Developing a digital twin for addressing complex mine ventilation problems

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ABSTRACT

Title: Developing a digital twin for addressing complex mine ventilation problems

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The ventilation system of a deep-level mine is complex and dynamic, which makes it challenging to identify changes in such a system and even more so to predict the effect of these changes with conventional approaches. An integrated approach is therefore required to analyse such complex scenarios while considering numerous variables. The purpose of this study is to derive a method for the development and application of a digital twin model for a deep-level mine ventilation system using such an integrated approach.

Developing a digital twin model for any system is a time-consuming process because of the complexity of the network and the numerous variables that must be considered. The methodology developed in this study allows setting up a model that includes an in-depth explanation of the individual components that will be calibrated and, ultimately, lead to the development of a calibrated digital twin that can be used to identify key problems in a ventilation system.

A case study on a deep-level mine was used to evaluate this methodology. In the case study, the main underground booster fans were operating at a higher differential pressure than that of the original blueprint model. This indicated primarily that there were restrictions within the return airways of the mine. Before applying this methodology, these areas were inaccessible due to high air temperatures and deteriorating ground conditions.

However, the digital twin model provided helped to identify the restricted areas and predict the potential impact on the entire ventilation system by addressing these restrictions. This information enabled a clear understanding as well as a solution for mining personnel to address the identified restrictions. Furthermore, the model was used to determine a ventilation strategy that enabled mining personnel to access these previously inaccessible areas.

As a result, the restrictions were removed, which yielded an increase of 7% in the total airflow through the mining block. Additionally, the digital twin model predicted the improvement in airflow to an accuracy of 96% when compared to measured results.

Therefore, this study highlights the value of using a digital-twin model to solve complex problems within deep-level mine ventilation systems. Ultimately, the digital twin model could be used successfully to identify the airway restrictions and managed to predict the total system impact and provide the optimum solution to solve this complex problem. This illustrates that the objectives of this study were achieved by implementing the derived methodology.

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NOMENCLATURE

Symbol	Description	Units
$\mathrm{t_{eff}}$	The effective temperature of the air	°C
$\dot{Q}_r$	Heat transfer of surrounding rock	kW
$\dot{Q}_w$	Heat transfer between water	kW
$\dot{Q}_a$	Heat transfer between air	kW
$\dot{Q}_a$	Heat transfer between water and air	kW
$\dot{Q}_{ore}$	Heating transfer between the ore and air	kW
$\dot{Q}_d$	Heating transfer between electromechanical equipment and air	kW
Q	Quantity of airflow	m^3/s
K_τ	The heat transfer coefficient between rock and air	$kW/m^2 \cdot °C$
U	The perimeter of the haulage	m
L	The length of the haulage	m
L_t	The rotating vane anemometer reading	m
Z	Height above datum	m
A	Heat dissipation surface area of water	m^2
A_h	The cross-sectional area of haulage	m^2
T	The average air temperature	°C
T_{VRT}	The average virgin rock temperature	°C
T_{ore}	The average temperature of the ore	°C
T_{in}	The inlet temperature of the water	K
T_{out}	The outlet temperature of the water	K
t	The time duration of the measurement	seconds
v_a	The average air velocity	m/s
g	Gravitational acceleration	m/s^2
P_c	The pressure correction factor	-

P_s	Saturated steam pressure the water	kPa
P_v	Partial vapor pressure of the water in the air	kPa
P_a	The atmospheric pressure of the air	kPa
$\dot{m}_{ore}$	Ore transport capacity	kg/s
$\dot{m}_w$	Mass flow of water	kg/s
$\dot{m}_a$	Mass flow of air	kg/s
C_{ore}	Ore specific heat capacity	kJ/kg·°C
C_p	Specific pressure of water	kJ/kg·K
h_{in}	The inlet enthalpy of the air	kJ/kg
h_{out}	The outlet enthalpy of the air	kJ/kg
N_d	Total power of all electrical equipment	kW
ρ	Air density	kg/m^3
W	The input of work by the fan	J/kg
F	Work was done against friction	J/kg
NVE	Natural ventilation energy	J/kg
V	The specific volume of air	m^3/kg
P	Barometric pressure	Pa
P_f	Frictional pressure drop	Pa
P_{fan}	Total pressure increase across a fan	Pa
NVP	Natural ventilation pressure	Pa
R	Atkinson resistance	kg/m^7
Greek		
β	Latent heat exchange coefficient	J/s·N
φ	Heat dissipation coefficient	-

LIST OF ABBREVIATIONS

VRT	Virgin rock temperature
LHD	Load, haul, and dump machine
RAW	Return airway
VUMA	Ventilation of Underground Mine Atmospheres
KPI	Key performance indicator
BAC	Bulk air cooler
PTB	Process toolbox
CFC	Chlorofluorocarbons
HCFC	Hydrochlorofluorocarbons
NASA	National Aeronautics and Space Administration
CSIR	Council for Scientific and Industrial Research
UA	Unit Area

DEFINITIONS

Half-levels:	The naming of the haulages that split from the main intake haulage of the level [48].
Stopes:	Underground excavation made for the removal of the ore body [48].
Regulator:	The component in the ventilation system which reduces the airflow to a desired value in a given airway or section of the mine [10].
Raise-line:	Tunnel with dimensions smaller than a shaft which advances upward on dip [48].
Auto compression:	The process of gravitational compression in the downcast shaft which produces an increase in temperature of the air [10].
Mines rescue teams:	The rescue service employed by the mine who work in extreme environments.

DOCUMENT OVERVIEW

Chapter 1

A background into the field of study is given to provide insight. Research is also done into the complexity of deep-level mines. The present approach in evaluating a ventilation network is discussed and the shortfall of this approach is highlighted. A comprehensive literature review of previous studies done in the field of study is conducted. The need for the study is derived from the review and the problem that this study will address is then stated.

Chapter 2

The method that was developed and used will be explained in detail. The method is described in such a way that it can be replicated in the development of any digital twin of a ventilation system along with the identification of problems within a system. The method to simulate solutions is described along with how it should be reported to the mine so that it can be implemented. The method to maintain the digital twin and keep it up to date is then described.

Chapter 3

The method described in Chapter 2 is applied to a case study to evaluate the effectiveness of the methodology. The results are then illustrated and discussed to verify the success of the method.

Chapter 4

The study is then concluded and recommendations towards future work are described.

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Preamble

The first discovery of alluvial deposits of gold in South Africa was in 1873 at Pilgrim's Rest [1]. However, it was not until June 1984 that the discovery of gold in South Africa led to a large influx of miners to the Witwatersrand [2]. This gold rush led to the establishment of the first large gold mining company in 1886 and became the building block of the modern gold mining industry of South Africa [2].

South Africa was the largest gold producer in the world for more than a century [3]. By the end of 2009, South Africa's ranking dropped to the fourth biggest gold producing country behind China, Australia, and the USA [1]. South Africa's gold production has been declining ever since, with it now holding the eighth position of the largest gold producer in the world [4]. Figure 1-1 illustrates the declining production trend of the South African gold mining industry [5].

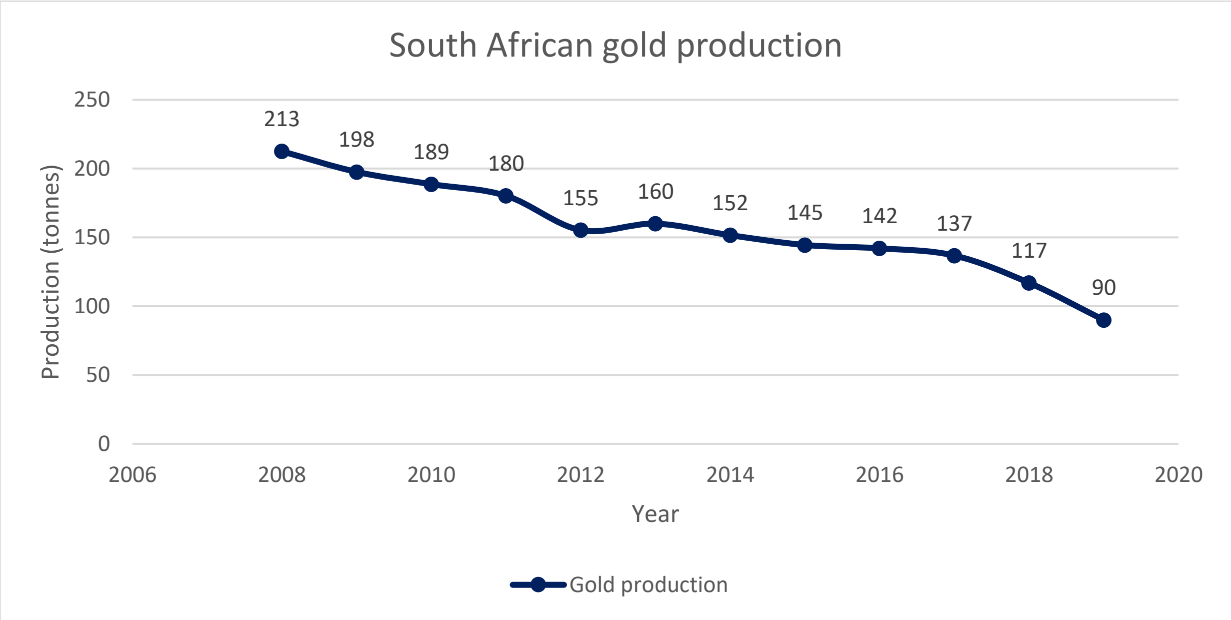

Figure 1-1: Historic gold production in South Africa [5]

Figure 1-1 shows that the gold production is declining further as time goes on. Despite the decline in production, the mines are reaching new record depths on an ongoing basis. These extended distances lead to several challenges, among which the increase in temperatures greatly affects the workforce. Figure 1-2 illustrates the virgin rock temperatures (VRT) of various locations as the depth below the surface increases.

