaft diameters, current underground conditions and requirements had to be obtained from the mine personnel for each shaft as each shaft falls under a different mining unit; the data gathered are shown in Table 7. Shaft C is not an active shaft, thus does not have an required mass flow to ventilate working areas.

Table 7: High-level data for mining complex A

	Unit	Shaft A	Shaft B	Shaft C
Upcast shaft diameter	[m]	6.5	-	6.2
Downcast shaft diameter	[m]	8.5	9.4	8.5
Fan power	[kW]	5 616	-	1 607
Average wet-bulb temperature for all working areas	[°C]	30.7	28.5	-
Average mass flow for all working areas	[kg/s]	12.38	N/A	-
Average velocity for all working areas	[m/s]	0.48	N/A	-
Required mass flow	[kg/s]	825	365	-

The data gathered in Table 7 broadly represent the requirements and effectiveness of the ventilation network.

Intermediate data

The level layouts indicating the depth and coordinates of the levels were obtained from the mining personnel. The ventilation survey data from the mine were obtained and gave all the ventilation control devices and volume flow in the levels. The surveys were only obtainable for Shaft A.

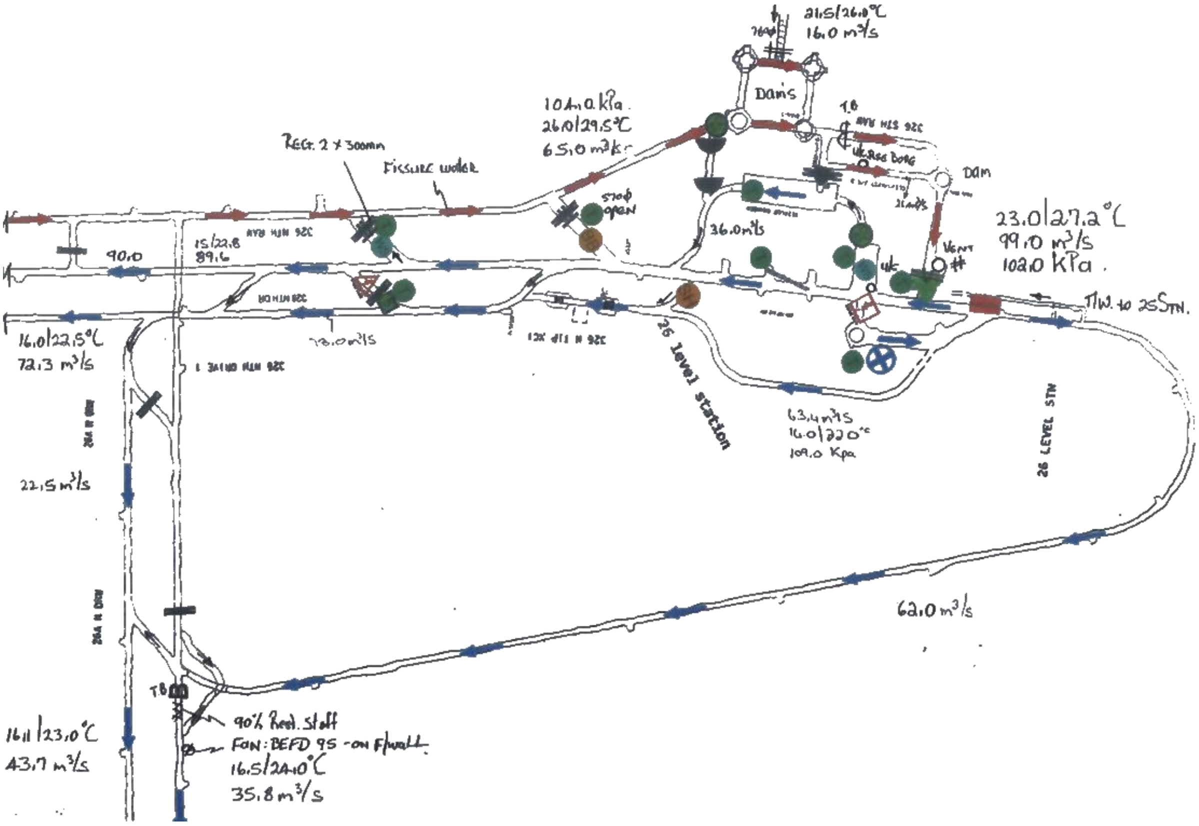


Figure 26: 26L ventilation survey drawings

The data from the Shaft A ventilation survey for 26 level (26 L) are shown in Figure 26. Furthermore, the volume flow for the levels is shown in Table 8.

Table 8: Volume flow for shaft A per level

Level	Volume flow (m^3/s)
20 L	19.1
22 L	65.8
23 L	30
24 L	106.7
25 L	156.3
26 L	206

Low-level data

The volume surveys obtained from the mine contained low-level data as well. The surveys showed the volume flow and temperatures in the cross cuts leading to the working places in the mine. Figure 27 illustrates a volume survey containing the information mentioned above.

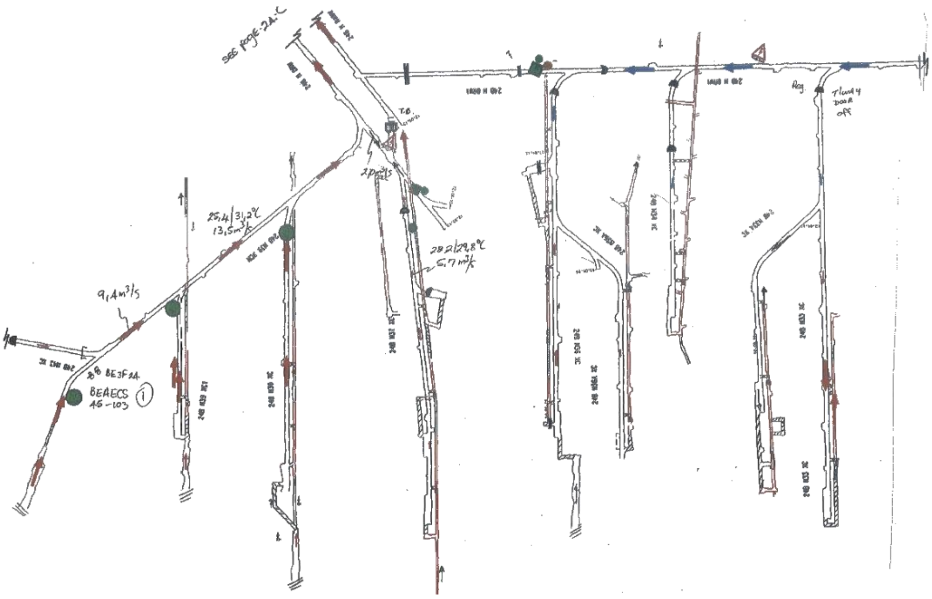


Figure 27: Ventilation survey of Shaft A 24 level

The data gathered from the volume surveys were used in the following steps to obtain a current ventilation layout and later in the simulation calibration. The mining personnel also obtained the equipment used in the levels and the number of employees on the levels to calibrate the heat added to the system.

Conduct manual measurements for required data

The mining complex A had no data available on SCADA for the volume flows through the surface fans. Thus, manual measurements with a pitot tube had to be taken. The process is described in Appendix A. The measurements are shown in Table 9.

Table 9: Manual surface fan measurements

		Shaft A			Shaft C		
	Unit	Fan 1	Fan 2	Fan 3	Fan 1	Fan 2	Fan 3
P_S **(Static pressure)**	Pa	4 460	4 560	4 440	-	1 800	1 800
v **(Airflow velocity)**	m/s	31.52	24.11	30.53	-	23.33	26.40
A (Cross-sectional area)	m^2	10.81	10.81	10.81	-	21.41	21.41
$\dot{m}$ **(Mass flow)**	kg/s	340.75	260.64	330.03	-	499.45	565.19
Q (Volumetric flow rate)	m^3/s	333.35	254.67	322.94	-	510.24	577.40

The data from Table 9 was crucial to identify inefficiencies and calibrating the simulation's surface fans. From the measurements, the static pressure in Shaft A’s Fan 2 was higher. An investigation is needed on the cause of the higher static pressure.

<u>Current ventilation network data</u>

The data obtained in the steps above were processed and added to a ventilation layout to understand the network better. Microsoft Visio was used to represent the network. The DXF files were used to represent the airflow in the levels visually. The ventilation network for a level is illustrated in Figure 28.

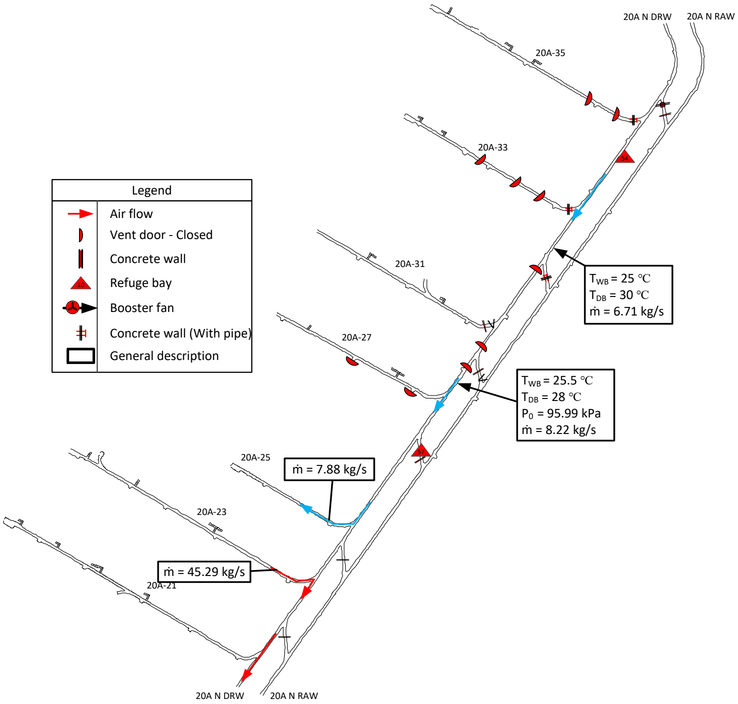


Figure 28: Ventilation network representation of 20 level

The blue arrows represent the fresh air direction and the red arrows represent the return air direction. The ventilation control devices and the airflow quantities are also shown. The network's visual representation helped to achieve a better understanding of the network.

Identify inefficiencies

After visually representing the current ventilation network and compiling all the gathered data, an observable spike in Shaft A's Surface 3 power consumption became apparent. Upon further investigation, it was determined that the cowling of Surface fan no. 2 was broken. In addition, the current to Surface fan no. 3 was increased to account for decreased efficiency and ensure the mine’s ventilation remained adequate. The power impact is illustrated in Figure 29.

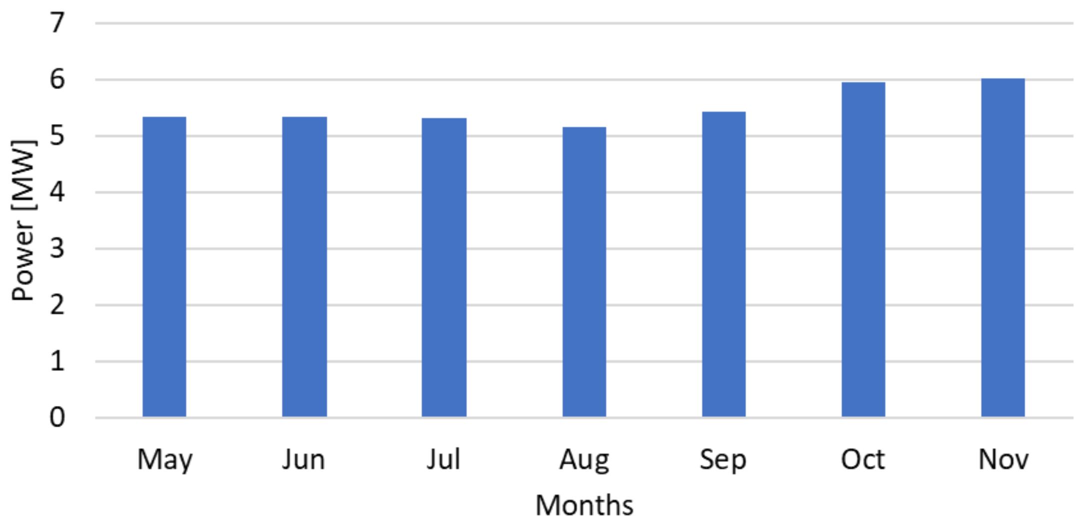
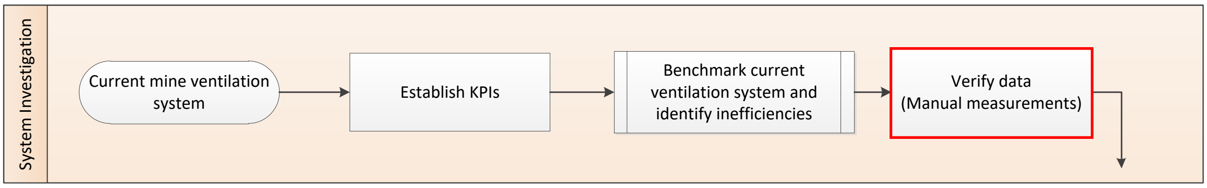


Figure 29: Average ventilation power demand for shaft A

The inlet cowling was designed to direct air smoothly through the fan section, reducing the system resistance [103].

3.3.3. Verify data with manual measurements



Multiple audits were conducted to ensure all the data from the mine were correct. The measurements taken included:

- haulage sizes,
- barometric pressures,
- airflow velocities, and
- temperatures.

The measurements taken for shaft A 22 level are represented in Table 10.

Table 10: Shaft A 22 Level audit measurements

Point	Pressure	Wet-bulb temperature	Dry-bulb temperature	Height	Width	Area	Velocity	Volumetric flow	Relative humidity	Air density	Mass flow
	kPa	°C	°C	m	m	m^2	m/s	m^3/s	-	kg/m^3	kg/s
1	96.84	21	25	3.43	3.24	11.11	3.67	40.75	0.71	1.12	45.7
2	97.01	20	25	3.35	3.42	11.46	4.39	50.31	0.64	1.12	56.58
3	97.12	19	24	3.52	3.66	12.88	3.71	47.85	0.63	1.13	54.09
4	97.34	17	23	3.67	3.31	12.15	4.43	53.8	0.56	1.14	61.23
5	97.52	16	21.5	3.93	3.53	13.87	4.59	63.67	0.57	1.15	73
6	97.6	15.5	21	3.51	3.84	13.48	4.48	60.4	0.57	1.15	69.44

Simultaneously, the sizes and locations of all ventilation control equipment were confirmed. The data gathered were then added to the ventilation layout to compare with the data gathered from the mine, as illustrated in Figure 30.

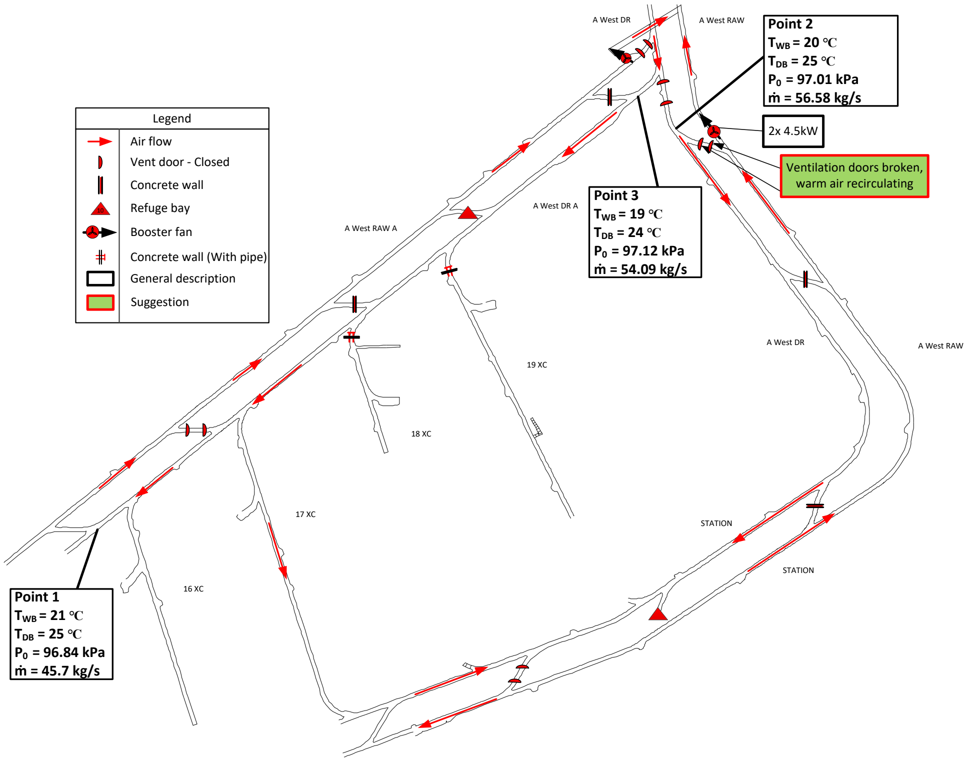


Figure 30: Shaft A Level 22 ventilation representation layout

Overall, the combination of multiple audits, manual measurements, and cross-checks helped to ensure the integrity and accuracy of the data gathered from the mine. The manual measurements helped verify the data and provide confidence in the results and were essential for calibrating the simulation.