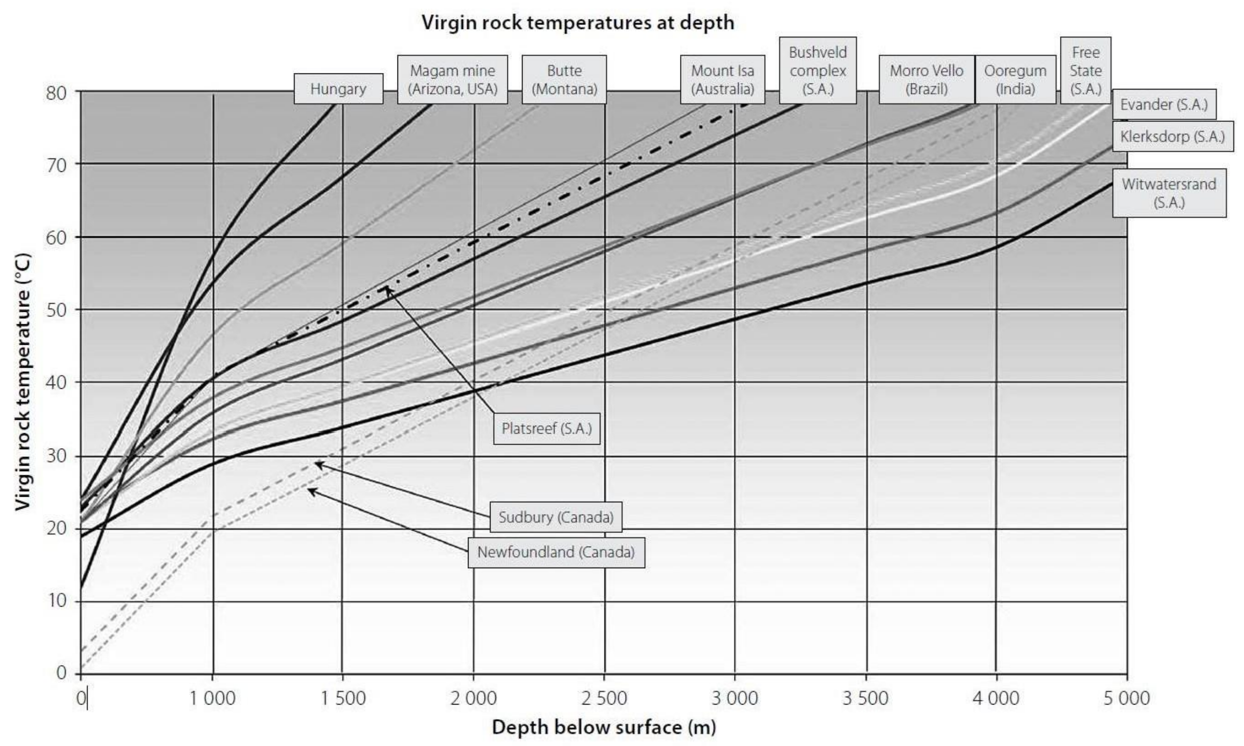

Figure 1-2: VRT's of various locations as the depth below surface increases [7]

Figure 1-2 shows that the VRT will increase as the depth below the surface increases. Therefore, the mining industry is facing many challenges in managing the heat that is introduced when mining at these depths [8]. The ventilation network, therefore, plays a primary role in ensuring that the heat that comes from mining at these depths is effectively removed.

The ventilation system is responsible for mitigating the heat that is emitted from the underground equipment as well as from the rock [6]. Mine ventilation systems are the primary cooling system used to mitigate this heat and it is therefore important to optimise and control this system effectively [9].

1.2 Underground ventilation system

The underground ventilation system is the largest system of an underground mine. The main difference between the ventilation system of a mine and that of an office building is that the mine is a dynamic system [10]. It continuously changes as the system extends deeper into the ground. The structure of the network changes and the resistances in the various branches of the network increase and decrease as changes occur. Vehicles, workers, and seals are constantly moved to different locations within the mine, which adds to the challenge of controlling the system.

To understand how to control and manage these challenges, it is first necessary to understand the operation of a typical ventilation system. The first section will give an overview of the flow of air through a conventional underground gold mine. This section will then be followed by the description of the various components within the system and then what secondary and tertiary cooling infrastructures are used to mitigate the heat within the system.

Overview

The underground ventilation system consists of a complex network of haulages which the air flows through to all the working areas of the mine. These mining areas require a ventilation system to supply fresh air and remove heat and airborne pollutants. Managing a system this complex and dynamic is challenging. Figure 1-3 illustrates the complete ventilation network of a conventional underground mine.

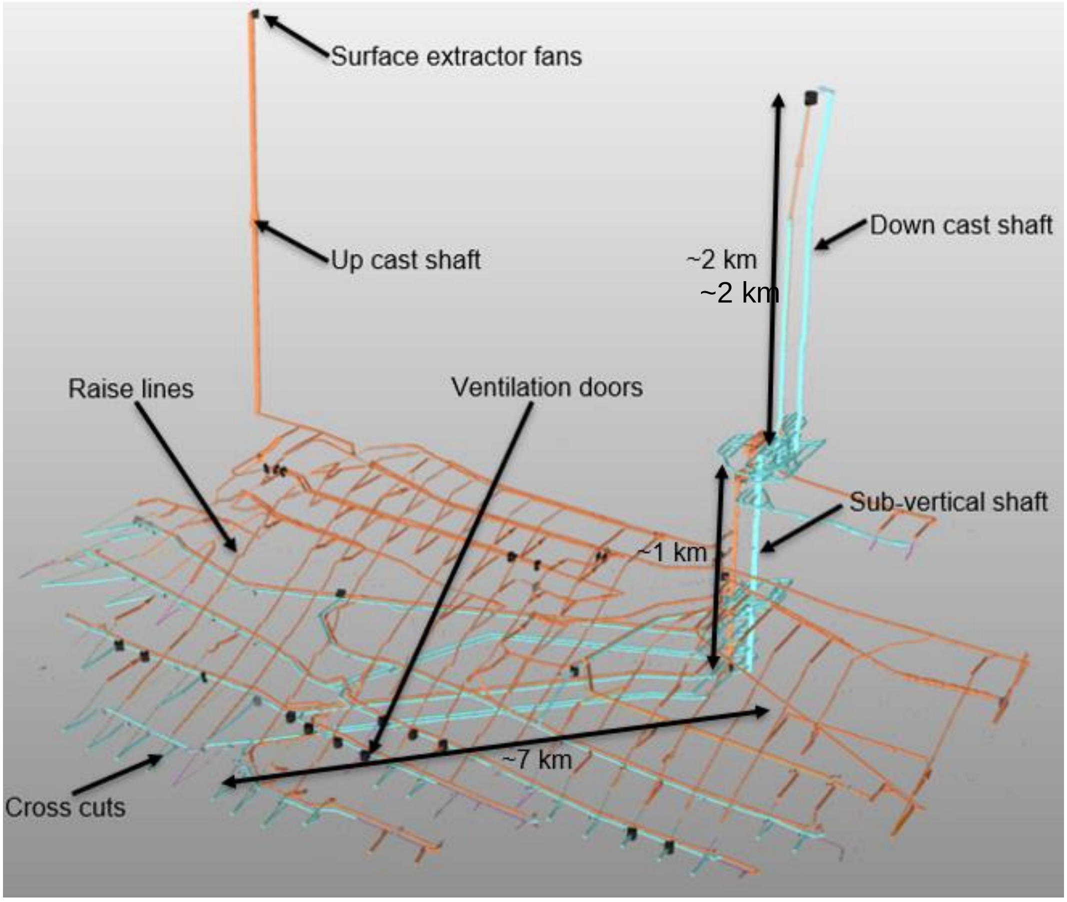

Figure 1-3: Ventilation network of a conventional underground mine[1]

[1] Screenshot taken by author – 3D ventilation model constructed in PTB.

Figure 1-3 shows the flow of air through the mine. The blue lines indicate the fresh intake airways and the orange lines indicate the hot return airways (RAW) that are used to exhaust all the air from the mine. Multiple access approaches are used to get to the gold reef, such as sub shafts and declines, depending on the ore depth. This means that the design of the ventilation system of each mine will differ.

There is, however, a basic layout and approach that each mine undertakes to mine out the gold reef. Most deep-level gold mines start with a downcast shaft as illustrated in Figure 1-3. Connected to the main shaft are haulages that is mined in the direction of the gold reef which leads to a sub-shaft. There are various haulages connected to the sub-shaft, which are referred to as the main mining level. These levels then split into half levels which in turn split into different directions parallel to the reef that is to be mined out. Figure 1-4 illustrates the orientation of the gold reef and the half levels.

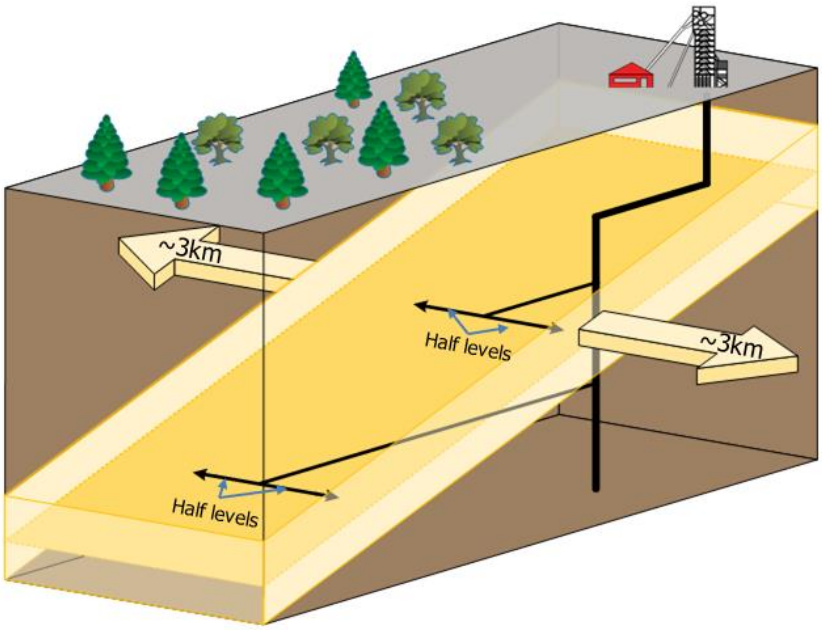

Figure 1-4: Reef orientation of a conventional mine[2]

Figure 1-4 shows why the half levels split in different directions. These half levels can stretch as far as 3 km from the station cross-cut are developed in the direction of the reef horizon, haulages are developed on strike of the gold reef, as shown in Figure 1-3. Cross-cuts are developed every two hundred metres apart in the direction of the reef to open stopes.

[2] Layout created by author.

Figure 1-3 also illustrates the ventilation doors that are located at the entrance of the crosscuts. These doors are used to control the flow distribution to each of the crosscuts throughout the mine [11]. Figure 1-5 illustrates a typical crosscut entry with a ventilation door and regulators.

Figure 1-5: Crosscut entry with a ventilation door and regulator[3]

Figure 1-5 shows the entrance of a crosscut through a ventilation door and regulator. The ventilation door is typically closed and stops the airflow to the crosscut [11]. The fresh air is then provided with axial fans through the ducting, as shown in Figure 1-5. This air then flows to the stope to provide fresh air to the workers in the working place.

The airflow quantity (normally between 0,5 and one metre per second) to the stope should not be too high because if the velocity of the air through a stope is too high, then the dust will be picked up, which is a health and safety risk to the miners. If this flow is too low, then there is the risk of gas build-up which is highly flammable [10]. Figure 1-6 illustrates the typical stope layout.

[3] Photo taken by author.

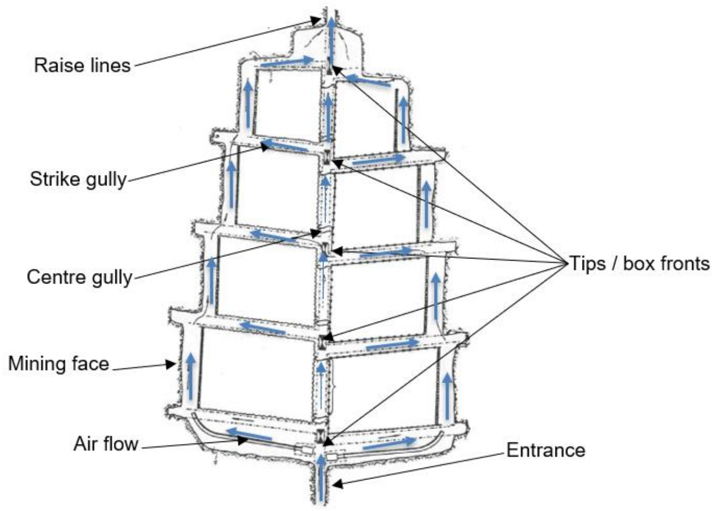

Figure 1-6: The typical stope layout [11]

The stope is where the reef is being mined and is angled in the direction of the dip and strike of the gold reef [11]. Within the stope, there is a raise line that is connected to the upper levels of the mine as shown in Figure 1-3. This raise line provides ventilation within the stopes so that the employees can work in fresh, cool air [11]. Ventilation curtains and backfill are used to control the flow of the air through the stopes [10].