3.4. Phase 2: Simulation development

The method outlined above was implemented in a study of a specific underground mine. Using data gathered from a system investigation, a ventilation simulation was built using the a simulation package. The ventilation layouts created using mine layouts, haulage sizes, shaft diameters, and ventilation control equipment locations and sizes were used to build the simulation. The simulation skeleton was built by adding various components such as air pressure boundaries, air nodes, air tunnels, air fans, and air pipes onto the mine layouts.

The simulation was calibrated using measured data to adjust the component parameters, specifically air mass flow, barometric pressure, dry-bulb temperature, and humidity.

Finally, the accuracy of the simulation was verified by determining the accuracy error and comparing the measured data to the simulation results at specific locations. If the accuracy error was below 5%, the simulation was considered accurate and was used to identify inefficiencies. If the error exceeded 5%, all the steps from benchmarking onwards were repeated until a satisfactory result was achieved.

Selection of software

The following deciding criteria were used to determine the software best suited for this study.

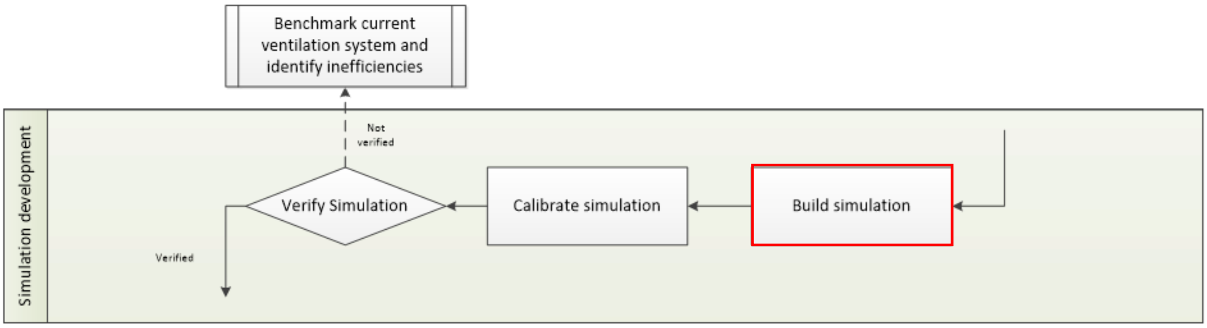
- Accuracy of the simulation
- Integrated software
- Calculate cost savings
- Familiarity
- User-friendliness

Table 11: Evaluation of simulation software

Simulation software	Accuracy of the simulation	Integrated software	Calculate cost savings	Familiarity	User-friendliness
VentSim	✓				
VUMA	✓	✓			✓
PTB 3D	✓	✓	✓	✓	✓
Environ	✓				

By evaluating the different simulation software using the first two criteria points, VUMA and PTB stood out. This is because both have advantages and could be considered suitable for this study. However, PTB was considered the most suitable due to its cost-saving calculations, accurate results, user-friendliness and familiarity.

3.4.1. Build ventilation simulation



This section focuses on constructing a ventilation network simulation for Mining complex A using Process Toolbox 3D mine ventilation simulation software. First, the ventilation model was built by using the acquired DXF files.

The simulation was built by placing nodes and connections onto the DXF-level layouts to identify the locations for the haulages and shafts. Airflow direction and ventilation control devices were added to the skeleton and placed according to the data gathered.

Due to Shaft C being inactive and inaccessible underground the ventilation network simulation was based on data gathered from the mine and simplifications needed to be made to the network.

Similarly to Shaft C most of Shaft B is inactive. Although some mining takes place the shaft is mainly still active to serve as a secondary escape route for Shaft A. Thus some assumptions had to be made on the directions of airflow and size of haulages were inaccessible. These assumptions were based on data gathered from mining personnel. The simulation was constructed to mainly focus on Shaft A due to the above-mentioned reasons, however the impact of the Shaft B and C on Shaft A is still considered.

The simulation model only represented the ventilation network of Mining complex A. Figure 31 illustrates the ventilation skeleton simulation model of Shaft A.

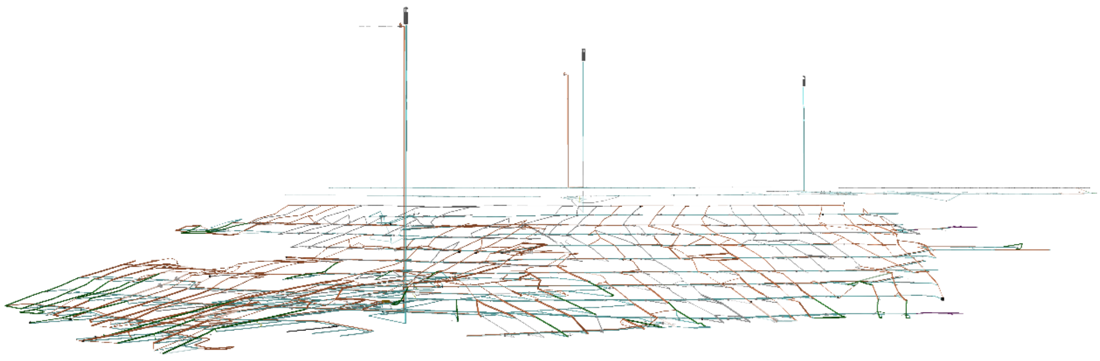
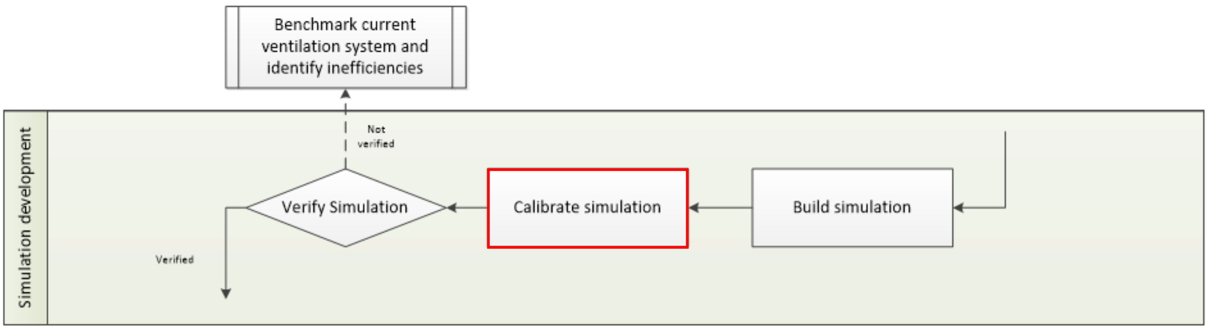


Figure 31: Ventilation simulation of Mining Complex A

The simulation shown in Figure 31 still needed to be calibrated before it could be used to identify inefficiencies and develop solutions.

3.4.2. Calibrate the simulation



Firstly, the surface fans were calibrated. The performance curves gathered from the mining personnel were used to calibrate the simulation. Figure 32 shows the operational point of Shaft A's Surface fan 1.

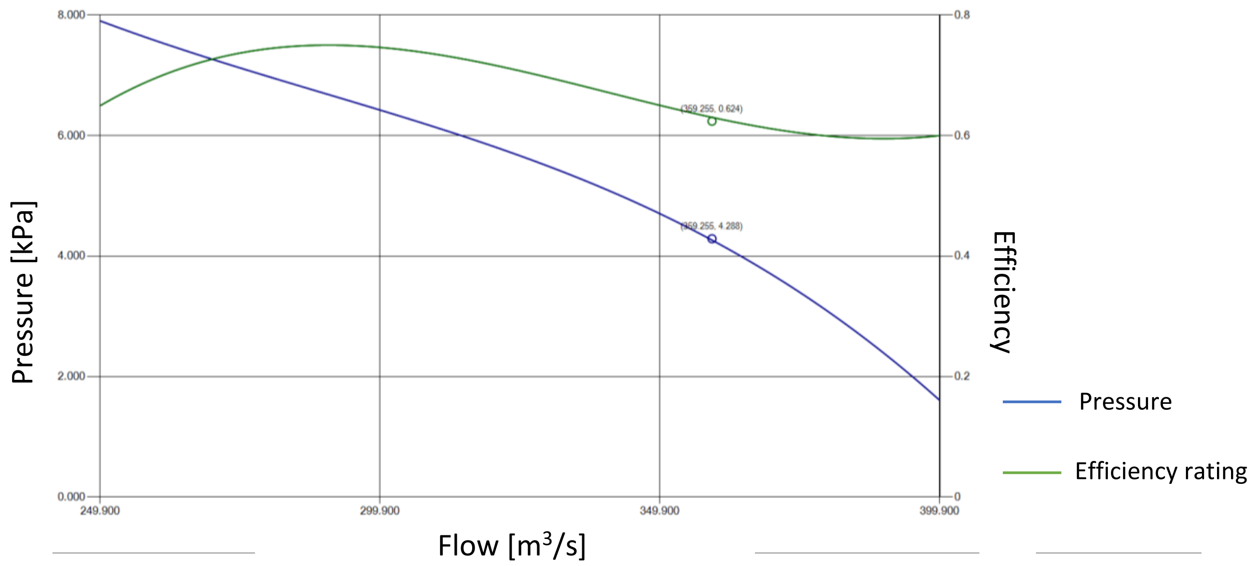


Figure 32: Shaft A's Surface fan one operational point

After the surface fans were calibrated, the underground systems could be calibrated. The remainder of the simulation was calibrated using calibration controllers and the following parameters:

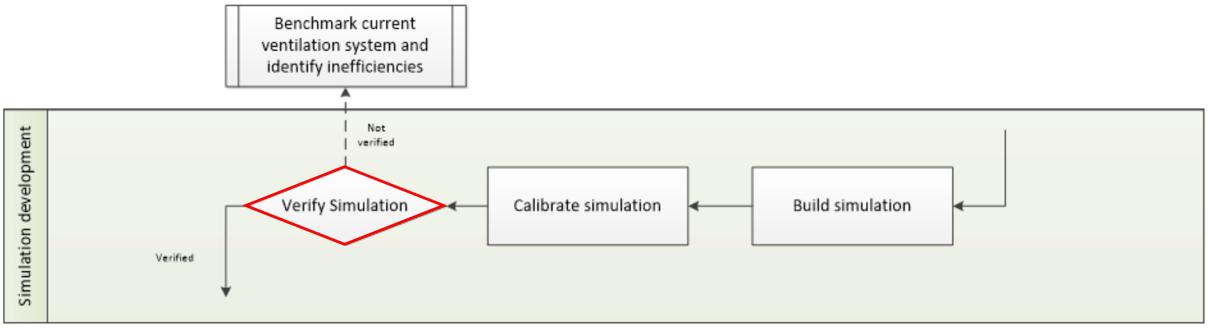
- air mass flow [kg/s] and barometric pressure [kPa],
- dry-bulb temperature [°C], and
- humidity [%].

An iterative approach was used to calibrate the simulation. The baseline simulation results for the last working area for each level are shown in Table 12. A complete set of results can be seen in Appendix B.

Table 12: Baseline simulation results compared to the actual measurements

	Air mass flow [kg/s]		Dry-bulb temperature [°C]		Wet-bulb temperature [°C]	
	Actual	Simulated	Actual	Simulated	Actual	Simulated
20 A West	0.25	0.25	32	33.2	25	27.2
22 A West	51.14	54.1	25	24.1	21	20.3
23 A West	24.5	24.7	32.5	30.7	26	27.6
24 A West	30.55	31.58	33	32.8	26.5	27
25 A West	25.51	25.51	28.5	27.9	24	24.7
26 A West	0.39	0.41	31	31.7	26.5	24.1

3.4.3. Verify simulation



To verify the accuracy of the simulation, the measured underground data were compared to the simulated data. The data were compared using the MAE method. The percentage error was calculated for the simulated and measured air flow through the surface fan for low-level verification.

The MAEs for the underground parameters and surface fan airflow are shown in Table 13, calculated using Equation (7).

Table 13: MAE results for simulation verification

Type	Unit	MAE
Air mass flow	%	4.378
Wet-bulb temperature	%	4.396
Dry-bulb temperature	%	4.249
Average surface fan flow	%	0.985

As shown in Table 13, all the parameters had an error margin percentage of less than 5%. The results show that the simulation was adequate and could be used to identify inefficiencies and simulate strategies.

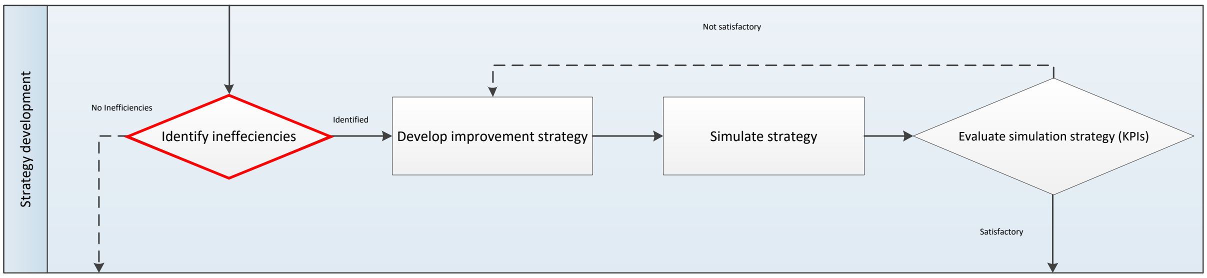
3.5. Case study 1

Data was gathered from the system investigation section of the project. This data and data from the previously developed simulation (see previous section) were used to identify an inefficiency in Case study 1. Based on this data, a solution was developed and implemented to address the identified inefficiency.

3.5.1. Phase 3: Strategy development

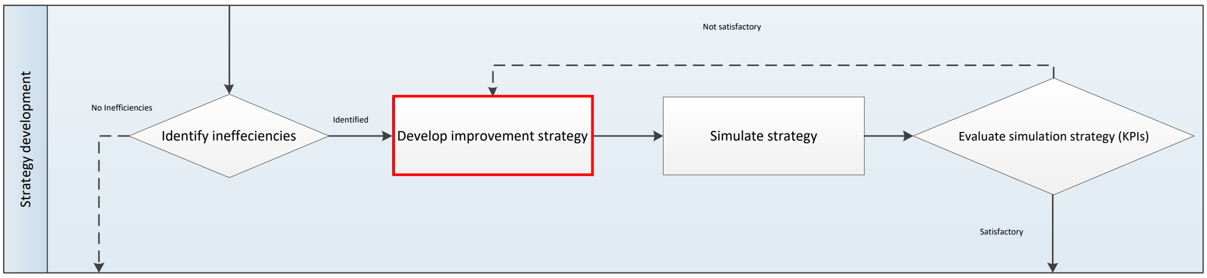
Using the simulation and the data gathered, an inefficiency was identified. Then, an improvement strategy was developed and simulated. Finally, the simulation result and the KPIs were used to evaluate the strategy.

Identify inefficiencies



A pending strike for the mining complex led to a need to find ways to reduce the energy consumption for the mine during that period. During the strike period, few to no workers would be underground, and no drilling and blasting would take place.

Develop improvement strategy

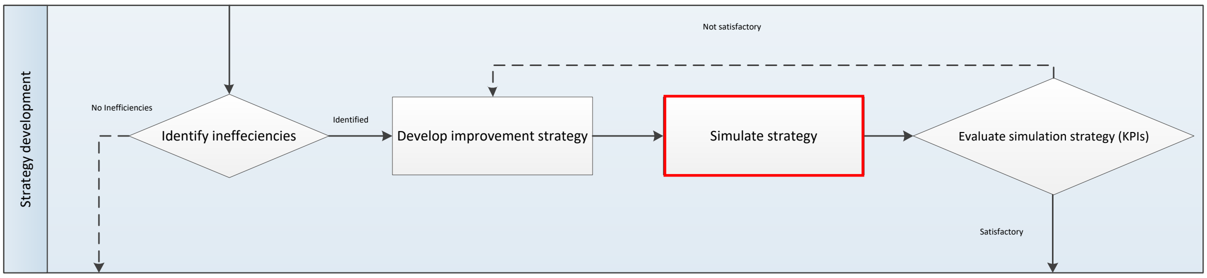


As work underground would be restricted to the main haulage, the ventilation in the stopes could be ignored. Thus, only maintaining safe working conditions in the main haulages had to be considered. Therefore, low air quantities were needed to maintain safe working conditions in the haulages.

The solution had to be temporary as the air demand would increase after the strike period. Thus, airflow control strategies would be best as they would be easiest to revert after the period.

Different air flow strategies considered include reducing the number of active fans and the frequency of the fans' VSDs. However, reducing the frequency would be challenging as the fans were already running on the manufacturer's lowest safe frequency. Thus, switching off the fans remained the best solution.

Simulate strategy



The strategy was simulated using the verified simulation. In addition, the necessary changes were made to the simulation, including reducing the number of running surface fans for Shaft A. Figure 33 illustrates the transition from three running fans on the left to two running fans on the right.

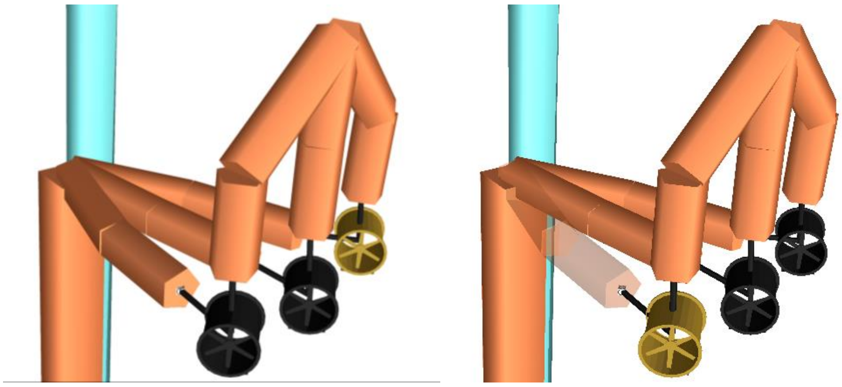
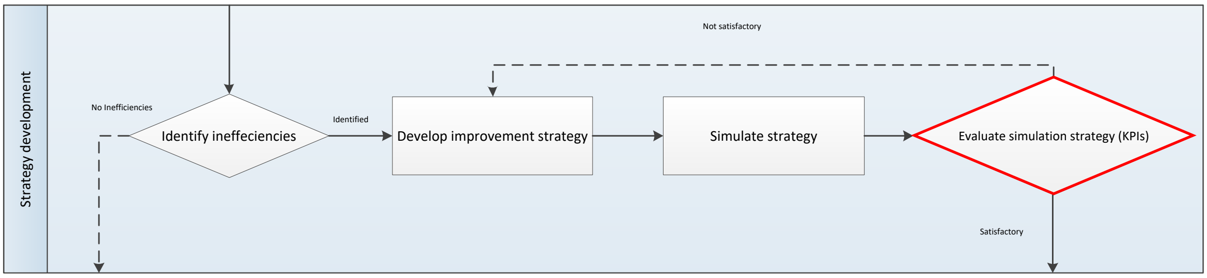


Figure 33: Reducing the number of running fans

The fan speed fraction was also adjusted to illustrate the frequency changes on the VSDs. To ensure enough air was pulled through the mine, the frequency had to be reverted to the manufacturer's preferred amount of 50 Hz. In addition, as work was limited to the haulages and no mining was to take place, the simulation parameters were changed to maintain safe working temperatures in haulages.

Evaluate strategy



Two KPI parameters were considered to evaluate the viability of the solution strategy. The KPIs were: maintaining safe working temperatures (below 37 ℃ dry-bulb and 32 ℃ wet-bulb) in the main haulages, and reducing the energy demand on the system. For the temperature, the average temperature on each level was used. The average simulated temperature is shown in Table 14.

Table 14: Average simulated temperatures per level

Level	Dry-bulb temperature [°C]	Wet-bulb temperature [°C]
20	32.99	29.44
22	27.98	23.98
23	33.85	29.9
24	32.65	29.25
25	29.01	26.47
26	30.14	26.52

As for the demand reduction, the simulated 24-hour power was compared to actual data to determine the expected demand reduction. Figure 34 shows the average 24-hour demand against the simulated demand.

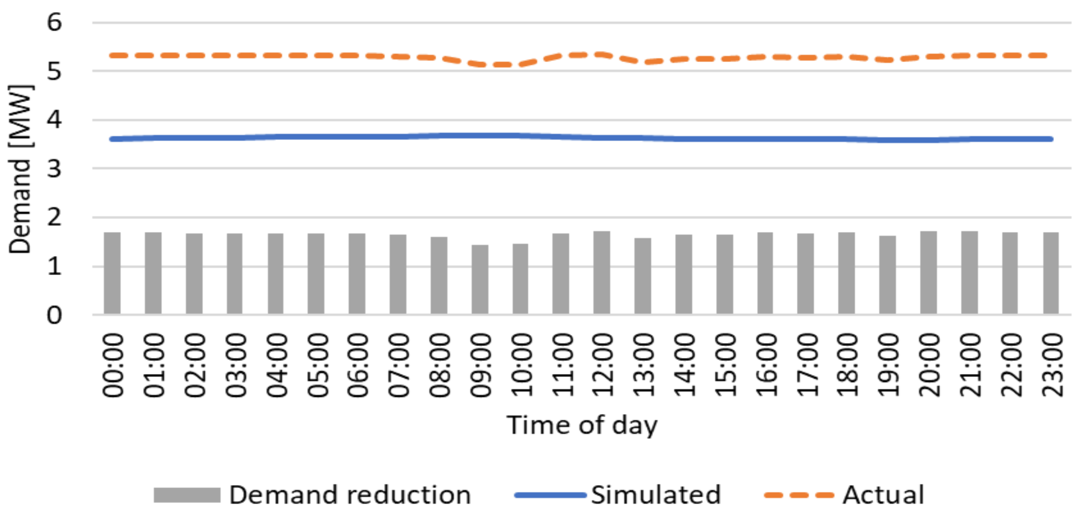


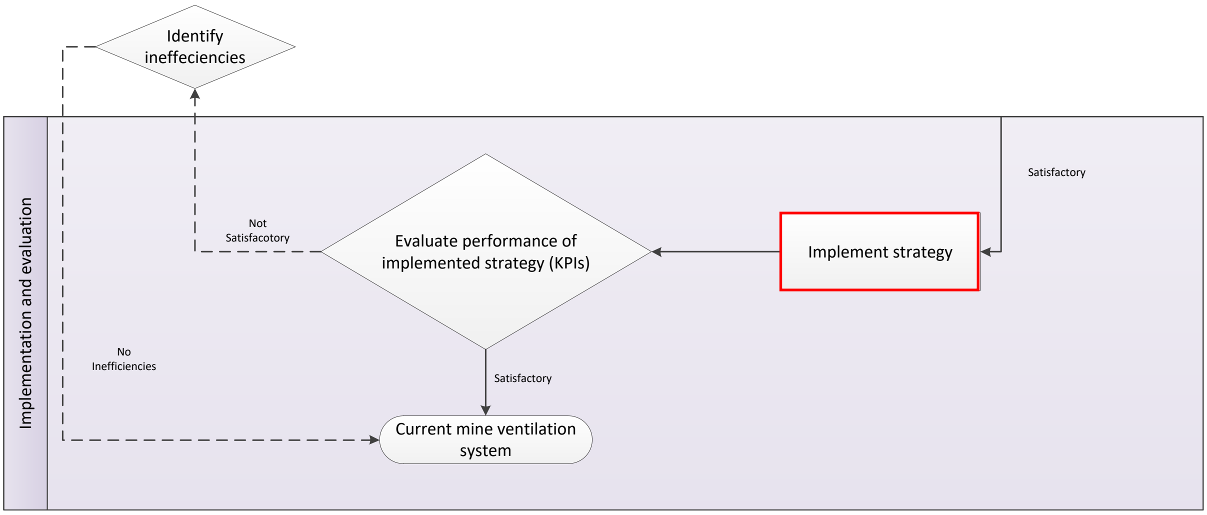
Figure 34: Simulated 24-demand against average demand

As depicted in Figure 34, the blue line, representing the simulated demand, is at 3.63 MW compared to the actual demand (orange line) of 5.28 MW. Thus, implementing the proposed strategy would reduce the power demand by 1.65 MW, while achieving an average underground temperate of 31.1 $°C$ dry-bulb and 27.59 $°C$ wet-bulb as shown in Table 14, which were below the maximum safe working temperatures shown in Table 1 (37 $°C$ dry-bulb and 32.5 $°C$ wet-bulb).

3.5.2. Phase 4: Implementation and evaluation

After the strategy had been developed and evaluated, the strategy needs to be implemented. Finally, the actual effect of the implemented strategy was evaluated.

Implement strategy



During the strike period, Shaft A's Surface fans 2 and 3 VSD frequencies were lifted to 50 Hz. Surface fan 1 was also switched off to reduce the power demand of the shaft.

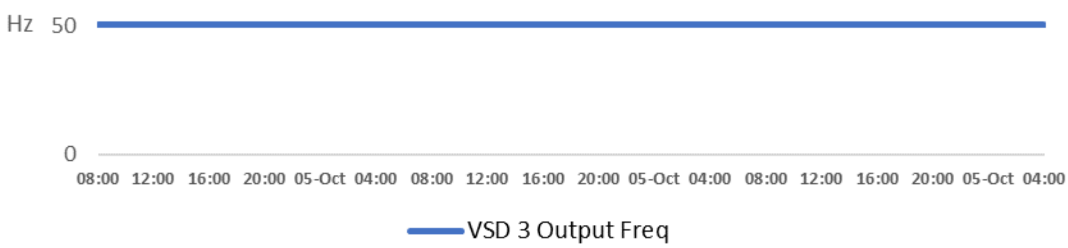
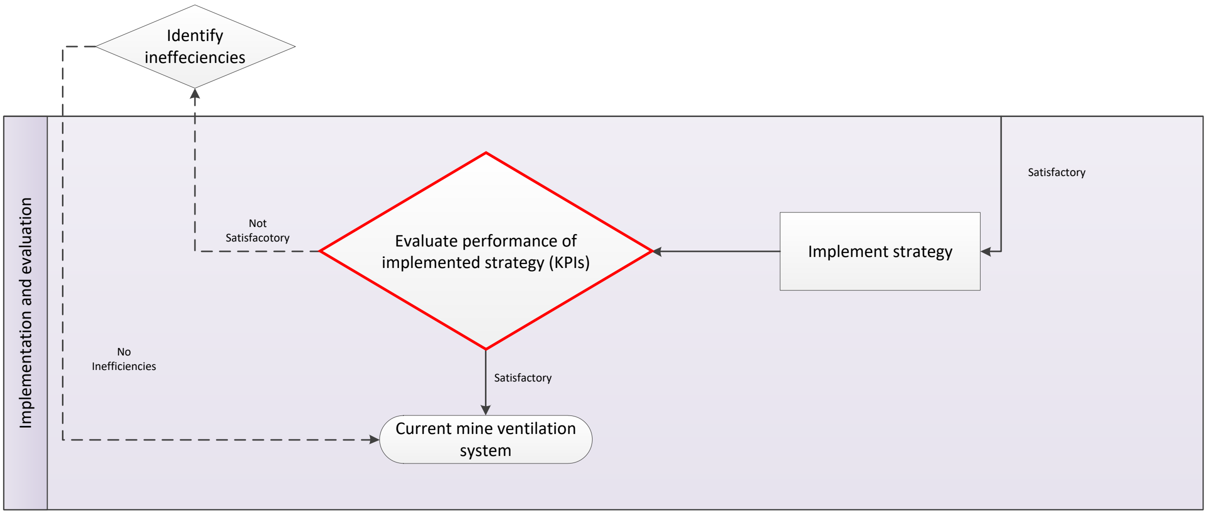


Figure 35: VSD for Surface fan 3 of Shaft A

Evaluate the performance of the implemented strategy



The performance of the implemented strategy was evaluated using the KPIs established in the Evaluate strategy section, namely maintaining safe working conditions and reducing the power demand.

However, due to safety restrictions, no temperature measurements could be taken. As the ventilation simulation was verified, the temperature was assumed to be within safe limits. Thus, only the energy demand could be used to evaluate the performance. Figure 36 shows the baseline demand (blue line), an average 24-hour profile of the months leading to the strike, against the actual demand of the surface fans during the strike period (orange line).

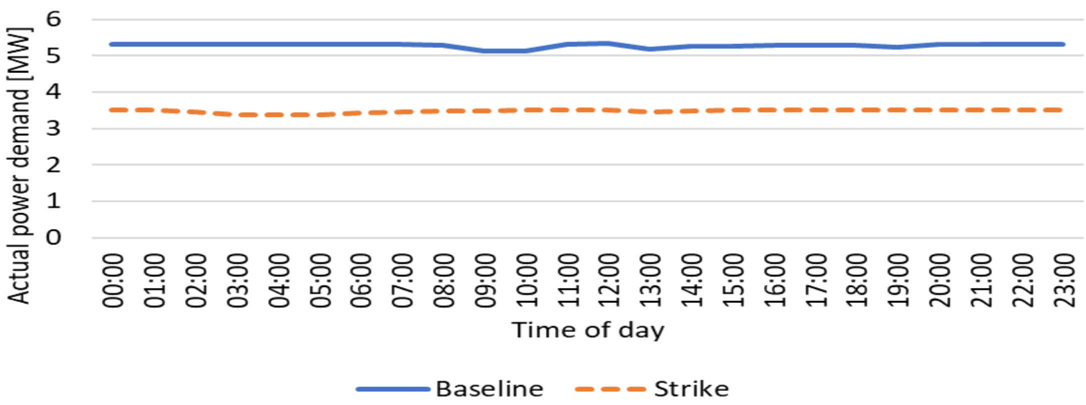


Figure 36: 24-hour average power demand baseline against the strike-period demand

As shown in Figure 36, the demand was reduced from 5.28 MW to 3.47 MW, leading to a demand reduction of an average of 1.8 MW during the period, resulting in an average saving of R 42 500 daily and a total saving of R 3.48 million during the 3-month strike period. The simulated demand was 3.63 MW the difference of 0.15 MW could be attributed to changes in the ventilation network or atmospheric conditions. As shown in Figure 37 the total demand for Shaft C stayed relatively constant throughout the period. A total demand reduction of 0.014 MW has however achieved and the mass flow dropped also to around 1 030 kg/s a drop in 40 kg/s.

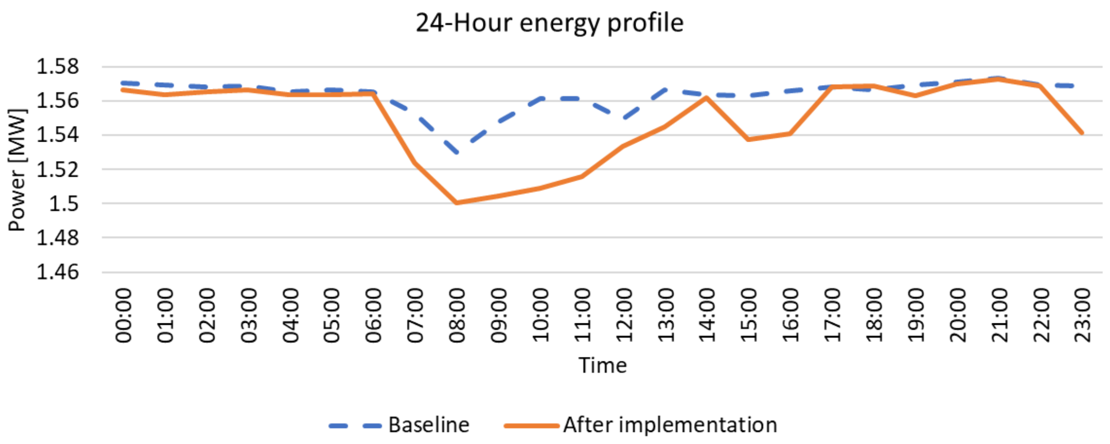


Figure 37: 24-hour average power demand baseline against the strike-period demand for Shaft C

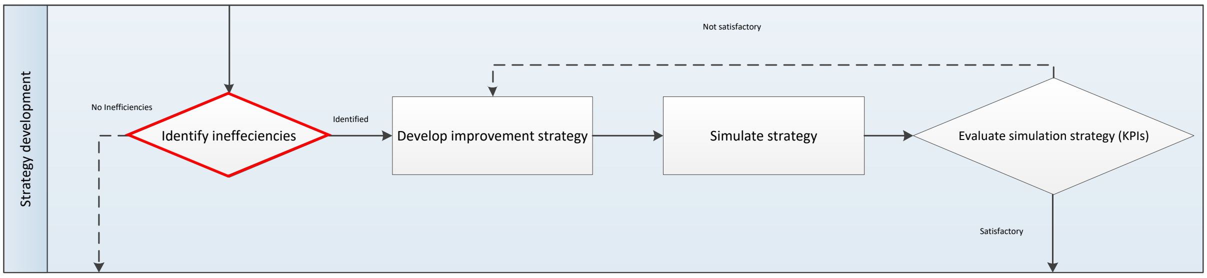
3.6. Case study 2

Data were gathered from the system investigation section of the project. This data and data from the previously developed simulation were used to identify an inefficiency in Case study 2. Based on this data, a solution was developed and implemented to address the identified inefficiency.