The air then flows through the working areas in the stope and returns through the upper portion of the raise lines to the upper part of the mine. The upper part of the mine where the air is rejected is known as the RAW of the mine. The final stage of the network is through the upcast shaft of the mine as shown in Figure 1-3. The flow of air through the mine and up the upcast shaft is provided by large extractor fans on the surface and, in cases where they are mining at great depths, booster fans to help ventilate the mine. There are various components, for example, regulators, air-crossings, and booster and extraction fans, in the ventilation system which helps to control the flow of air and other components that influences the flow and temperature of the air.

Ventilation components

One of the most important components in the ventilation network is the fans that forces or exhausts the air to certain areas of the mine. The fans are used to overcome the pressure drop in the haulages and subsequently induces a flow. Figure 1-7 illustrates the large extractor fans that are located on the surface which are used to extract all the air from the mine and are therefore connected to the return side of the mine.

Figure 1-7: Surface extractor fan of a deep-level mine [12]

Figure 1-7 shows the large extractor fans that are responsible for the total flow of air through the mine. In some cases, booster fans are placed in certain areas of the mine to help distribute the flow of air through the mine [13]. Figure 1-8 illustrates two booster fans that are built into a wall to prevent the recirculation of air through the fan.

Figure 1-8: Booster fan located underground to provide airflow [14]

These fans shown in Figure 1-8 are placed in series with the main extractor fans on the surface. The goal of these fans is to assist the surface fan in overcoming the system resistance and induce a flow through the deeper parts of the mine when mining at great depths. In some extreme cases where the mine reaches great depths, there are many booster fans underground.

The complexity of a ventilation system is not the only challenge faced when managing the system. The dynamic aspect of the different moving elements also adds to the overall challenge. Equipment such as vehicles and machinery that add heat to the system and restricts the flow of air. Figure 1-9 shows the vehicles that are typically found underground [15-18].

Figure 1-9: Underground vehicles [15] [16] [17] [18]

Figure 1-9 illustrates at the top left a locomotive that is used to transport ore from the tips of the stopes to the station where it is taken for further processing. To the right of it is a typical loader that is used in trackless mining to load ore onto the dump trucks as shown on the bottom left. The bottom right of Figure 1-9 shows a drill rig that is used to drill holes into the rock for various purposes such as supporting the haulage or drill holes to insert explosives. The movement of these vehicles requires the opening and closing of ventilation doors. This influences the flow of air through the mine.

The other challenge that is being faced is the sealing of areas that have completed their life of mine. This is achieved by retrieving all the equipment and infrastructure that was used during production. This is known as vamping and reclamation. Next, the entrance of the crosscut is sealed with a wall, bulkhead, or temporary ventilation seal [11]. Figure 1-10 illustrates some of the different permanent seals found underground.

Figure 1-10: Typical ventilation seals[4]

Figure 1-10 shows a brick wall on the left and a bulkhead on the right. The difference between the two seals is the strength of the structure. A wall is built out of bricks and cement, which will break easily under the pressure exerted by the explosives in mining. The bulkhead is made from a double layer of reinforced concrete and is designed to withstand large shock forces.

The challenge when building these ventilation seals is that the area behind the wall becomes inaccessible even though it is still interconnected with the rest of the ventilation system. This is due to the high temperatures behind the seals. This means that when evaluating the system assumptions must be made of what is happening behind the wall. This is one of the many challenges faced when evaluating an underground ventilation network.

Secondary and tertiary cooling

The ventilation system is the primary cooling system of the mine. This is however in some cases not enough to mitigate the total heat load of the mine. This is when secondary and sometimes tertiary cooling is introduced to help mitigate the heat and lower the temperatures of the various working places.

The calculation of the amount of cooling that a mine need is determined using a heat load study [6, 10]. The heat load study quantifies the heat added to the system by all elements within the mine as mentioned before. This will indicate the amount of cooling that is needed throughout the

[4] Photos taken by author.

mine [10]. The calculation of the amount of heat that is introduced into a system is shown in Appendix A.

The use of fridge plants in the mining industry is common practice. The fridge plants are used to cool down water to very low temperatures. This chilled water is used as a thermal transport medium which absorbs heat from the air and is transported back to the fridge plant [19]. The typical fridge plant that is used for underground applications use R134a gas since it is only flammable at very high temperatures and since other gasses are classified as chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) which are damaging to the environment [20]. The typical fridge plant uses the principle of a refrigeration cycle [19]. The refrigeration cycle of a fridge plant can be seen in Figure 1-11.

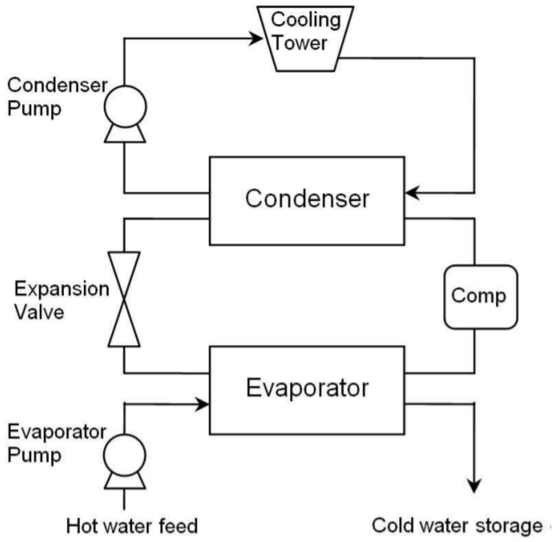

Figure 1-11: The refrigeration cycle [19]

In Figure 1-11 the refrigeration cycle starts with electrical power being provided to the compressor of the chiller unit which compresses the refrigerant. The water flowing through the evaporator heat exchanger is then cooled down by the refrigerant and flows to a cold-water storage dam. Pumps ensure the flow of water through the evaporator and condenser heat exchangers. Water circulates through the condenser heat exchanger to a cooling tower which ensures that the heat is rejected from the water to ambient or return air [19].

The cooling is mostly implemented by heat exchangers that use cold water to cool down the air or to reject the heat from hot water to the RAWs [11]. There are various forms of heat exchangers used in the mining industry such as direct contact heat exchangers, as seen in Figure 1-12, and indirect contact heat exchangers as seen in Figure 1-13 [11].

Figure 1-12: Direct contact heat exchanger used underground

Direct contact heat exchangers spray cold or hot water directly into the air through nozzles. This allows the air to exchange energy with the cold water as the air flows through the heat exchanger. Figure 1-13 illustrates an indirect heat exchanger used underground.

Figure 1-13: Indirect contact heat exchanger used underground [21]

Figure 1-13 illustrates the typical indirect heat exchanger that is used for underground cooling or in special cases to reject heat from hot water. An indirect contact heat exchanger allows for a flow of cold or hot water through coils that are called cooling banks. The air flows through the heat exchanger and comes into contact with the cold cooling bank and this allows for the transfer of energy [21]. The placement of these heat exchangers is important since some areas require more cooling than others [10].

The cooling of a mine is imperative to the health and safety of mineworkers. Mineworkers in deep-level mines tend to be under a great amount of physical stress. This stress can be attributed to thermal, noise, vibrations, ionizing radiation, and many more which influences their overall performance [22]. In contrast to a machine that has a sudden drop in performance once something starts to deteriorate, a human shows a more gradual decrease in performance as its placed under stress [22].

The human body absorbs and radiates heat readily and is generally considered an effective radiator [22]. Heat stress occurs once the body is unable to keep body at a constant temperature. This means that the body cannot dissipate the excess heat into the environment, and this places the body under stress [22].

The symptoms are vasodilation, which is the dilation of blood vessels, increased heart rate, and excessive sweating [22]. In severe cases of excessive heat stress, there could be a total collapse of the body's thermal regulation which results in death due to heatstroke. [9] This is why there are rules and regulations in the mine health and safety act with regards to the requirement that need to be met for a conducive and safe working environment.

According to Section 22 of the South African mine health and safety act, no workplace may exceed temperatures of 32.5°C wet bulb and 37°C dry bulb [23]. When it is found that an area within the mine exceeds these limits the miner, ventilation department, or an Inspector of Mines can halt all production under section 54 of the mine health and safety act [23]. This means that the mine will lose production and place a further strain on the financial state of the gold mining industry. Therefore, the management is of utmost importance of which evaluating the ventilation network forms an integral part.

1.3 The present approach to ventilation system optimisation

1.3.1 Ventilation surveys

The current method in measuring, managing and optimising the ventilation system starts with ventilation surveys by the ventilation department on the mine. This is an organised procedure of obtaining data that quantifies the distribution of airflow, air quantity, air temperature, and pressure throughout the main parts of the ventilation system [10]. These measurements should be taken in all underground facilities, within ninety days, as prescribed by law [10]. This is to ensure that all areas within the mine receive the required amount of airflow [10].

The measurements of pressure differentials across doors, walls, and bulkheads are also important. The differential pressure should be within prescribed limits and in the correct direction so that ventilation doors can withstand it. This is important especially in areas where there may be toxic or nuclear materials and for places that may spontaneously combust [10].

These ventilation surveys must be conducted regularly due to the dynamic nature of underground mining [10]. This is to help build up a database of information that is reliable and verified. This information is used to help plan the ventilation of a mine as it expands and interconnects [10]. The main objective of these ventilation surveys is to obtain the frictional pressure drop and airflow of each of the main haulages [10]. This data will then be used to determine the following [10]:

- Air temperatures in working areas.
- Airflow distribution and pressure drops.
- The operating costs throughout the system.
- The volumetric efficiency of the ventilation system.
- The overall system resistance.
- The natural ventilation effects.

These ventilation surveys will quantify the airflow and distribution of flow through the mine, but it is also important to measure other environmental factors such as wet- and dry-bulb temperatures, barometric pressures, dust levels, and the concentrations of various gases in the mine [10]. The method that is used to conduct a ventilation survey is explained in more detail in Appendix B.

1.3.2 System evaluation

One of the most vital components in the design and management of an underground ventilation network is planning of the airflow distribution, location, and duties of fans and other ventilation controls [10]. It is always necessary to plan and to constantly evaluate the performance of the system [10]. As mentioned previously, a mine is a dynamic system with new working areas constantly being developed and old areas being closed off [10]. This means that the evaluation and optimisation of a ventilation network is a continuous and routine process [10].

The information gathered by the ventilation surveys, such as the resistances within the haulages and how they are connected, is important. This makes it is possible to predict the location and duties of required fans. It is also possible to determine the combination of fans and the structure of the network if the system's resistance is known [10].

Various techniques are currently being used to evaluate ventilation networks. Analytical methods include evaluating the equivalent resistances and applying Kirchhoff's law [10]. This is explained in further detail in Appendix C. There are also numerical methods such as the Hardy Cross technique, which is also explained in Appendix C.

The current method of evaluating and optimisation is localised to the area of the occurring problem. The shortcoming of this method is that other issues might arise in other areas within the mine that are not quantified. This necessitates a digital twin of the ventilation network.

1.3.3 The digital twin

The digital twin is a new concept that was first introduced by the National Aeronautics and Space Administration (NASA) [24]. The idea of a digital twin is to accurately model a physical system so that experiments can be conducted on that model through simulation. This provides the user the means of implementing changes on the system without implementing changes on the physical system.

The term digital twin has, however, evolved over the years, and some studies have interpreted it in different ways. The original idea was to have a digital twin that can simulate a physical system, but some studies view it as a monitoring platform for a system [25] [26]. The idea of this is to have real-time data from the system displayed to the managing personnel. This will in turn provide a means for them to control and manage the system.

The article titled "Experimental Digital Twins for a Modelling and Simulation-based Engineering Approach" focused on the development of a digital twin that can be used for experimentation on cross-domain engineering systems [36]. A clear method was developed in how they construct the digital twin and it was used in experimentation. This study did not focus on applying it on deep level mines but rather in space missions. This is still of interest to study since it shows the capabilities and benefits of digital twins.

This study will, however, focus on using a digital twin as a simulation tool for a complex underground ventilation network. The previous section provided insight into the complexity of an underground ventilation network. It further illustrated that managing the system is difficult and that a new method is necessary to solve these issues.

The development and increasing accuracy of ventilation network simulation software has revolutionised the methodologies of mine ventilation planning [10]. Ventilation engineers can execute simulations without any knowledge of what happens within the computer [10]. This can, however, only be done if there is a better understanding of the software's limitations and the workings of the actual ventilation network [10].

The Ventilation of Underground Mine Atmospheres (VUMA) model is one of the main software packages that are currently being used to simulate mine ventilation systems [27]. The article titled "VUMA Mine Ventilation Software" [27] describes the development and use of a mine ventilation software as a digital twin of the system. The main goal was to illustrate the importance of having a simulation tool to help plan and optimise ventilation systems. The article describes the use of the simulation software and how to apply it. However, it does not illustrate how to use the simulation to identify problems within the system. This study aims to improve upon this area.

Available software packages

There have been developments in the mining industry for the use of simulation software to accurately model ventilation networks. It is, therefore, necessary to evaluate the different software packages and decide which will be the most suitable in developing a digital twin of an underground mine ventilation network.

The software packages that are evaluated should be able to simulate an integrated system as both a transient and steady-state model.

VUMA3D

Ventilation of Underground Mine Atmospheres (VUMA) is a software package that has widely been used in the mining industry to simulate underground ventilation networks [27]. It is used to assist ventilation engineers in the designing, planning, and operation of an underground ventilation system [28].

The software is used for the simulation of the airflow underground as well as the thermodynamic behaviour of the air. It can also simulate gas and dust emissions in underground haulages. This simulation software does, however, cannot simulate a transient integrated cooling and ventilation system [28].

ENVIRON

ENVIRON was developed in the late 1980s by the Council for Scientific and Industrial Research (CSIR). The purpose of the development of this software was to provide a tool for the ventilation engineers. The program consists of two main modules, namely HEATFLOW and VENTFLOW [28].

The VENTFLOW simulates the distribution of air through the mine and HEATFLOW simulates all the heat loads and air coolers in the mine. ENVIRON can therefore not simulate the integrated ventilation and cooling network of an underground mine [28].

Flownex

Flownex is a thermal-fluid network analysis code that can be used to simulate and analyse complex systems. The building of simulations in Flownex consists of using nodes and elements to represent the simulated system. H.J. Van Antwerpen's study proved that Flownex can be used to simulate integrated deep-level mine systems [43], which is an important use given that a ventilation network is integrated with the cooling system of the mine.

Process toolbox (PTB)

PTB is a one-dimensional Computational Fluid Dynamics (CFD) code that solves complex thermo-hydraulic networks [29]. The software can simulate compressible, incompressible, and two-phase fluids [29]. PTB can therefore simulate a transient, integrated cooling and ventilation network of an underground mine. It has been used in many studies to accurately simulate various underground systems [28] [29] [30].

These four simulation software packages are evaluated and compared to choose the best package to use in this study. The criteria that are used to evaluate these packages are:

- **Integrate systems:** The ability to simulate an integrated cooling and ventilation system.
- **Digital twin:** The ability to provide an accurate representation of an actual system.
- **Optimisation:** The ability to simulate various scenarios to optimise the ventilation system.
- **Transient capabilities:** The ability to simulate transient systems where the conditions of the system vary throughout a day.

These criteria were then applied to the software packages discussed earlier. Table 1-1 evaluates the different software packages with the discussed criteria.

Table 1-1: Simulation software package comparison

Software package	Integrate systems	Digital twin	Optimisation	Transient capabilities
VUMA 3D		✓	✓	✓
ENVIRON		✓	✓	
Flownex	✓	✓	✓	✓
PTB	✓	✓	✓	✓

Table 1-1 shows that VUMA 3D and ENVIRON will not be suitable for this study. Flownex and PTB are both eligible choices for use in this study. However, PTB will be used in the study.

1.3.4 Summary of previous studies

To effectively evaluate previous work conducted, criteria were identified for the evaluation of each study. These criteria are as follow:

- Method to develop a digital twin of a system.
- Using a digital twin to evaluate a system.
- Using a digital twin as a simulation tool to simulate solutions to identified problems.
- Applying digital twin on deep-level mines to improve ventilation systems.

These criteria will now be discussed further to explain the rationale behind using these criteria to evaluate previous work done.

Development method

The first issue of using a digital twin of any complex physical system is to build and calibrate the digital twin system using a simulation software package. Various methods have been developed to obtain an accurate model of physical systems.

The article titled "Evaluating complex mine ventilation operational changes through simulations" [30] focused on the evaluation of complex mine ventilation operational changes with the use of simulations. This study was applied to a mine with a depth of 2 100 m its deepest point, which is not as deep (average 3 600 metres below surface) as the gold mines in South Africa. The study did evaluate the main KPIs of a ventilation system with the use of the simulation model.

This study did have a method to develop a digital twin of a deep-level mine. However, the method lacked the detail of exactly how to calibrate and utilise the digital twin to improve the ventilation system.

The thesis titled "An Integrated approach towards the optimisation of ventilation, air cooling and pumping requirements for hot mines" [44] focused on proving the value of a simulation model for optimising deep-level mine systems. The study showed the development of the mathematical model used to simulate the various underground systems.

These simulations were, however, tedious to develop but are made easier to do so with the use of the simulation software packages available today. This study proved that simulations are critical to the optimisation and improvement of underground systems.

The thesis titled "Novel simulations for energy management of mine cooling systems" used simulations to help optimize the energy management of deep-level mines [28]. The study focused on building novel transient response simulations of mine cooling systems. The study showed the value of having a digital twin of a physical system. The study also developed a method to utilizing the digital twin. This method was analysed to help develop the method in this study.

The article titled "Benefits of site-specific simulation models for assessing electrical energy savings potential on mine cooling systems" created a digital twin of a mine cooling system to assess electrical energy savings [32]. This a good example of using a digital twin to optimize a system. They do however not state how the digital twin was built and only show the results of the simulation.

System evaluation

The use of a digital twin to evaluate a system and identify problems within a large-scale system such as an underground ventilation network is still a new concept. There have been many instances where a digital twin was used as a monitoring platform to evaluate a ventilation system [25] [26]. In these cases, they used real-time data of the actual system and with this data, they identified problems as they occurred [25] [26].

As mentioned before, simulation software has been used to evaluate and optimise ventilation systems [30]. The method that was utilised in that case was done by optimising the system to improve the main KPIs that were identified [30].

The article titled "Computational evaluation of thermal management strategies in an underground mine" [31] focused on the computational evaluation of the effect of various thermal factors on the airflow through an underground tunnel. This study evaluated these effects on a single underground tunnel. The study concludes by recommending that this study be expanded to evaluate the optimisation of the ventilation and refrigeration systems.

This study demonstrates the benefit of having a simulation model to evaluate the effect of thermal management within a mine. It will not evaluate the entire ventilation system. This study will evaluate and optimise the entire complex ventilation system with the use of a digital twin.

The article titled "Implementation of Industry 4.0 Technologies in the Mining Industry: A Case Study" investigates the use of real-time data to help with the management of a system within the mining industry [25]. This study was used to start with the implementation of Industry 4.0 methods in the mining industry. This study evaluated the use of a digital twin as a real-time monitoring platform to evaluate and improve underground systems. The use of a digital twin as a simulation tool was not investigated.

The article titled "Integrated Monitoring of Engineering Structures in Mining" focused on the use of monitoring systems for engineering structures of mining [26]. This is to help with the better management of the system and can show real-time data so that issues can be identified earlier. This study evaluated the use of a digital twin as a real-time monitoring platform to evaluate and improve underground systems. The use of a digital twin as a simulation tool was not investigated.

The article titled "The management of heat flow in deep mines" focused on the evaluation of the various heat sources in an underground mine [9]. The study provided equations for calculating the heat that is added by various entities within the mine. In doing so, the flow of the heat within the mine can be improved and managed. However, this study did not utilise a digital twin to improve the ventilation system of a deep-level mine.

Simulation

A digital twin is a powerful tool when used as a simulation tool. It is widely used in many industries to simulate complex physical systems. Numerous studies have used simulation models to improve, evaluate, and design underground systems. Simulations models have also been used to identify electrical energy savings [32].

Simulation software has also been used to plan the logistics in underground tunnels to provide optimal movement of underground vehicles [33]. This saved time and resources for the mining company.

The article titled "Simulation of Fire Spreading in Underground Mine Based on Cellular Automata and Particle System" [34] focused on creating a simulation of an underground tunnel that will simulate the spread of an underground fire. This simulation utilises the automata and particle system theory. The goal of this study is to propose a new simulation method for underground fires that will help with the prevention of underground fires.

This study does describe how the simulation model was developed. This simulation does not help with the improvement of the ventilation system, but rather just how a fire will spread through a mine. This study illustrates the benefit of simulation software in the planning and decision making in a mine.

The study conducted by [30] that was previously described also illustrated the benefit of having an accurate simulation tool to simulate and optimise a ventilation system. These studies provide clear evidence of the benefits of having a digital twin to simulate various scenarios. Its ability to test many different scenarios without having to make any physical changes to the system makes it very cost-effective. Therefore, this study will focus on utilising these benefits to solve problems in ventilation systems.

The article titled "The use of 3D simulation system in mine ventilation management" [45] focused on using a 3D ventilation software package to simulate an underground ventilation system. They simulated a scenario of reducing the resistance in the airways to help improve the flow of air through the mine. This study did use simulations to improve the ventilation systems. However, they did not provide a reproducible method to apply to other systems.