3.6.1. Phase 3: Strategy development

Using the simulation and the data gathered, an inefficiency will be identified. Then, an improvement strategy was developed and simulated. After evaluating the strategy, the simulation result and the KPIs were used.

Identify inefficiencies



A previously discussed section explained that Surface fan 2 of Shaft A may be operating inefficiently. The simulated operational point of the fan is in Figure 38. Figure 38 shows that the blue dot deviates from the fan curve, indicating a potential issue.

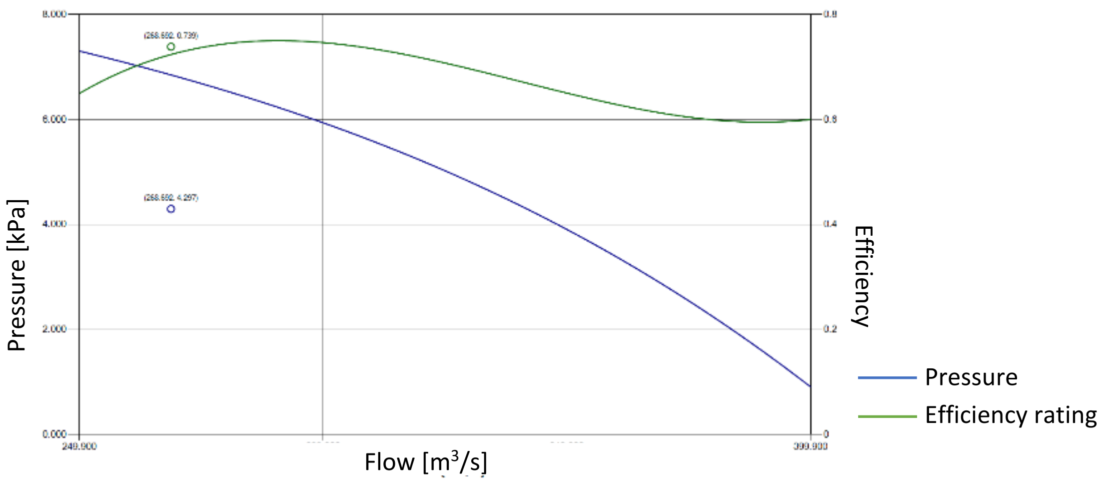
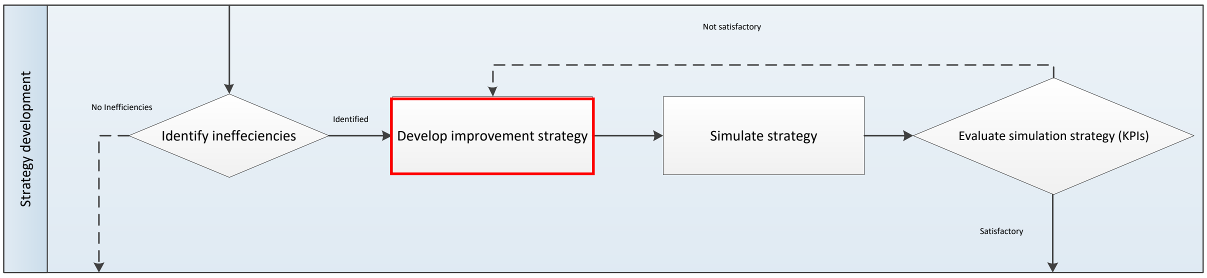


Figure 38: Simulated operational point of fan 2

Further investigation revealed that the fan cowling for this particular fan was broken and needed to be replaced and could be the reason of the deviation from the curve. To compensate for the resulting loss of air volume, the mining personnel increased the frequency on all three surface-fan VSDs. Unfortunately, this solution had increased power demand and higher energy costs. Therefore, it was necessary to identify and address the inefficiencies associated with the broken cowling and increased frequency to ensure optimal performance of the ventilation system in Mine A.

Develop improvement strategy



When it comes to improving the ventilation system in Shaft A, there were a few key strategies that could be implemented. These strategies aimed to address the inefficiencies identified with the broken cowling and increased frequency of the VSDs for Surface fan 2.

One strategy was to replace the broken fan cowling to restore the air volume to its intended level. This solution would require a short period of downtime for the fan. However, the benefits of increased efficiency and reduced energy costs would likely offset this inconvenience in the long term.

Another strategy was to change the frequency of the VSDs for all three surface fans. This could be achieved through careful analysis of the fan curves and the ventilation requirements of the mine. Adjusting the frequency to match the optimal operating point for each fan could reduce energy consumption while maintaining the necessary air volume for ventilation.

A third strategy was that introducing VSDs for the underground fans would allow for finer control over the air volume and pressure in the underground sections of the mine, reducing the need for frequent manual adjustments and improving energy efficiency. This strategy may require some initial investment, but the long-term benefits of reduced energy costs and improved ventilation performance would likely offset the upfront costs.

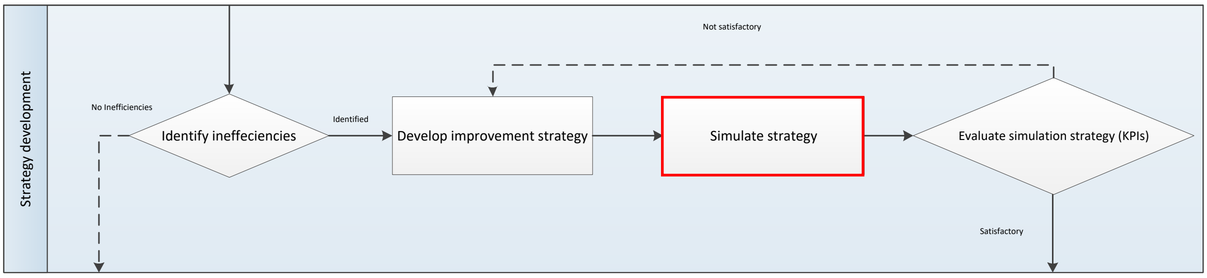
Overall, a combination of these strategies may be the most effective way to improve the ventilation system in Shaft A. By replacing the broken cowling, changing the VSD frequencies, and introducing VSDs for underground fans, significant energy savings could be achieved without compromising on the ventilation requirements of the mine. It is essential to carefully evaluate the costs and benefits of each strategy before implementing them to ensure an improved performance of the ventilation system.

Considering the labour-intensive and costly nature of installing VSDs on all underground secondary fans, combining the first and second strategies would be the most practical and effective solution. By replacing the broken fan cowling and lowering the frequency of the VSDs output frequencies for all three surface fans, significant energy savings could be achieved without compromising on the ventilation requirements of the mine.

This approach allows for a more targeted and cost-effective solution to improve the ventilation system in Shaft A. While introducing VSDs for the underground fans may provide finer air volume and pressure control, the potential costs and labour required may not be justifiable. However, by focusing on replacing the broken cowling and lowering the existing VSDs output, significant improvements could still be made to the ventilation system.

Combining the first and second strategies offered a balanced approach that considered each solution's potential costs and benefits. Therefore, it was essential to carefully evaluate the feasibility and potential impact of these strategies before implementation to ensure the improved performance of the ventilation system in Shaft A.

Simulate strategy



The simulation strategy involved modelling the changes in VSD frequency and fan cowling repairs to assess their impact on the ventilation system in Shaft A. A frequency output of 45Hz was selected as it corresponds to the minimum safe running condition specified by the fan manufacturer.

The speed fraction was adjusted to simulate the frequency changes, as shown in Figure 39. The simulation parameters were carefully selected to ensure safe working conditions of the ventilation system. By altering the simulation this way, it was possible to assess the potential energy savings and ventilation improvements that could be achieved by lowering the VSD frequency and repairing the fan cowling.

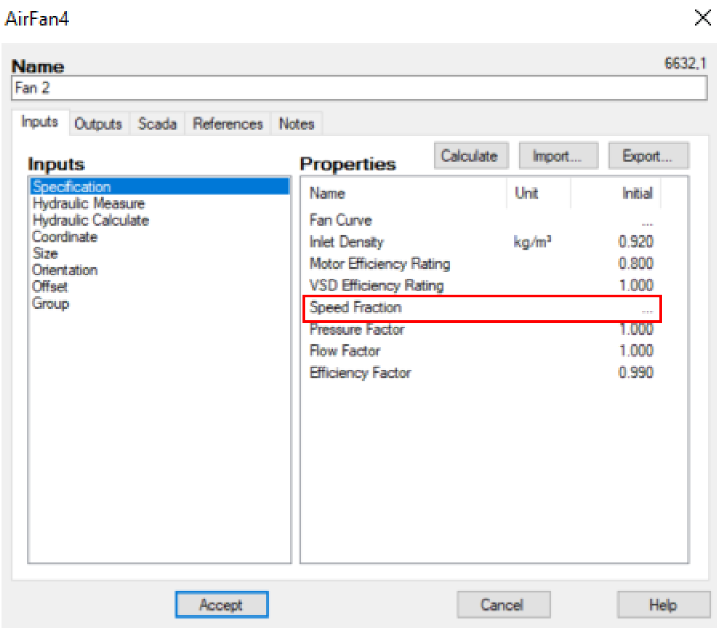


Figure 39: Simulating frequency changes in the surface fan

The air velocity, dry-bulb temperature, and wet-bulb temperature at specific simulated locations were averaged to see if safe working conditions were maintained. The resulting simulated data were then tabulated in Table 15 for each operational level.

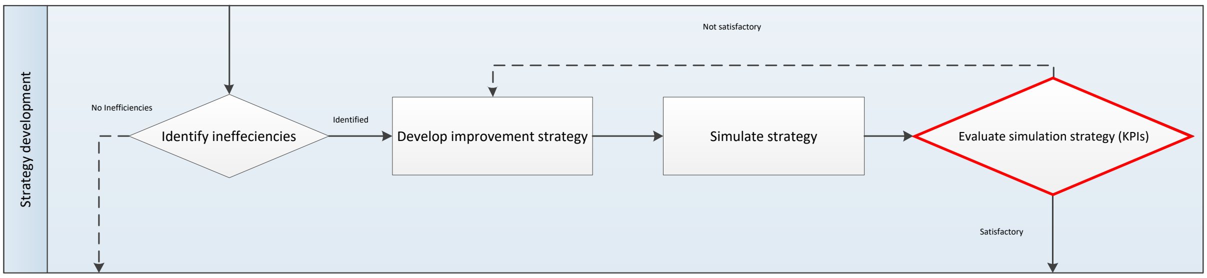
Table 15: Simulated results for Case Study 2

Level	Dry-bulb temperature [°C]	Wet-bulb temperature [°C]	Velocity [m/s]
20	33.6	30.9	0.55
22	36.9	29.7	0.45
23	33.1	30.8	1.18
24	32.9	30.3	0.78

25	32.3	29.4	0.78
26	32.9	29.9	0.75

As the results show in Table 15, the average simulated results were sufficient to ensure safe working conditions, despite the high humidity, as stipulated in Table 1 [30, 32, 33, 46, 47].

Evaluate strategy



In Table 15, the simulated results show that safe working conditions would be maintained. Table 16 shows the baseline and simulated average temperatures and velocity differences.

Table 16: Differences between baseline and simulated average stope temperature and velocity

	Baseline	Simulated	Change [%]
Dry-bulb temperature [°C]	33.4	33.6	0.51
Wet-bulb temperature [°C]	29.7	30.4	2.38
Velocity [m/s]	0.77	0.75	-2.34

As for the demand reduction, the simulated 24-hour power was compared to actual data to determine the expected demand reduction. Figure 40 shows the average 24-hour demand against the simulated demand.

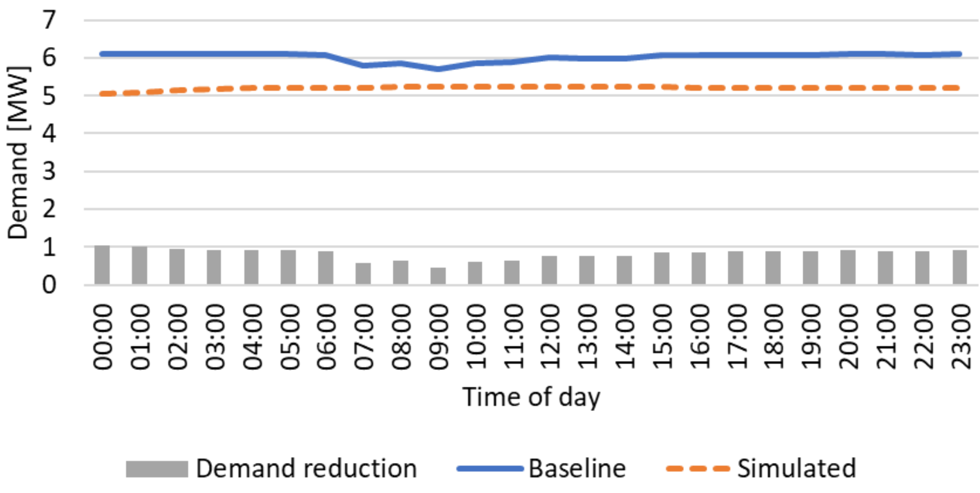
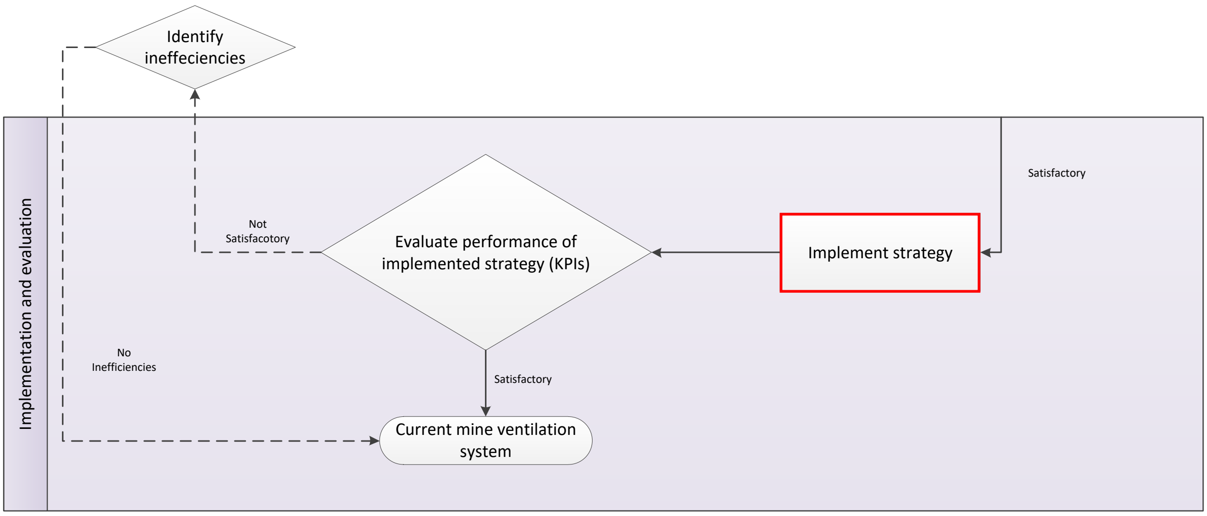


Figure 40: Simulated strategy power demand results against baseline demand

As shown in Figure 40, the simulated demand represented by the orange line was 5.2 MW, which was considerably lower than the actual demand (blue line) of 6.02 MW. Implementing the proposed strategy would significantly reduce the power demand by 0.82 MW while maintaining an average underground temperature of 33.6 °C dry-bulb, 30.36 °C wet-bulb and 0.75 m/s, as illustrated in Table 16. These temperatures are well below the maximum safe working temperatures outlined in Table 1, which are 37 °C dry-bulb, 32.5 °C wet-bulb and 0.5-1 m/s velocity. Therefore, the proposed strategy offered a viable solution for improving the energy efficiency of the ventilation system in Shaft A without compromising on the safety and comfort of the workers.