The book titled "Subsurface Ventilation Engineering" describes everything relevant to deep-level mine ventilation [10]. This book describes how to develop, control and manage an underground ventilation network. It is used to train all ventilation engineers and occupational hygienists in South Africa.

This book describes how to use the simulation software VNET which can be used to simulate ventilation systems. This approach can be improved upon for further optimization of the method to using a simulation model to improve a ventilation system.

The article titled “Logistic evaluation of an underground mine using simulation” focused on using a simulation tool to analyse different logistic layouts [33]. The simulation tool was used to model the different layouts and a conclusion was made as to what layout will work best. The study illustrated the value of having a simulation tool to help with the decision making of how to plan and underground network.

The article titled “Estimating mine planning software utilization for decision-making strategies in the South African coal mining sector” discussed a new method for measuring and defining mine planning software [38]. This study only focused on what data sets are to be used and how the software should be used to measure the utilization of the gold mining sector. This study illustrated the benefit of having software to help with decision making. One of the main outcomes of having a digital twin is the better management and decision-making capabilities that it provides through simulation.

The article titled “VUMA: A Visual User Modelling Approach for the Personalisation of Adaptive Systems” focused on a visual user modeling approach of adaptive systems [40]. The software is easy to use and can be modified by the user. This study focused more on the method and calculation behind the software that is being used and not how it is applied. It does however prove the possibility of simulating underground ventilation systems.

The article titled “Surrogate Models for Design and Study of Underground Mine Ventilation” focused on using simulation software as a complementary design tool on underground ventilation systems [41]. There is no reference to digital twin however there is some reference to the mathematical model behind the simulation. This study illustrated that simulation software can be used to plan a mine ventilation system. The study did not investigate the possibility of improving an existing system. This is where this study improved upon.

The article titled “A simulation–optimization framework for short-term underground mine production scheduling” focused on the simulation of the short-term production schedule of a deep level mine [42]. This is an example of the many capabilities of simulation in the mining industry. This study illustrated the benefit of having a simulation tool to simulate underground production systems.

The article titled “Combined system simulation of cooling and ventilation for the world's deepest mine” focused on proving that simulation technology can be applied to the compressed air, cooling, and ventilation systems of the deepest mine in the world [43]. The goal was to integrate these systems and prove that it is possible to do a mine-wide simulation of the system. The study made use of Flownex and was able to build the entire system.

The study proved the possibility of building a digital twin of a complex deep-level mining system. The study did however focus more on the refrigeration system and not the ventilation system. This is where this study improved upon.

Deep-level mine ventilation improvement

Various studies have focused on the improvement of ventilation systems. The study titled **“**Heat Treatment and Ventilation Optimization in a Deep Mine**”** focused on the treatment of the various heat sources in an underground mine [8]. The ventilation system was then rebuilt and optimised to help improve the temperature of the underground ventilation system. The mine that was evaluated in this study is approximately 1.7 km deep at its deepest point. This means that this mine is not as deep as the deep-level gold mines in South Africa.

The study did not utilise a digital twin to improve the ventilation system of the mine but practical methods of measurement and mathematical calculations to evaluate the system instead.

The article titled “The management of heat flow in deep mines (part 2)” investigated the effect of heat on people working underground [35]. They also determine which areas within a mine are places where cooling is needed and in so doing improving the working conditions for the workers. This study shows how practical methods were used to improve the ventilation system of an underground mine.

The article titled “An Integrated energy efficiency strategy for deep mine ventilation and refrigeration” [37] focused on developing an integrated energy efficiency strategy for ventilation and refrigeration system in deep-level mines. This means that they investigated both systems to develop an optimal approach that will benefit both systems. This proves that both systems can be optimized without negatively affecting the other. The study did not utilise a digital twin. This is where this study will improve upon.

The article titled “Evaluating the impact of auxiliary fan practices on localised subsurface ventilation” focused on the impact of underground fan assemblies was investigated [13]. The performance of the fans was analysed, and the possible improvement was quantified. In this article, they stated that it would be good practice to first simulate what the possible improvement will be. That is why this study is relevant since the need for a digital twin is stated.

The use of digital twins in the mining industry is still a new topic. Various digital twins are used on mines such as the VUMA models which are used to simulate ventilation systems [27]. These models are, however, not utilised efficiently to optimise the ventilation system because there is no clear method for applying digital twins on ventilation systems to optimise them sufficiently.

The study conducted [30] did use a digital twin to optimise a ventilation system, although the study lacked to explain how deeper and more complex mines can be optimised where there are multiple operational changes and where some areas within the mine are inaccessible.

Digital twins were used in some studies to test various initiatives to improve ventilation systems. The article titled "Subsurface flow and transport process model for time-dependent mine ventilation simulations" [39]. This study shows the development of time-dependent underground ventilation simulations. This study developed a mathematical model to simulate underground haulage. This study illustrates that underground haulage can be simulated.

However, the entire system was not developed in this study. This study will build upon what has been done by evaluating the entire system performance using the digital twin.

The article titled "The use of 3D simulation system in mine ventilation management" focused on developing a ventilation model of an underground ventilation network that is 1000m in depth [45]. The main objective of the study was to use the model to help with the decision making in the development of the ventilation network. This helped improve the management of the system and not necessarily to optimise the current system. This is where this study will improve upon.

State of the art

Evaluating the state of the art of this study is of great importance. This illustrates the gaps that have been found in the literature which will be covered in this study. The studies that were highlighted and discussed previously illustrated the aspects that this study will improve upon. Table 1-2 illustrates where the gaps are in these previous studies and what aspects can be applied in this study.

Table 1-2: Summary of what research has been done in previous studies

Source	Development of digital twin	Digital twin used to evaluate a system	Digital twin used as the simulation tool	Deep-level mine ventilation improvement
[8] [9] [13] [35] [37]				
[27] [31] [34] [39] [40] [41]				
[24] [28] [32] [33] [36] [38] [42]				
[10] [30] [43] [44] [45]				
[25] [26]				

Table 1-2 shows that there is still much that is unknown relating to the use of state-of-the-art methods such as twin models. These gaps present the opportunity to build on the work that has been done and better explain why this study is necessary.

These studies illustrate a need to develop a methodology in building and calibrating an accurate digital twin of a mine ventilation system. It also illustrates that there should be a clear utilisation methodology of a digital twin to identify problems within the system and to optimise the system by solving these problems.

1.4 Problem statement and objectives

Deep-level mine ventilation systems are dynamic and complex. The challenges brought by inaccessible areas, expanding ventilation haulages, and daily system changes add to the issue of solving complex mine ventilation problems. The development and utilisation of an accurate digital twin to identify and solve complex mine ventilation problems are necessary for better management, control, and improvement of the system. This digital twin can be applied to help improve and further optimise the system. Therefore, the objectives of this study are the following:

- Develop a methodology for building accurate digital twins of deep-level mine ventilation networks.
- Design a technique to evaluate a ventilation network by using a digital twin to identify problems within the system.
- Improve the ventilation network by implementing the digital twin.
- Provide a method for maintaining a digital twin to continuously represent the performance of the actual system.

1.5 Conclusion

The ventilation system of a deep level mine is complex. The present methods of managing and optimising these systems are not sufficient and so there is a need for a new approach. Therefore, there is a need for a new integrated approach where a calibrated digital twin is developed and used to solve complex ventilation problems.

Previous studies have indicated that there have been instances where a simulation tool was used to optimise a certain part of a ventilation network. There were however some cases where a method was derived to develop a digital twin, but this study will expand upon these methods. There is also no clear method to evaluate a system with the use of a digital twin.

Therefore, the objectives of this study will be to:

- Develop a methodology for building an accurate digital twin of deep-level mine ventilation networks.
- Design a technique to evaluate a ventilation network by using a digital twin to identify problems within the system.
- Improve the ventilation network by implementing the digital twin.
- Provide a method for maintaining a digital twin to continuously represent the performance of the actual system.

CHAPTER 2: METHODOLOGY

2.1 Introduction

This chapter gives insight into the methodology that was developed for this study. The first section gives an overview of the overall strategy and then discusses each of the steps to provide insight into the goal of the method and how it is constructed. The methodology is then be summarised and the key points of the chapter highlighted. The main outcome of this section is to derive a methodology that will achieve the objectives of this study.

2.2 Strategy for developing a digital twin

Figure 2-1 illustrates the basic overview of the method that is to be used in this study.

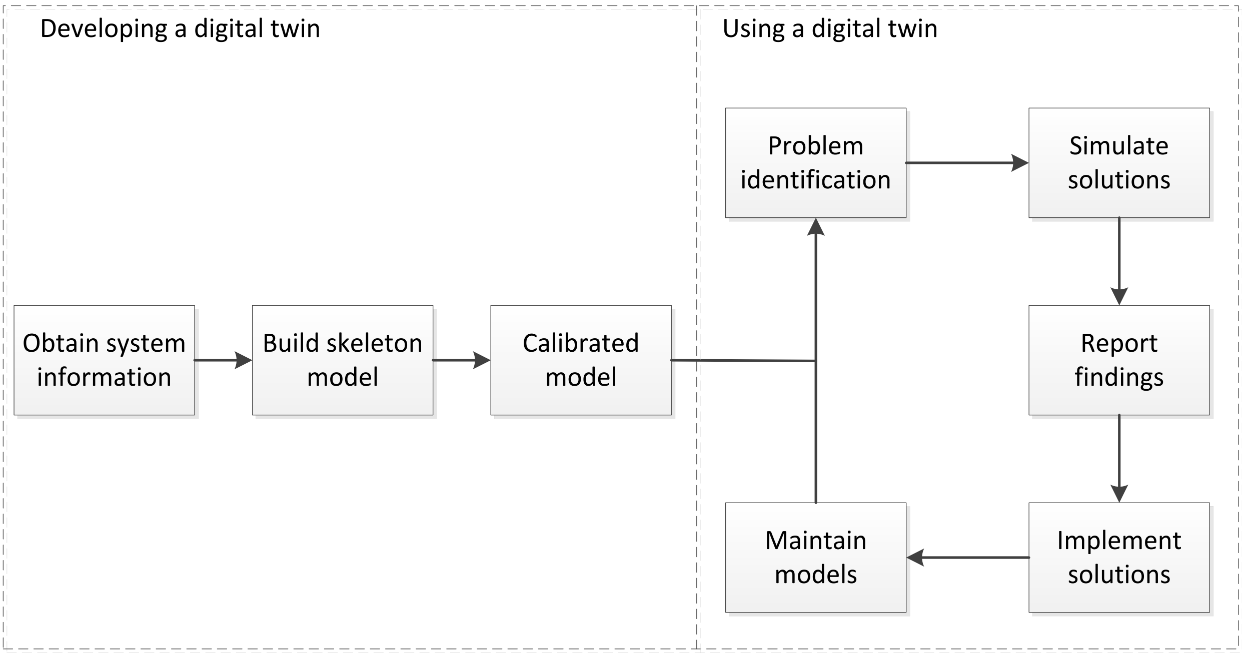

Figure 2-1: Methodology used for this study

Figure 2-1 shows the step-by-step process that must be taken to build a digital twin and to then use the digital twin to identify and solve problems within the system. This process was followed and evaluated in this study.

2.2.1 Obtain system information

This step is the first step in developing any digital twin of a system. This step entails the collection of all the necessary information of the system. Figure 2-2 illustrates the information that is required to build a digital twin of a mine ventilation system.

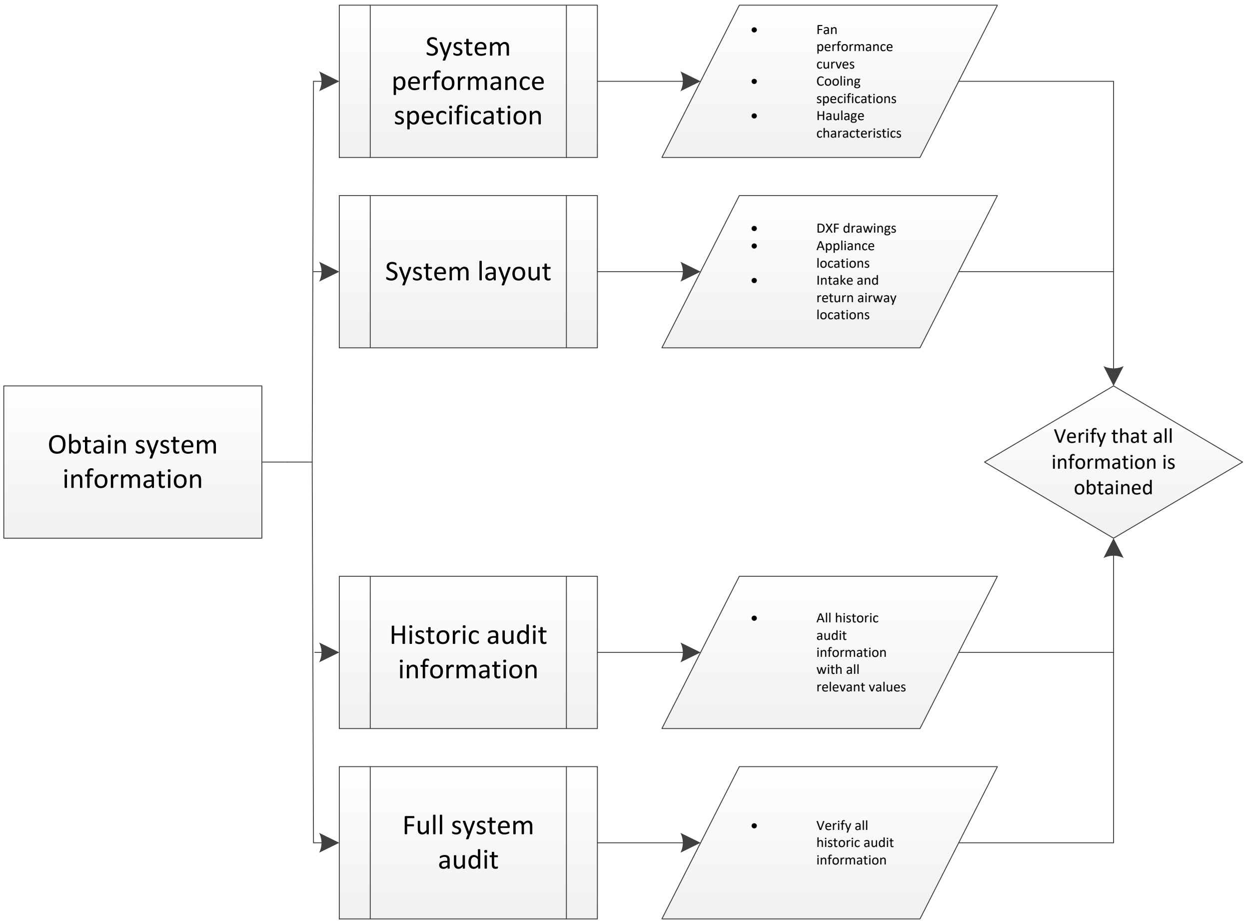

Figure 2-2: Required information to build a digital twin

Figure 2-2 shows the various information that must be obtained. The specific information that is required for each of the subcategories are the following:

- System performance specifications:
  - Fan performance curves.
  - Secondary and tertiary cooling appliance performance specifications.
  - The size, lining, and age of the haulages within the ventilation network.
- System layout:
  - The layout of the ventilation network in Drawing Exchange Format (DXF)
  - Locations of all walls, seals, doors, and bulkheads.

  - Determine which haulages are used as intake airways and which are RAWs.
  - The locations and configuration of all the fans within the system.
  - The locations and configuration of all the cooling equipment.
  - Define where people are working.
- Historical audit information:
  - It is important to obtain the following information for all the areas within the ventilation network:
    - Airflow quantity and direction.
    - Dry-bulb and wet-bulb air temperatures.
    - Barometric pressure.
    - Restriction locations.
    - Water accumulation locations.
    - Condition of ventilation equipment, such as walls, doors, seals, and fans.
- Historical audit information verification:
  - It is important to do an audit of the entire system by utilising the methods described in Appendix B. This will enable the digital twin to be calibrated with the latest information of the system.

2.2.2 Build skeleton

Building the skeleton of the digital twin entails beginning with building the basic layout of the system using simulation software. Figure 2-3 illustrates what information is used to build the skeleton of the digital twin.

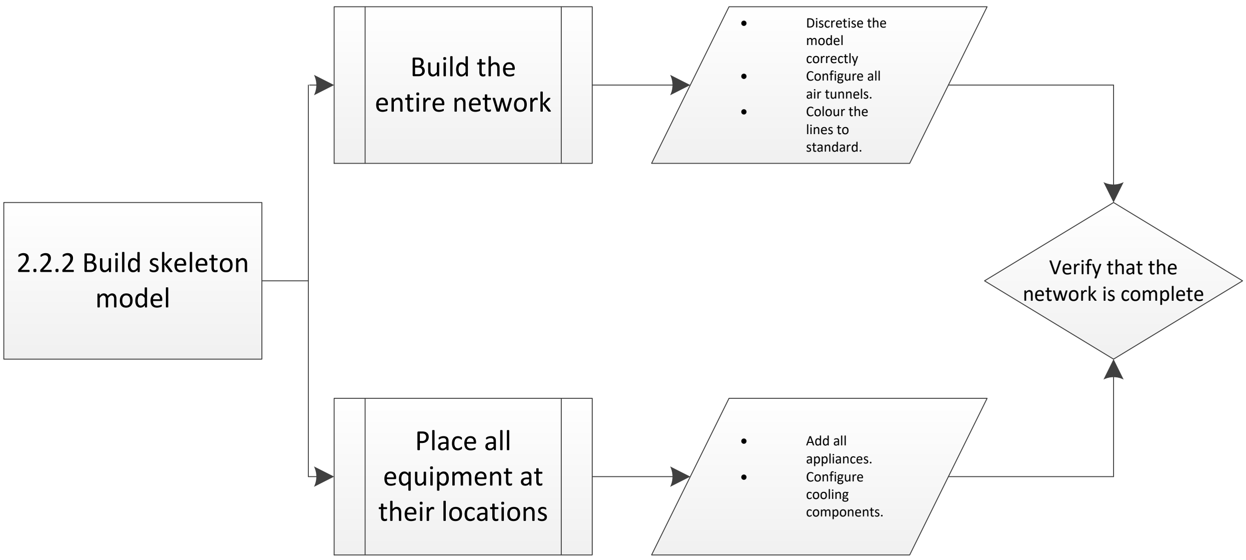

Figure 2-3: Information that is to be built into the skeleton

Figure 2-3 shows that building the skeleton entails building all the intake and RAWs as well as placing the equipment at their various locations. This means that the complete layout of the system is built and ready for calibration. Therefore, this model is not to be used as a representation of the performance of the system.

Building a model in the process toolbox (PTB) is achieved by using discretised nodes and components. These nodes and components characterise actual components within the system. The description of each of the components in PTB can be seen in Appendix D and a description of PTB can be found in Section 1.3.3 of this dissertation. These components are inserted into PTB to represent the layout of the system.

The discretisation of these components must be done correctly to ensure accurate calculations within the simulation software. The nodes that are used in PTB simulate elevation differences between the nodes, and for a vertical shaft, the elevation difference increases rapidly. Figure 2-4 illustrates the discretisation of nodes and components in a vertical shaft.

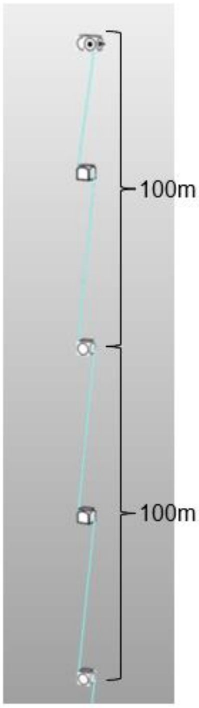

Figure 2-4: PTB discretised nodes in a vertical shaft[5]

[5] Screenshot taken by author – PTB vertical shaft example.

Figure 2-4 shows that the nodes are discretised in 100-m increments to ensure the accurate calculation of the air's auto compression as it flows into and out of the mine. It is important to note that, although it is not illustrated, each tunnel is discretised in 10 segments.

The discretisation of nodes in a horizontal haulage is different because the elevation difference between nodes is not as rapid as the vertical shaft. This means that the focus of building horizontal haulages should be on maintaining the shape and layout of the network. Figure 2-5 illustrates the discretised nodes and components of an area in an underground mine.

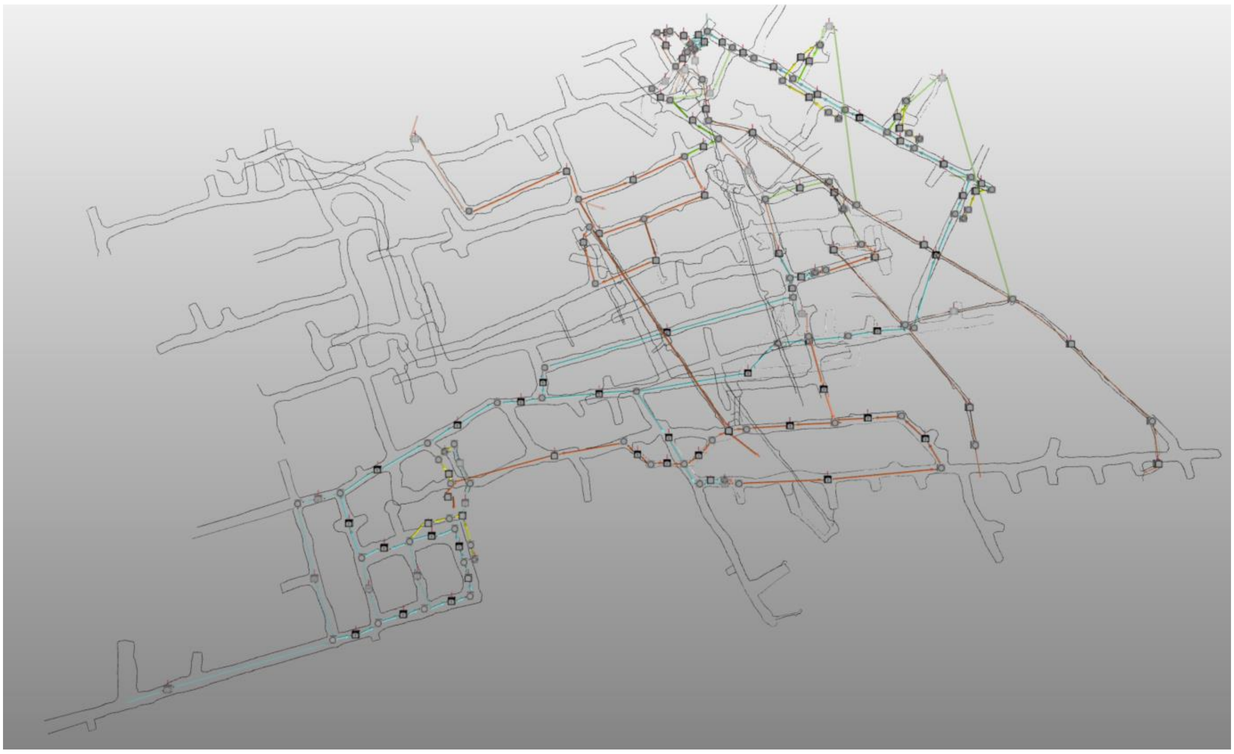

Figure 2-5: PTB discretisation of horizontal haulages[6]

Figure 2-5 shows that the shape of the network remains, which will enable the accurate placement of equipment within the system. This will also enable the accurate simulation of various scenarios since all the relevant haulages within the network are built into the model.