3.6.2. Phase 4: Implementation and evaluation

Implement strategy



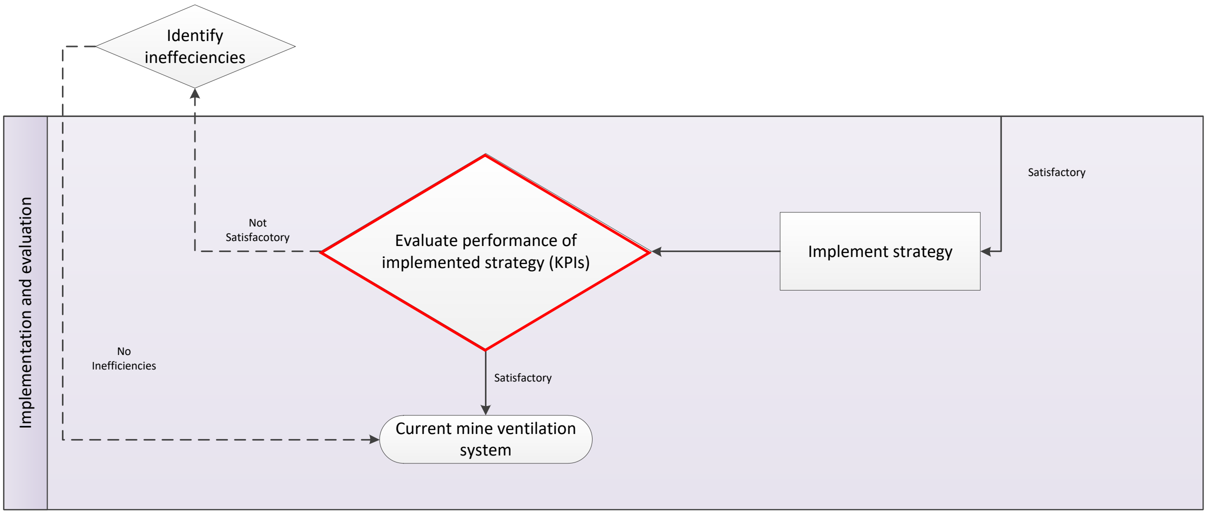
The proposed strategy was implemented by repairing the broken fan cowling on Surface fan 2 and adjusting the VSD frequency.

The first step involved repairing the broken fan cowling on Surface fan 2, restoring the fan's air volume and reducing the need to compensate by increasing the frequency of the VSDs. Specialised equipment and skilled personnel ensured that the required fan cowling repair was done safely and effectively.

The second step involved changing the VSD frequency on the surface fans. The desired airflow was achieved by reducing the frequency of all three fans which required careful calibration of the VSDs and close monitoring of the ventilation conditions to ensure the system operated safely and efficiently.

Once both steps were completed, the system was re-audited to verify that the desired improvements were achieved by adjusting the simulation parameters to reflect the new ventilation conditions and comparing the results to the simulation. Any further adjustments were made as necessary to optimise the system's performance.

Evaluate the performance of the implemented strategy



The mine was re-audited to ensure the effectiveness of the implemented strategy. The simulated results were compared to the actual measurements. Figure 41, Figure 42 and Figure 43 show the simulation and measurement results for 23 level.

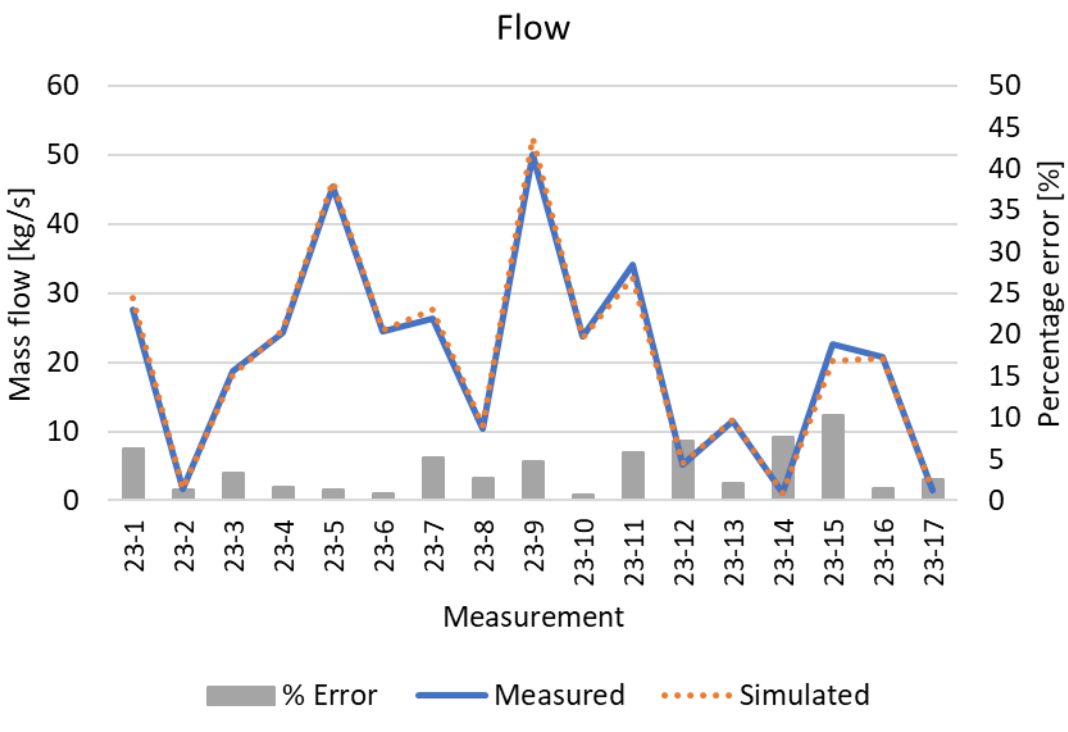


Figure 41: 23 Level flow simulated results versus actual results

The flow shown in Figure 41 had a MAE of 3.8%, indicating, by implementing the solution, that the simulation results were accurate. The opening and closing of ventilation doors and other ventilation control equipment could affect the measurements and explain the outliers.

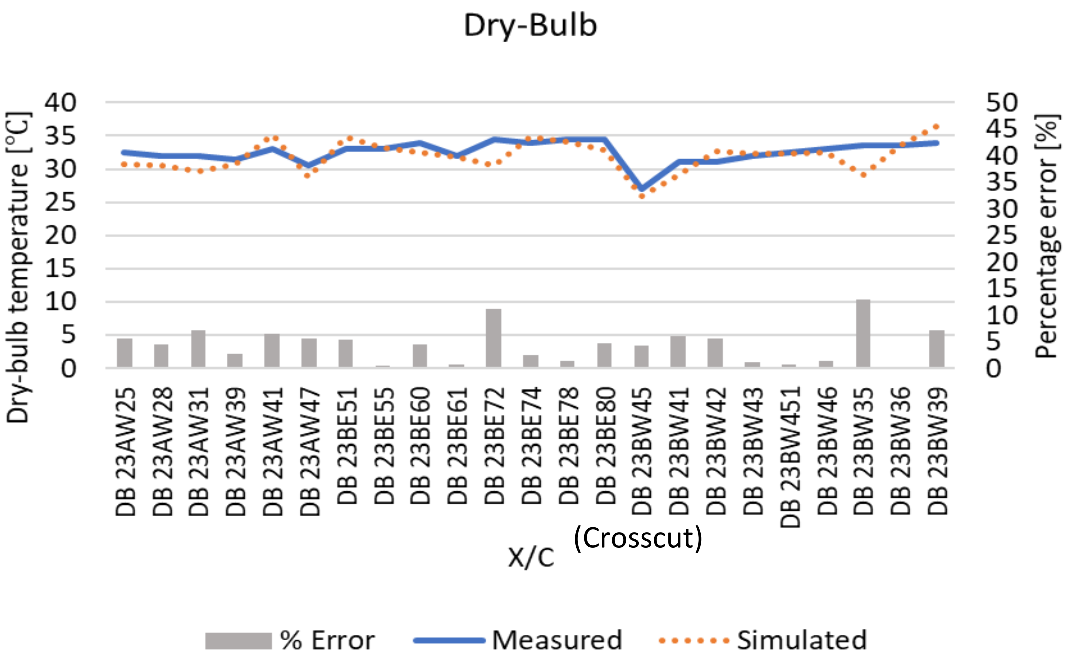


Figure 42: 23 Level dry-bulb temperature simulated results versus actual results

The dry-bulb temperature (Figure 42) and wet-bulb temperature (Figure 43) had MAEs of 4.4 % and 4.5 %, respectively. The ambient conditions on the surface could significantly impact the measurements taken and explain the outliers.

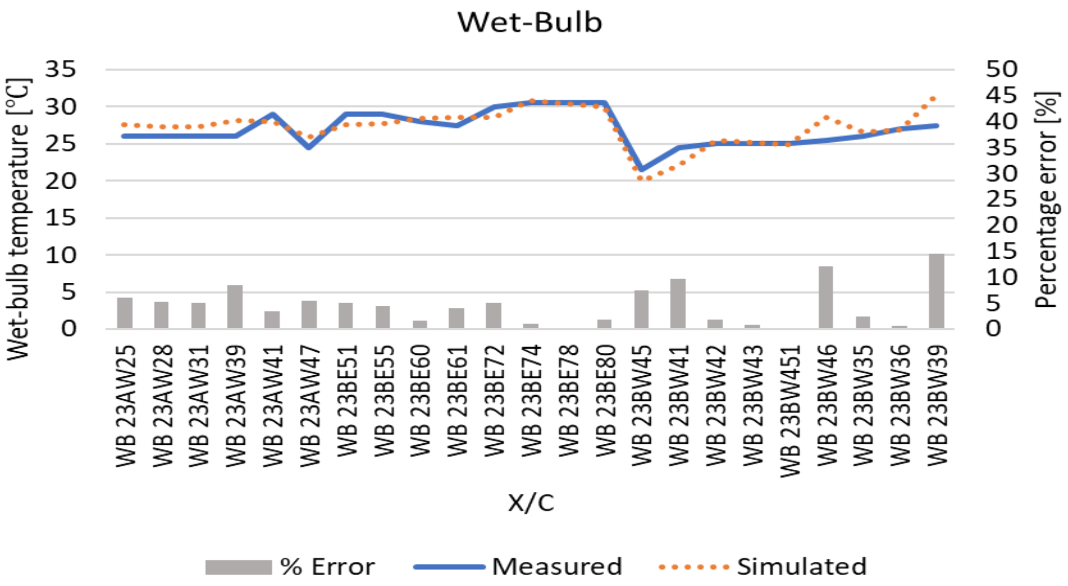


Figure 43: 23 Level wet-bulb temperature simulated results versus actual results

The results showed that the simulated results and actual measurements followed the same trend, with an average error below 5%. The outliers can be explained by the dynamic nature of the ventilation network, such as the opening and closing of ventilation doors that would affect the measurements.

The actual power demand reduction is shown in Figure 44. The blue line represents the baseline 24-hour average demand and the orange line represents the 24-hour average demand after implementation. The grey columns show the average demand reduction over 24 hours.

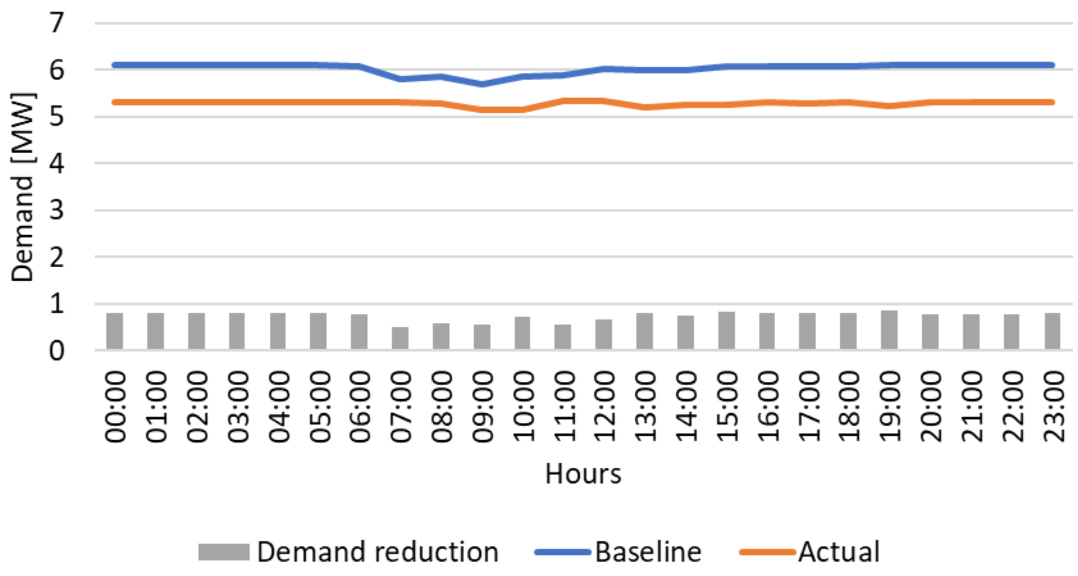


Figure 44: Actual 24-hour average ventilation demand reduction after implementation

After the implementation, the demand was reduced by 0.74 MW from 6.02 MW to 5.28 MW. The demand reduction roughly equates to a cost saving of R 7.19 million p.a. while still maintaining safe working conditions for the workers. The simulated demand was 5.2 MW the difference of 0.08 MW could be attributed to changes in the ventilation network or atmospheric conditions. Figure 45 depicts the demand reduction for Shaft C after implementation, as can be seen a significant reduction in demand is observed 0.114 MW. However, the changes made to Shaft A had an impact on the reduction in demand. Other contributions still needs to be considered, like the down scaling of Shaft C after the effects of the labour strike in case study 1.

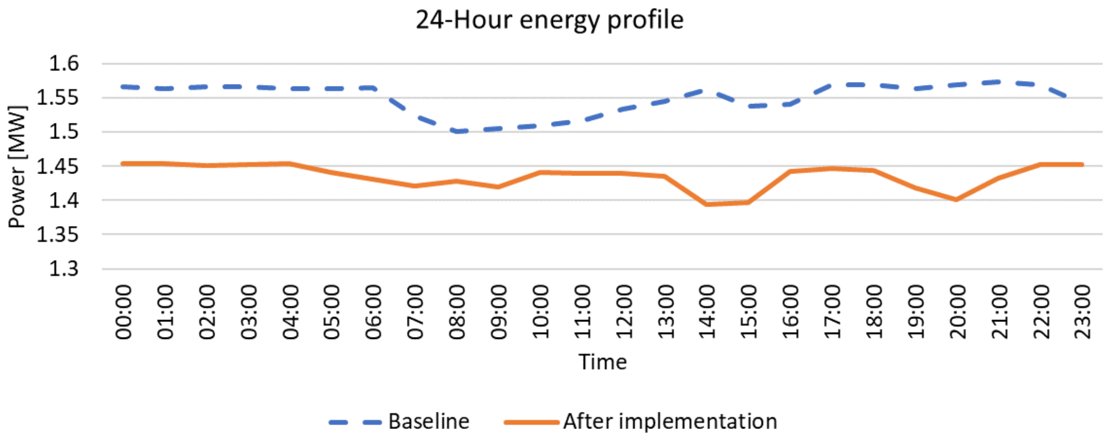


Figure 45: Actual 24-hour average ventilation demand reduction after implementation for Shaft C

3.7. Conclusion

The method developed (Objective 1) as described in Chapter Two, Figure 22, was used to improve the ventilation system for Mining complex A. Firstly, data were gathered during the system investigation to understand the ventilation network better.

Secondly, with the help of the data gathered, the ventilation network was simulated, calibrated, and verified. The verified simulation helped identify inefficiencies and develop strategies to improve the system.

For Case studies 1 and 2, the simulation was used to simulate the proposed improvement strategies. In Case study 1, it was decided to run only two surface fans and increase the VSD output frequency. For Case study 2, it was decided to repair the cowling of the fan and decrease the VSD frequency output. In both scenarios, the simulation was used to prove that safe working conditions would be maintained. By implementing the strategies, the mining complex A saved R 3.28 million during the three months in Case study 1 and R 7.19 million p.a. for Case study 2, all while maintaining safe working conditions.

The integrated ventilation network was improved by implementing the derived method on Mining complex A to reduce operational costs (Objective 2). Using ventilation control and simulation software, the derived method proved beneficial in improving the integrated ventilation network and reducing the operational costs of Mining complex A.

Chapter 4: Conclusion

Figure: Surface fan motor[4]

"The best investment is in the tools of one's own trade." – Benjamin Franklin

[4] S Louw, Personal photograph, Welkom, 2023

4. CONCLUSION

4.1. Preamble

The chapter summarises the study overview, encompassing the study background, problem statement, methodology, solution and results. This is followed by examining the shortcomings and limitations encountered during the research process. Lastly, concluding remarks for the study are discussed.