The next crucial step in the process is ensuring that all the relevant components have been built into the system, such as fans, cooling systems, walls, doors, seals, and haulages. The failure to add any of the necessary components could lead to the possibility of not obtaining an accurate

[6] Screenshot taken by author – 3D ventilation model constructed in PTB

digital twin of the system. Figure 2-6 illustrates how to configure a tunnel to represent different ventilation components.

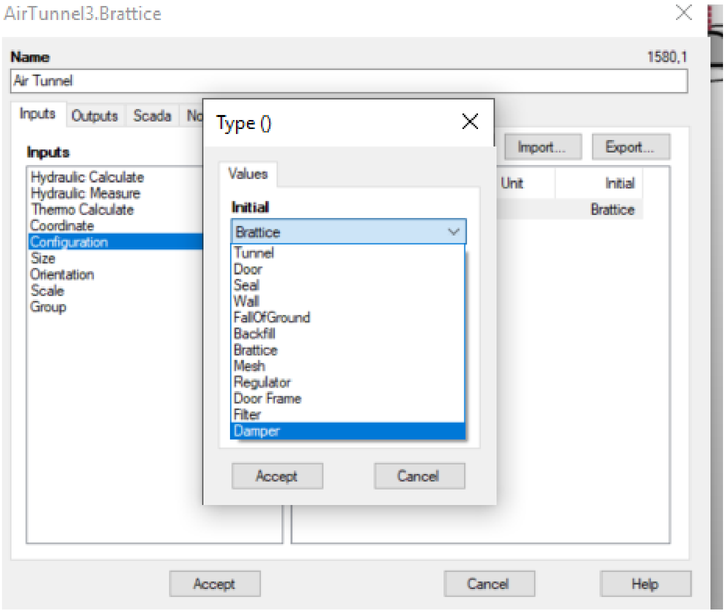

Figure 2-6: PTB tunnel configuration[7]

Figure 2-6 shows that various configurations can be placed on the tunnel to represent various components. The gathered information of the component locations is then used, and the components are placed at the correct locations. It is also important to add all the fans at the correct locations.

The ventilation digital twin does not contain the entire refrigeration network, so it is, therefore, necessary to characterise the flow of water through each component in a different way. In some cases, the refrigeration network is to be integrated into the ventilation digital twin, but this depends on the needs of the user. This study focuses on keeping the refrigeration model separate from the ventilation digital twin. Figure 2-7 illustrates the configuration of cooling components in a ventilation model.

[7] Screenshot taken by author – PTB inputs.

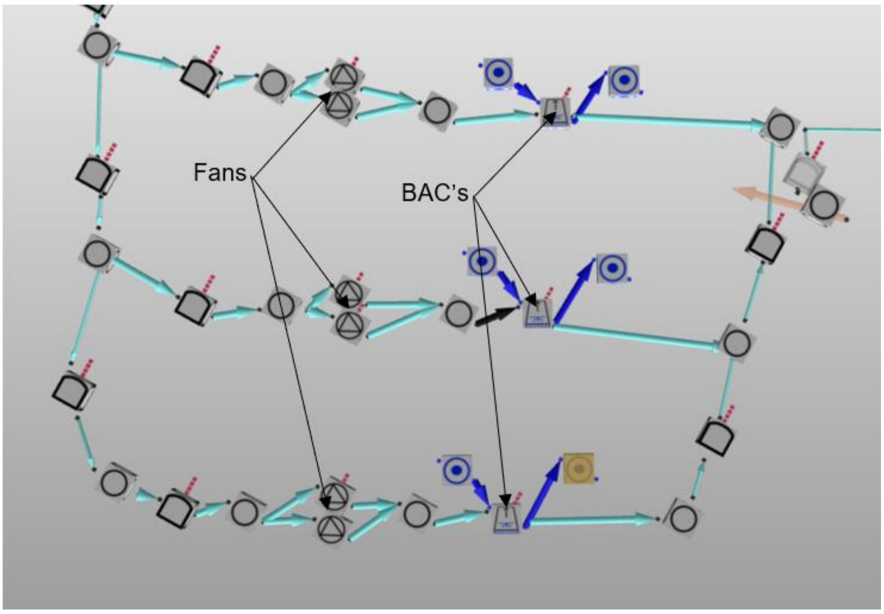

Figure 2-7: PTB configuration of cooling components[8]

Figure 2-7 shows the configuration of cooling components within a ventilation model. The flow of water through the component is achieved with the water pressure boundary component in PTB. These components simulate a pressure difference and inlet water temperature for the cooling components. This means that the cooling duty and heat transfer rate of the component can be simulated under the assumption of its inlet and outlet conditions.

The next step is to characterise all the tunnels within the digital twin with the fixed values. These values are the following:

- Haulage sizes
- Lining or friction factor
- VRT

These values can easily be specified in PTB to accurately characterise the haulage. Figure 2-8 illustrates the window in PTB in which the haulage size and lining are specified.

[8] Screenshot taken by author – 3D ventilation model constructed in PTB

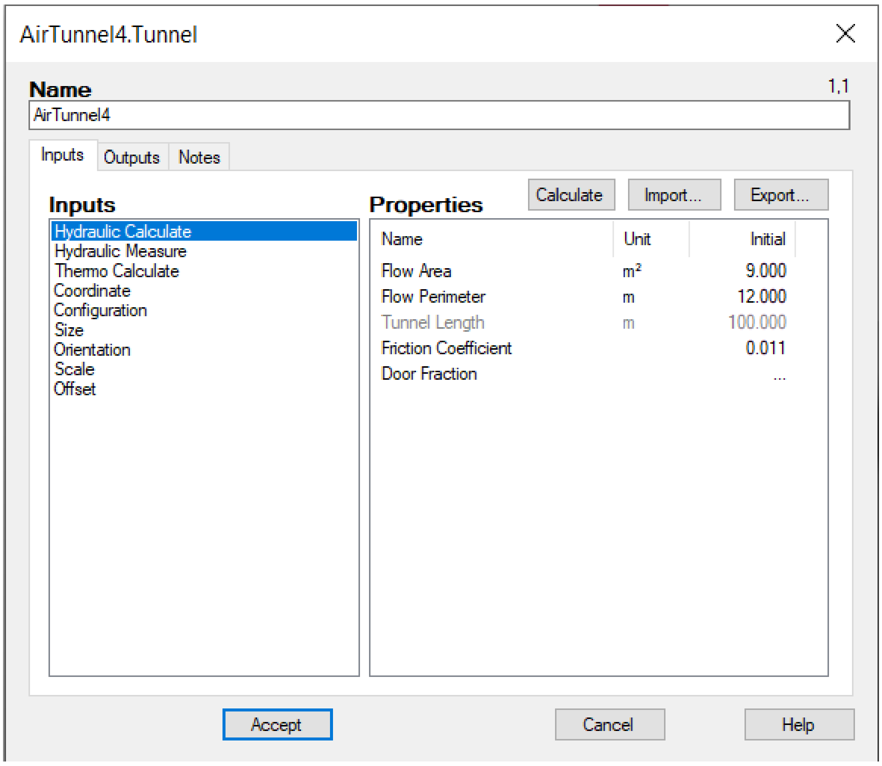

Figure 2-8: PTB input for the sizing and lining of a haulage[9]

Figure 2-8 shows that the haulage size is specified by changing the flow area and flow perimeter. This is the cross-sectional area and perimeter of the actual haulage. The friction coefficient can be indicated in this window as well. The standard values for the friction coefficient of different types of haulages can be found in Appendix E.

The door fraction is changed to represent the fraction to which the haulage is throttled or closed. The value of 1 is completely open and 0 is closed. This is changed to represent walls, doors, and other restrictions such as brattices and vehicles.

The VRT of the haulage can also be specified easily in PTB. Figure 2-9 illustrates the window in PTB in which you specify the VRT of a haulage.

[9] Screenshot taken by author – PTB inputs.

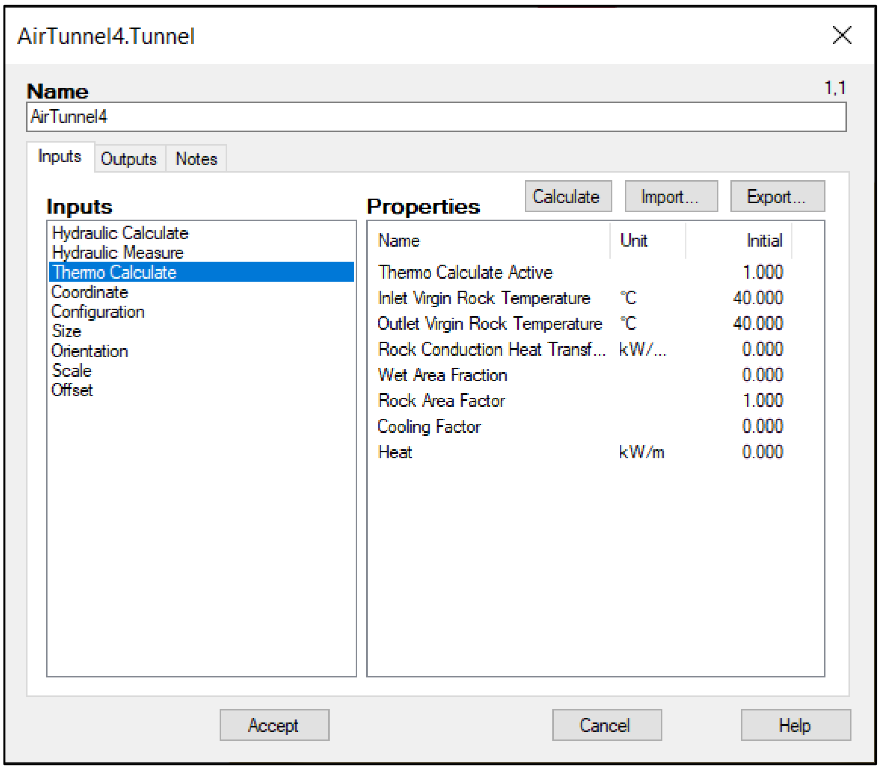

Figure 2-9: PTB inputs for the VRT of a haulage[10]

Figure 2-9 shows the thermal calculation inputs used in PTB to characterise underground haulage. It is important to ensure that the thermal calculation is active by providing the standard input of 1. The VRT inputs should then be provided for each haulage.