4.2. Study overview

The gold mining industry in South Africa has seen a steady decline in productivity in the past years. Some factors include increasingly high operational costs, with rising electricity tariffs being a leading cause.

With ventilation and refrigeration systems responsible for around 28% of a typical gold mine's electricity usage and the system's inefficiencies due to the management, complexity, and dynamic and integrated nature of ventilation systems, there is a need for initiatives to improve and reduce the operational costs of ventilation systems.

Simulation software makes it possible to represent complex deep-level ventilation systems accurately. In addition, ventilation simulations give a better representation and understanding of the airflow distribution and ventilation network. Accordingly, ventilation simulations can identify potential energy-saving initiatives and evaluate whether initiatives are feasible to implement.

Integrated ventilation networks add new branches and ventilation control devices to an increasingly complex system, thus increasing the difficulty of managing the ventilation networks and expressing the need for simulation software to evaluate the system.

Thus, energy-saving initiatives on gold mine ventilation systems were investigated to reduce operational costs. Minimal literature was found on improving integrated ventilation networks using simulation software and ventilation control.

Using existing research, a method was derived to improve integrated ventilation networks by implementing ventilation control methods and simulation software. The method can be summarised in four phases: system investigation, simulation development, strategy development, and implementation and evaluation.

The method was used to improve the ventilation network of Gold mining complex A in two case studies. The mining complex consists of three integrated shafts. Two of these are active (Shaft A and B) and one is inactive shaft (Shaft C). Shafts A and C cast air down and up and Shaft B is only downcasting. Shaft B also supplies Shaft A with fresh air through a decline.

In Case study 1, the system was investigated, and a simulation was developed. The simulation was verified using measured data with less than 5% MAE. Due to a pending labour strike, the ventilation electricity demand had to be lowered. With the aid of the simulation, it was decided that one surface fan on Shaft A would be switched off, and the frequency output of the other fans would be increased. By implementing the solution, the demand was reduced by 1.8 MW, and a saving of R 3.48 million was achieved while maintaining safe working conditions in the main haulages.

In Case study 2, it was determined that the fan cowling of Surface fan 2 was broken. Therefore, the frequency output of all the fans was increased to compensate for the airflow reduction due to the inefficiency. With the help of the simulation, a new frequency output was chosen after the fan cowling had been fixed. As a result, the electricity demand was reduced by 0.74 MW and savings of R 7.16 million p.a. was achieved while maintaining safe working conditions.

The derived method, containing ventilation control methods and simulation, proved to aid in improving the integrated ventilation network for Mining complex A and reducing operational costs.

4.3. Achievement of objectives

The objectives for the study are given below:

1. Develop a method to improve integrated ventilation networks using simulation software and ventilation control.
2. Evaluate the feasibility of the method by implementing it on a case study.
    a. Develop a ventilation model of an integrated ventilation system using simulation software by
        i. calibrating the ventilation simulation and
        ii. verifying the accuracy of the simulations within a 5% MAE.
    b. Investigate the effects of implementing ventilation control methods using the simulation.
    c. Evaluate the different methods using the KPIs.
    d. Implement the ventilation control method on the integrated ventilation network.
    e. Validate the effects of the control method on the system.

The first objective was met in Chapter 2. Using existing literature, a method was developed to improve integrated deep-level ventilation networks using simulation software and ventilation control methods. The method was then tested in two separate case studies on the same mining complex to evaluate the feasibility of the method, as described in Chapter 3.

An accurate ventilation simulation was built, which was then used to identify inefficiencies and simulate solution strategies using ventilation control. The chosen solutions were implemented and the effects of the solutions was evaluated.

4.4. Shortcomings and recommendations for further studies

The shortcomings and limitations experienced during the study are summarised below:

- Generalisation: The study only focused on one specific gold mining complex. The findings and recommendations may not apply to all gold mines due to the diversity of ventilation networks and operational conditions. Implementing the method on different mining complexes will be beneficial.

- Data availability: The study relied on the accuracy and availability of the data required, such as ventilation measurements and energy consumption. Most of the ventilation data gathered was done manually by numerous people. Therefore, data inconsistencies may affect the results' accuracy and reliability.
- Assumptions and simplification: Due to the complexity and scale of the ventilation system, some assumptions and simplifications had to be made. These assumptions, although required, may lead to minor variations between the results and simulated performance.
- External factors: Due to the dynamic nature of an underground mining network, not all external factors could be accounted for consistently. These factors can affect the effectiveness of the proposed initiatives and include changing weather conditions, ventilation regulatory equipment and changing mining working areas.
- Time constraints: The time limitation for the study may have limited the scope of the investigation. Certain aspects of the ventilation networks of Mining complex A could have been better investigated. Other energy-saving initiatives could have been thoroughly investigated. Other mining complexes could also have been explored.

Considering the abovementioned shortcomings is essential when interpreting the results obtained or applying the findings in other mining operations. Therefore, these shortcomings should be considered in future research and finding ways to address these issues is crucial. Furthermore, by addressing the issues above, a better understanding of ventilation networks and improving these systems could be gained.

Recommendations for future work regarding this study and field are as follows:

- Comparative analysis: Include multiple mining complexes in the study. More mining complexes could assess the applicability and effectiveness of energy-saving initiatives. Applying the study to multiple scenarios will gain a broader understanding of ventilation networks. More energy-saving initiatives could be identified and investigated.

- Long-term monitoring: Long-term monitoring would enable more comprehensive data to be gathered. Continuous monitoring and evaluation could provide a more detailed and accurate understanding of the networks. The long-term effects of the energy-saving initiatives could be measured. Continuous system evaluation could lead to more cost-saving initiatives and inefficiencies identified.
- Integration with automation and control systems: Incorporating real-time monitoring and advanced measurement devices will lead to more dynamic control strategies. It would also enable faster response to network changes such as the weather. Further reducing the energy demand of these systems could be easier with real-time monitoring and control systems. Real-time monitoring would also aid in system investigation and data collection as the data would be readily available.
- Environmental impact assessment: Conduct comprehensive environmental impact analyses on mining ventilation systems, including greenhouse gas emissions, energy source sustainability and pollutant emissions. An environmental impact analysis would provide a perspective on the sustainability and the environmental performance of mine ventilation systems.

A comprehensive understanding of gold mining ventilation systems can be achieved by including these points in further studies, leading to improved energy efficiency, cost savings and environmental sustainability in the industry.

4.5. Concluding remarks

The study focused on investigating energy-saving initiatives for South-African gold mine integrated ventilation systems to reduce operational costs by using simulation software. A methodology was derived using similar studies and applied to two case studies on mining complex A. Significant improvements and savings were achieved when implementing the proposed methodology.

The results show the derived methodology's effectiveness in identifying and implementing energy-saving strategies. Significant electrical power reductions were achieved by improving fan operations, adjusting output frequencies, and fixing equipment inefficiencies while maintaining safe working conditions.

However, it is crucial to acknowledge the limitations of this study. The results and findings of the study focused on South African gold mines, and their applicability to different mining complexes may vary. Additionally, the study focused on improving the ventilation system to reduce operating costs without extensive investigation into factors such as environmental impact. Further research is recommended to address these limitations and expand our understanding of gold mine ventilation systems.

Overall, the findings in the study highlight the importance of energy-efficient ventilation systems in the gold mining industry. By implementing energy-saving initiatives and continuously improving ventilation network management, mining companies can reduce costs by up to R 7.16 million p.a. and contribute to a more sustainable and efficient mining sector.

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6. APPENDICES

6.1. Appendix A

Underground ventilation measurements

<u>Air velocity</u>

The air's velocity is measured using a rotating vane anemometer and a stopwatch. The anemometer, shown in Figure 46, measures the amount of air (in meters) that has traversed the vane. Then, the air velocity (m/s) is calculated by the Davis vane measurement divided by the duration of the measurement [97].

Figure 46: Rotating vane anemometer

The rotating vane anemometer, or Davis vane, has a measuring range of between 0.5m/s and 30 m/s. The measurement duration should not be less than 50 seconds, and every Davis anemometer comes with a calibration certificate indicating an adjustment factor to ensure accurate measurements [97]. The anemometer measurements should be done in a traverse method. The puff-puff method could be used if the velocity is below 0.5 m/s.

Traverse method

For the traverse method, the measurements should be taken in a laminar airflow section, far away from any obstructions or bend in the haulage that causes turbulent flow. In addition, the measurements should be taken in parallel with the laminar flow, with the Davis vane facing in the direction of the flow, starting at one corner, traversing the haulage from side to side or from top to bottom the entire cross-sectional area of the haulage until the opposite corner. Once done, take the Davis vane measurement and the duration the measurement took. Apply the adjustment factor to the measurement as shown in the calibration certificate [38].

Puff-puff method

The puff-puff method could be used when the velocity is lower than 0.5 m/s. A measuring tape or laser distance meter, a stopwatch, and a powder are needed. The puff-puff method also requires two people to take the measurement accurately [38].

The two taking the measurements should be standing some distance apart, parallel to the airflow direction, with one person puffing the powder in the airflow direction and the other person timing the duration of the powder from one end to the other. The distance the powder travelled is then divided by the duration to gain the velocity of the air [38].

<u>Flow area</u>

The flow area is essential to determine the airflow at a specific point. Therefore, a laser distance meter, depicted in Figure 45, is used to measure the dimensions of the haulage.

Figure 47: Laser distance meter

Three measurements of the height and breadth are taken at various positions within the haulage to ensure accuracy. These measurements are then averaged to obtain representative values. Finally, the averaged height and breadth are multiplied to calculate the haulage's cross-sectional area [19].

Airflow

The average airflow at the specific location is calculated by multiplying the velocity with the adjustment factor with the cross-section area. Then, the adjusted velocity is calculated using Equation (8).

$$v_{adjusted} = v \times F \qquad (8)$$

Where:

$v_{adjusted}$	-	Adjusted air velocity [m/s]
v	-	Measured air velocity [m/s]
F	-	Correction factor [-]

- Intake side factor- 0.92

- Outlet side factor- 0.82

Temperature

Temperature measurements are taken with a whirling hygrometer, shown in Figure 48. The whirling measures the dry-bulb and wet-bulb temperatures. The temperature measurements are taken in the middle of the haulage away from heat sources [19].

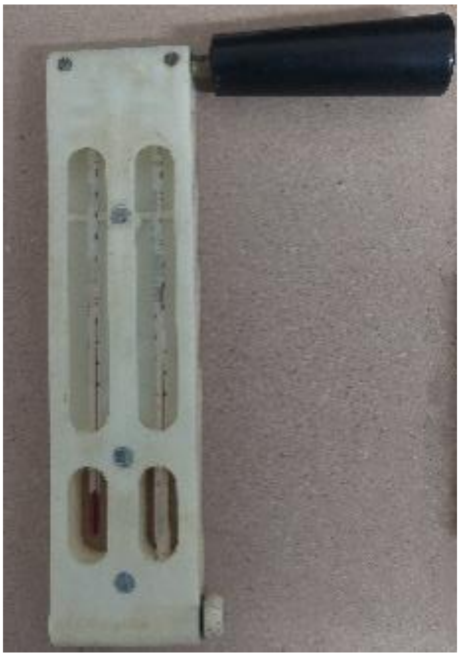

Figure 48: Whirling hygrometer

Barometric pressure

Barometric pressure is measured using a barometer, shown in Figure 49. With the barometric pressure and temperatures known, the air density can be calculated [97]. Using thermodynamic property tables specific to the air, the air density is typically expressed in kilograms per cubic meter (kg/m^3).

Figure 49: Barometer

Mass flow

The mass flow rate is gained by multiplying the air density by the volumetric flow rate [97], resulting in the mass of air moving per unit of time, as illustrated in Equations (9) and (10).

$$Q = v_{adjusted} \times A \qquad (9)$$

$$\dot{m} = Q \times \rho \qquad (10)$$

Where:

Q	-	Volumetric flow rate [m^3/s]
$v_{adjusted}$	-	Adjusted velocity [m/s]
A	-	Area [m^2]
$\dot{m}$	-	Mass flow [kg/s]
ρ	-	Air density [kg/m^3]

Audit sheet

Before the audits are done, knowing where the measurements will be taken is essential. Thus, while conducting an audit, the measurement location should be marked. The audit template sheet in Table 17 could be used to take the measurements.

Table 17: Underground ventilation audit template

Shaft											
Level											
Date											
Point	Pressure	Wet-bulb temperature	Dry-bulb temperature	Height			Breadth			Meters of air	Time
Unit	[kPa]	[°C]	[°C]	[m]			[m]			[m]	[s]
1											
2											
3											

Surface fan audits

The same equipment is needed when auditing the surface fans if the measurements can be taken within the fan ducting. Otherwise, a pitot tube and U-tube manometer determine the air velocity.

<u>Air velocity</u>

A pitot tube (Figure 48) and vertical U-tube manometer, shown in Figure 49, are used to determine the air velocity in a pipe or duct. The airflow velocity can be determined by inserting the pitot tube into the fan's ducting [97].

Figure 50: Pitot tube

Figure 51: Vertical U-Tube manometer

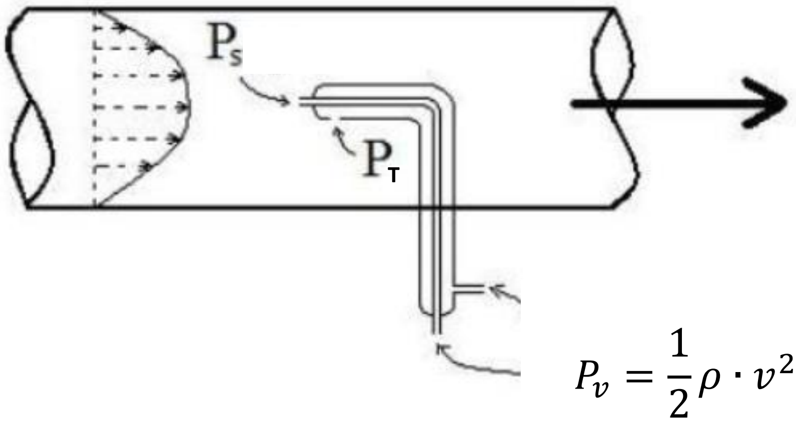

Figure 52: Pitot tube schematic

The setup shown in Figure 52 allows for the measurement of static and stagnation pressures. The difference between the two pressures gives the dynamic pressure [19]. With these measurements, as well as temperature and barometric pressure measurements (used to determine the air density), the air velocity can be calculated using Equation (11).

$$P_v = \frac{1}{2}\rho \cdot v^2 \tag{11}$$

Where:

P_v	Dynamic pressure [Pa]
ρ	Air density [kg/m^3]
v	Velocity [m/s]

Audit sheet

2 Shaft Surface Fan Audit					
Tatm (**WB)**		**°C**	Patm (**Pa)**		
Tatm (**DB)**		**°C**	Tube Radius		**m**
FAN 1					
Pinside (Pa)					
Tin (°C)					
Measurement	**Pitot Tube (Pa)**				
	Static	Total			
1					
2					
3					
4					
5					
6					
7					
FAN 2					
Pinside (Pa)					
Tin (°C)					
Measurement	**Pitot Tube (Pa)**				
	Static	Total			
1					
2					
3					
4					
5					
6					
7					
FAN 3					
Pinside (Pa)					
Tin (°C)					
Measurement	**Pitot Tube (Pa)**				
	Static	Total			
1					
2					
3					
4					
5					
6					
7					

6.2. Appendix B

The dry-bulb, wet-bulb and flow measurements and simulation results for the baseline at specific locations (x-axis), Case study 1 and Case study 2 are shown in this appendix. The blue solid line represents the measured values. The dashed orange line represents the simulated values, and the grey column shows the error percentage.

6.2.1. Baseline simulation and measurements

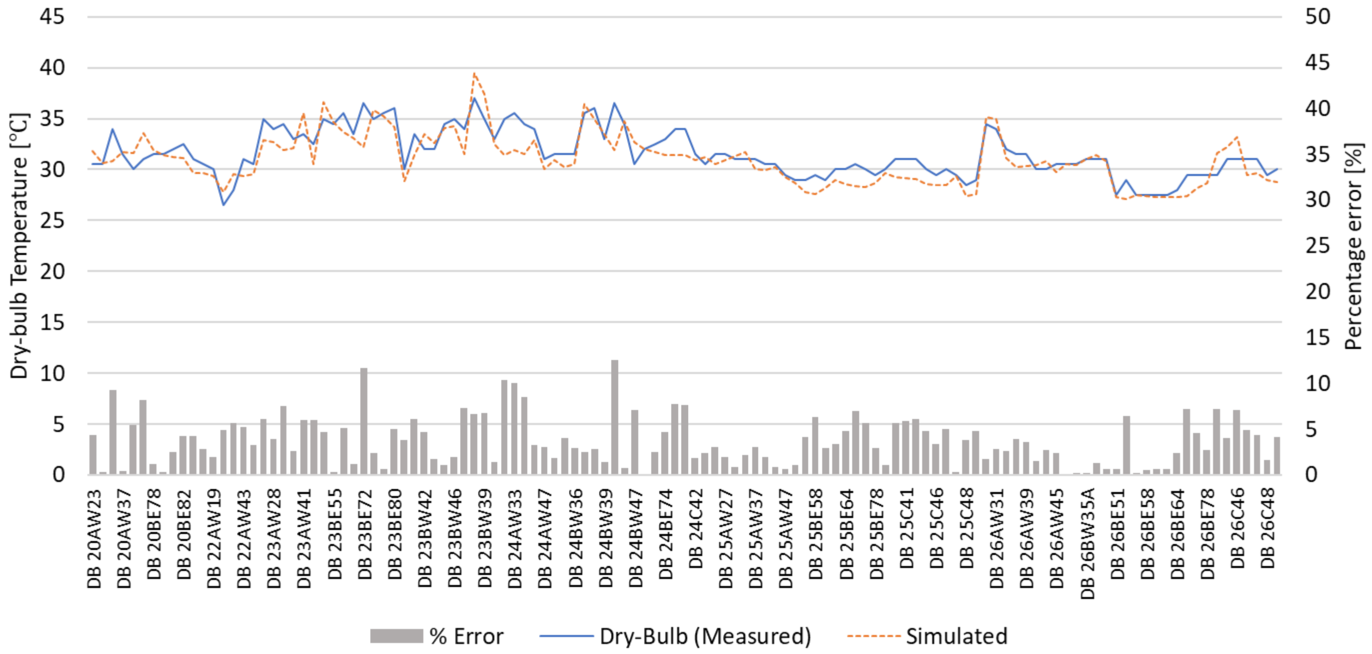

Figure 53: Dry-bulb temperature baseline measurements and simulation results

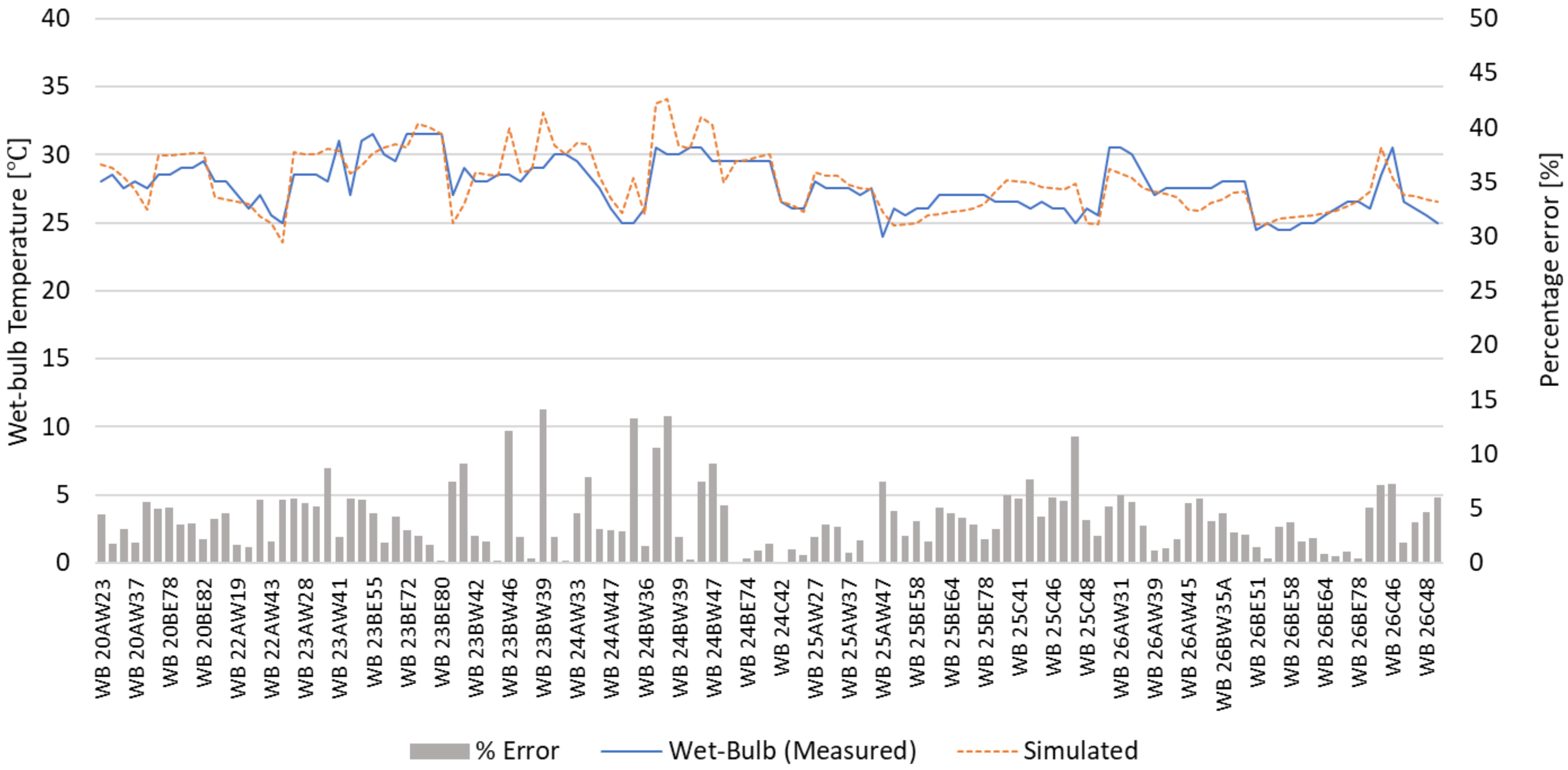

Figure 54: Wet-bulb temperature baseline measurements and simulation result

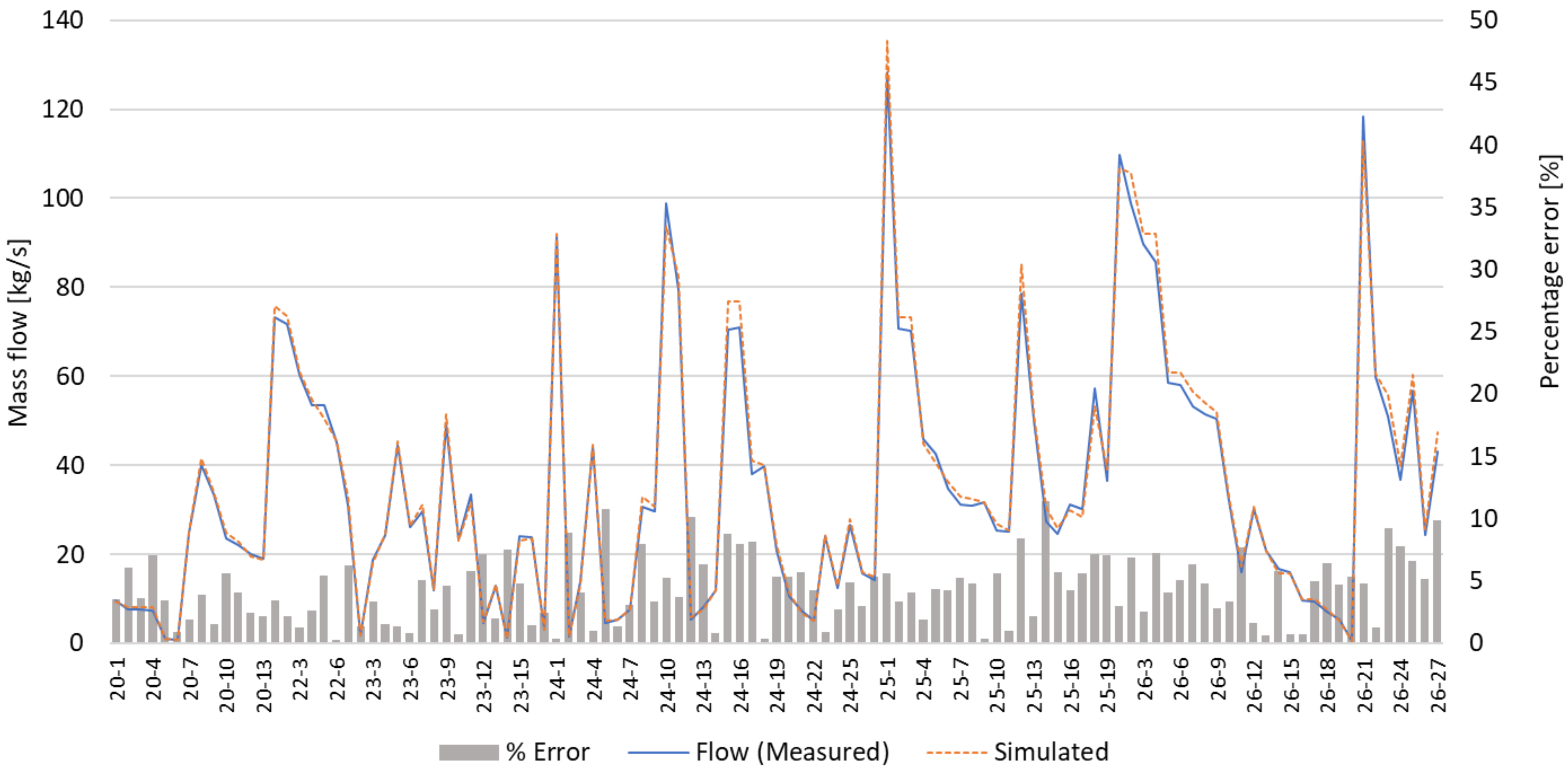

Figure 55: Mass air flow baseline measurements and simulation result

6.2.2. Case study one simulation results

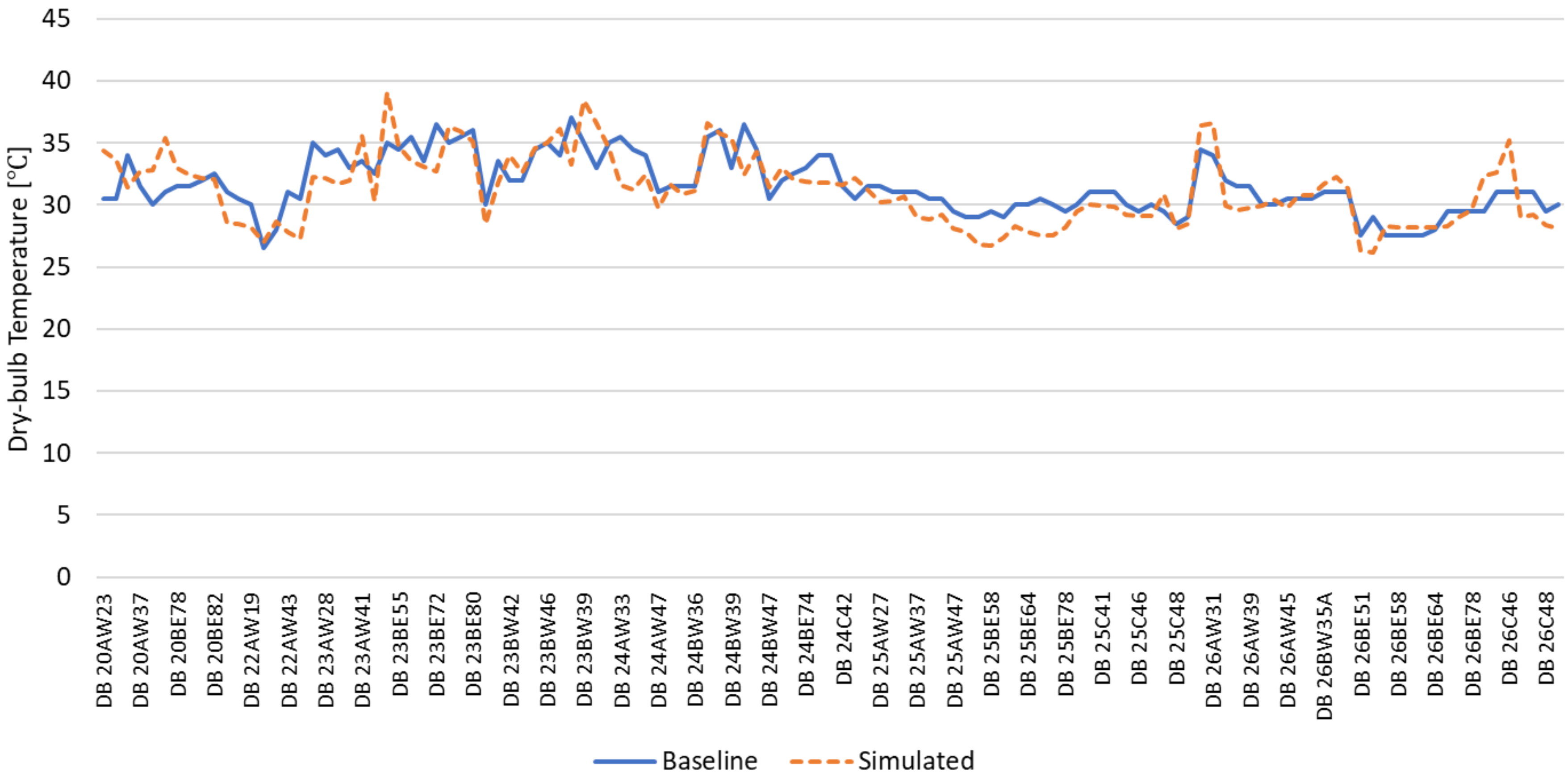

Figure 56: Dry-bulb temperature simulation results versus baseline for Case study 1

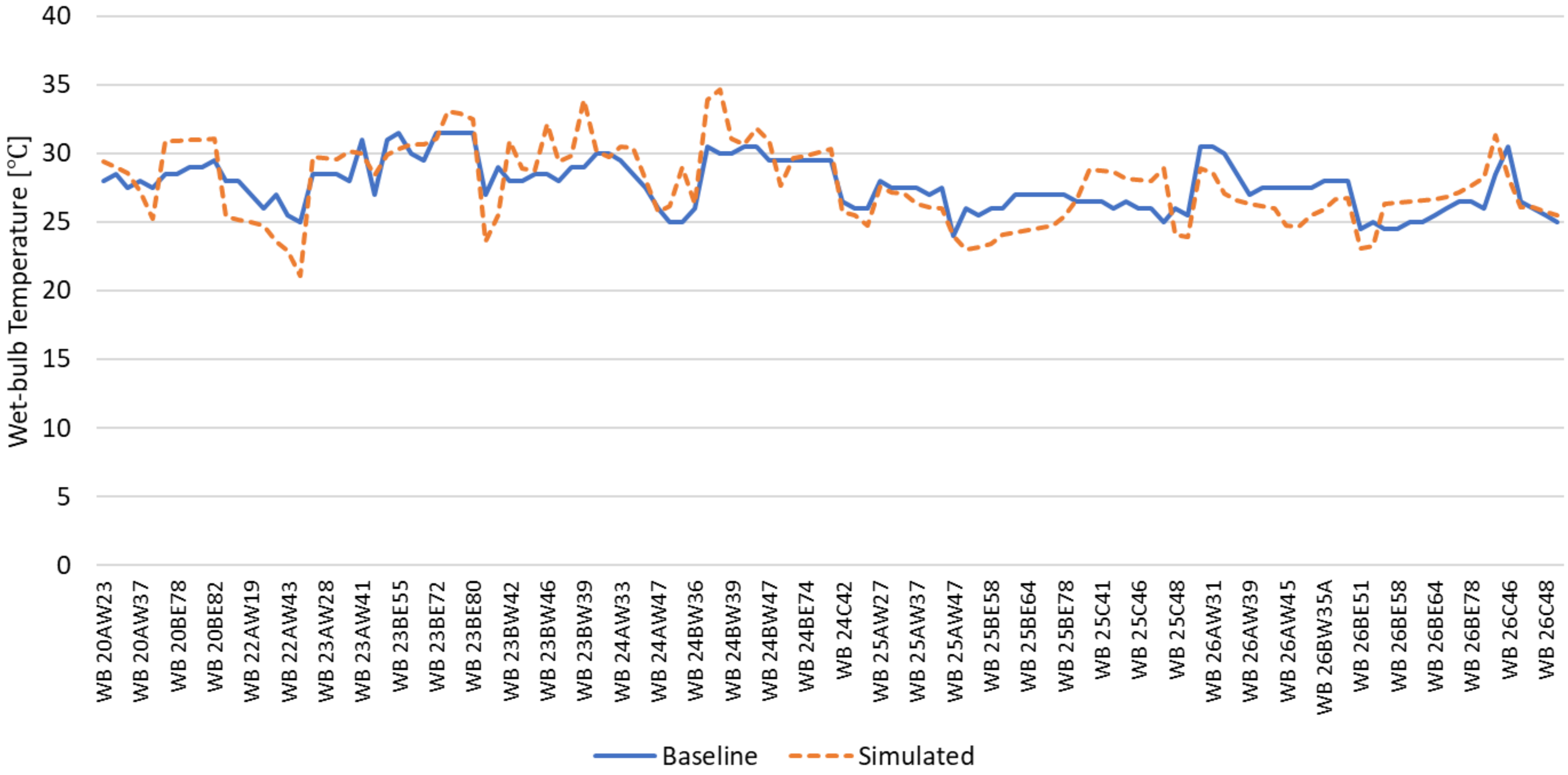

Figure 57: Wet-bulb temperature simulation results versus baseline for Case study 1

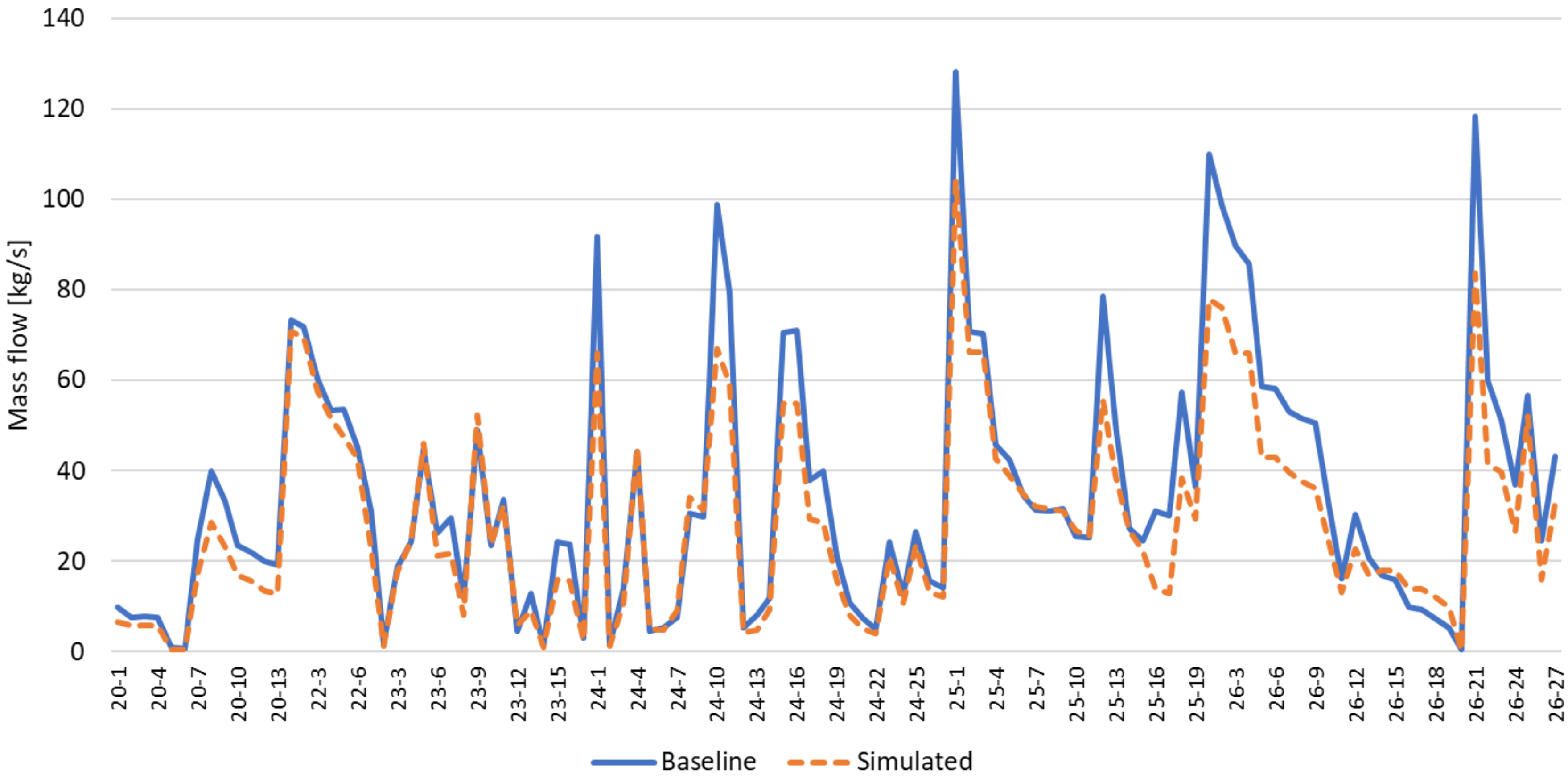

Figure 58: Air mass flow simulation results versus baseline for Case study 1

6.2.3. Case study two simulation results and measurements

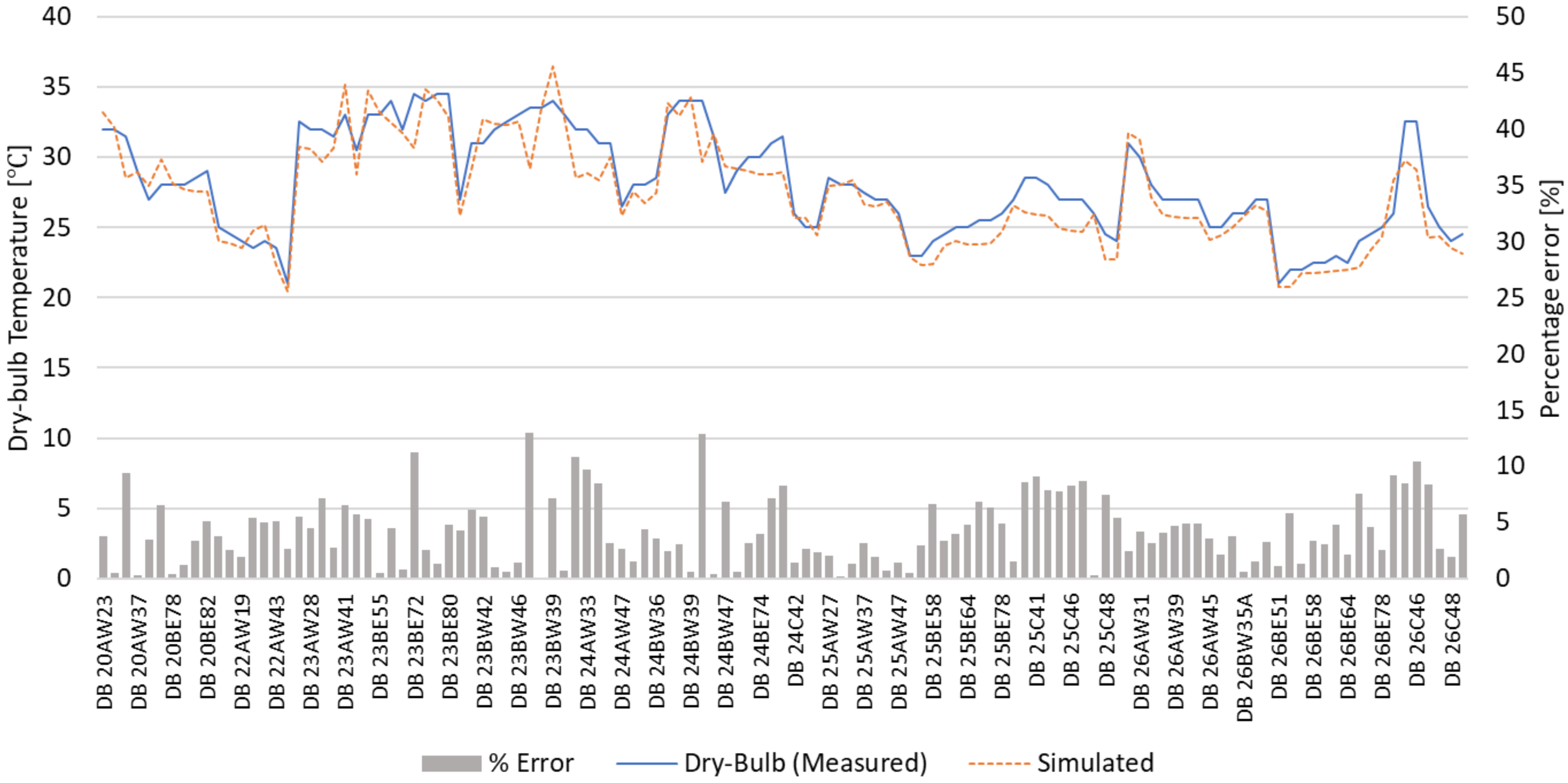

Figure 59: Dry-bulb temperature simulation results against measurements for Case study 2

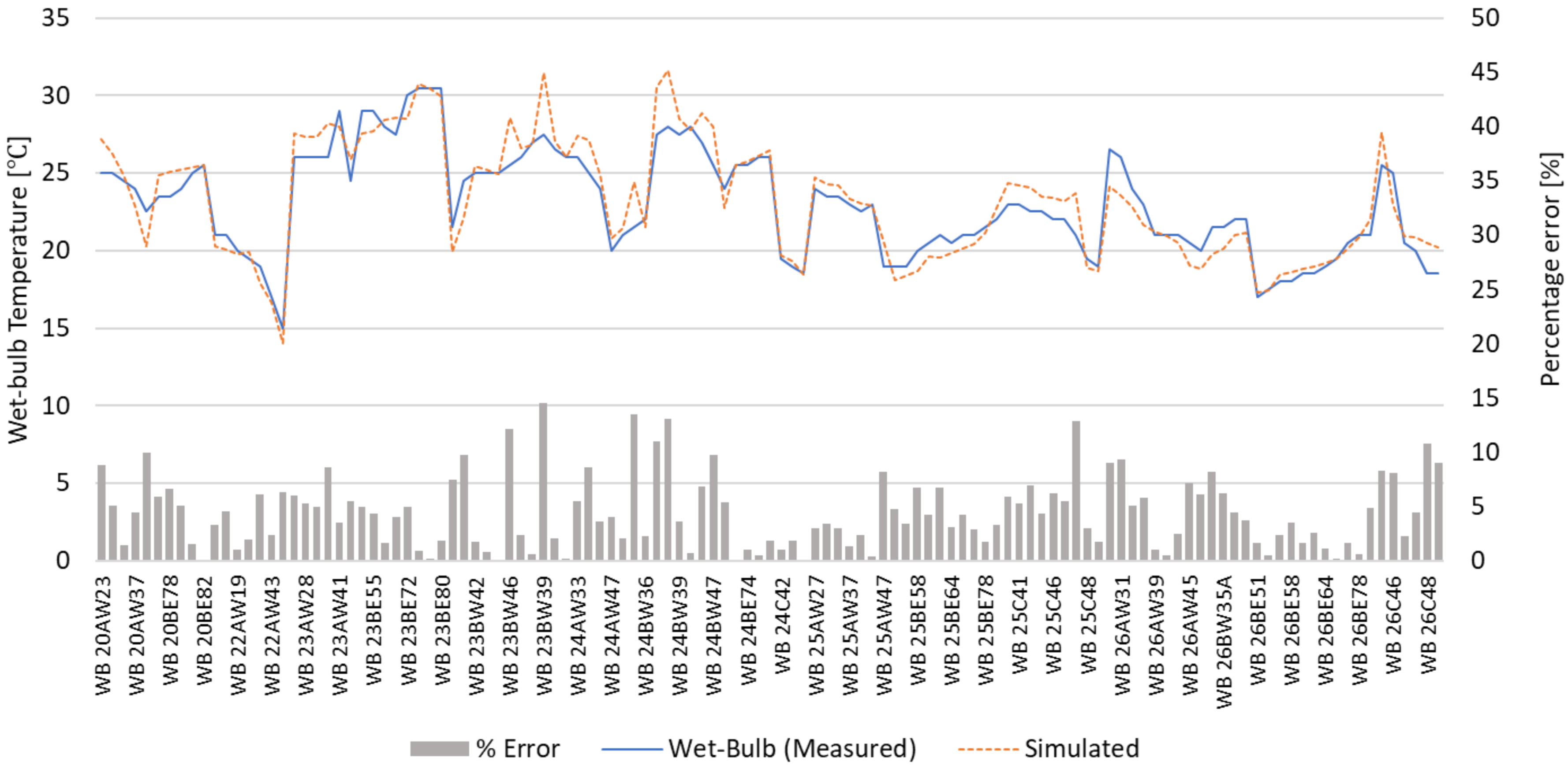

Figure 60: Wet-bulb temperature simulation results against measurements for Case study 2

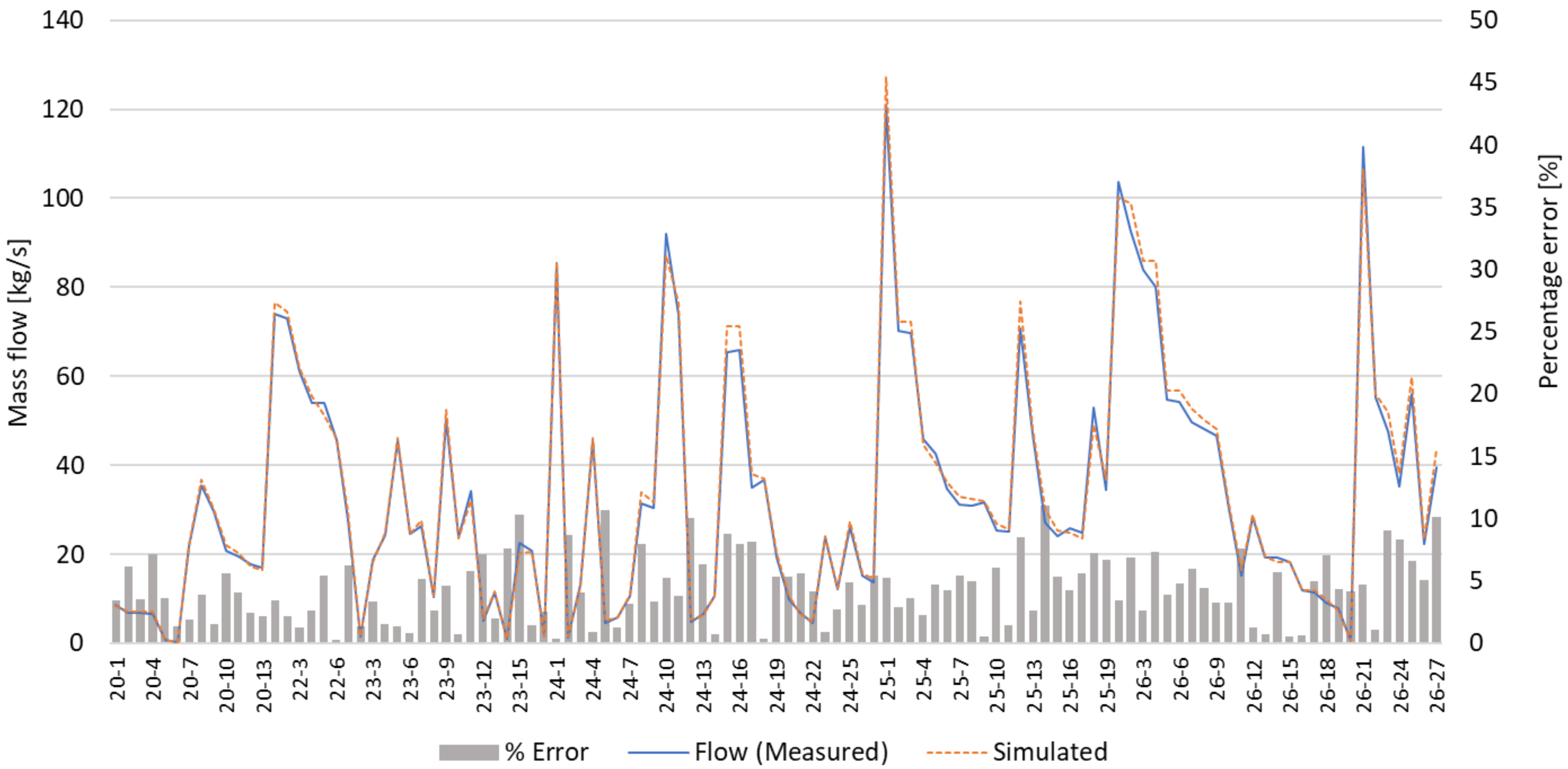

Figure 61: Air mass flow simulation results against measurements for Case study 2