The final step is to change the colour of the lines that connect the components. This is to help with the identification of the various areas within the system. The standard colours that are used in this study are:

- Intake airways – Light blue
- RAWs – Orange
- Active mining areas – Green
- Future areas – Yellow
- Areas with no airflow – Black

[10] Screenshot taken by author – PTB inputs.

This concludes the building of the skeleton of the model. The calibration of the model can now start, and a true reflection of the system's performance will be achieved.

2.2.3 Calibrated model

The calibrated model is the next step towards achieving an accurate digital twin of the ventilation system. This model is a digital twin that is a representation of the ventilation system performance. Figure 2-10 illustrates the method that will be discussed in this section.

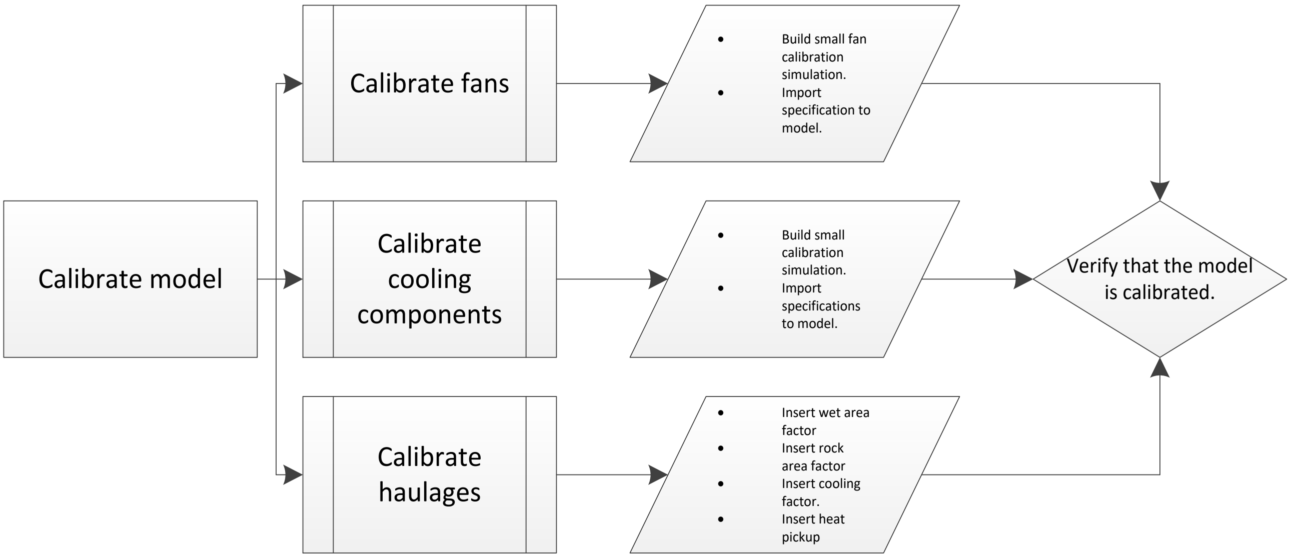

Figure 2-10: Method used to calibrate ventilation models

Figure 2-10 shows that the calibration of the digital twin starts with the calibration of each of the components according to their design specifications. This is achieved by using smaller simulations to calibrate each component and ensuring that they function as the actual component. This is done for all the ventilation fans and cooling equipment. It is also important to note that in some cases there is no information about the design specification of some equipment. In these cases, the equipment is audited, and this information is used to calibrate the component.

Ventilation fans

The calibration of each fan is achieved by calibrating the specific fan to operate according to its performance curve. This is achieved by building a smaller simulation in PTB. Figure 2-11 illustrates the setup of the fan calibration simulation.

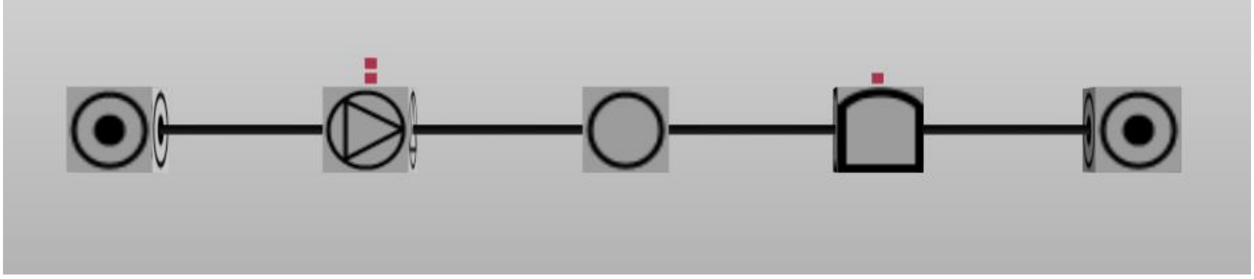

Figure 2-11: PTB ventilation fan calibration simulation setup[11]

Figure 2-11 shows the setup of the fan calibration simulation. This setup aims to simulate a pressure difference over the fan with the use of air pressure boundaries. Figure 2-12 illustrates the menu with which you input all the relative properties.

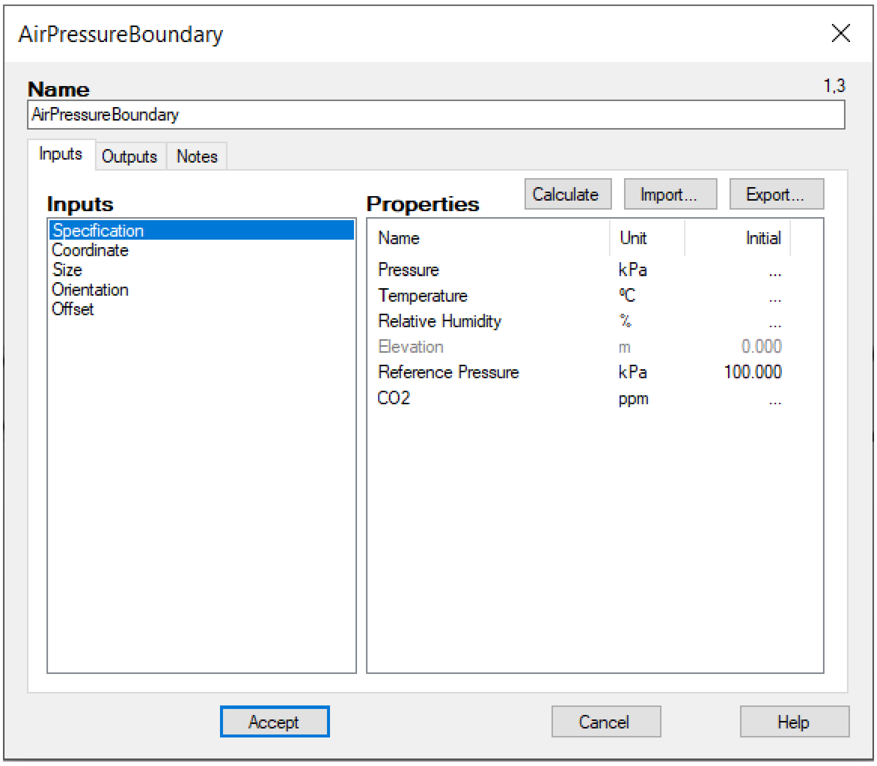

Figure 2-12: PTB air pressure boundary inputs[12]

Figure 2-12 shows the environmental properties that can be used as inputs in the simulation. This entails the barometric pressure, dry-bulb temperature, and relative humidity. It is important to note for the calibration of a fan that the inlet properties must be the same as the conditions at which

[11] Screenshot taken by author – PTB fam component calibration.

[12] Screenshot taken by author – PTB inputs.

the performance curve of the fan was plotted. The outlet air pressure boundary will only require a barometric pressure input which simulates the required pressure difference over the fan.

The inputs required for the specification of the fan are obtained from its performance curve. Figure 2-13 illustrates the various inputs required for a ventilation fan in PTB.

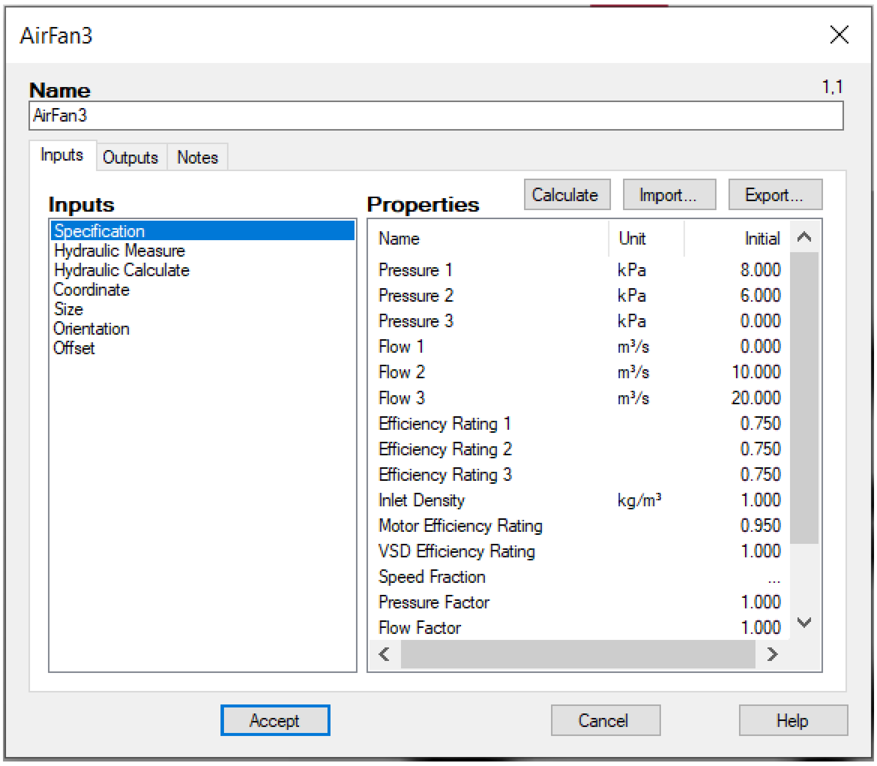

Figure 2-13: PTB ventilation fan inputs[13]

Figure 2-13 shows the inputs required for the setup of a ventilation fan. It requires three points on the pressure curve and the corresponding airflow and efficiency at that pressure. It also requires the air density at which the fan performance curve was determined. This ensures that the fan used in the model will react the same as the actual fan. PTB illustrates how the fan is operating according to its performance curve. Figure 2-14 illustrates the display of the fan performance curve in PTB.

[13] Screenshot taken by author – PTB inputs.

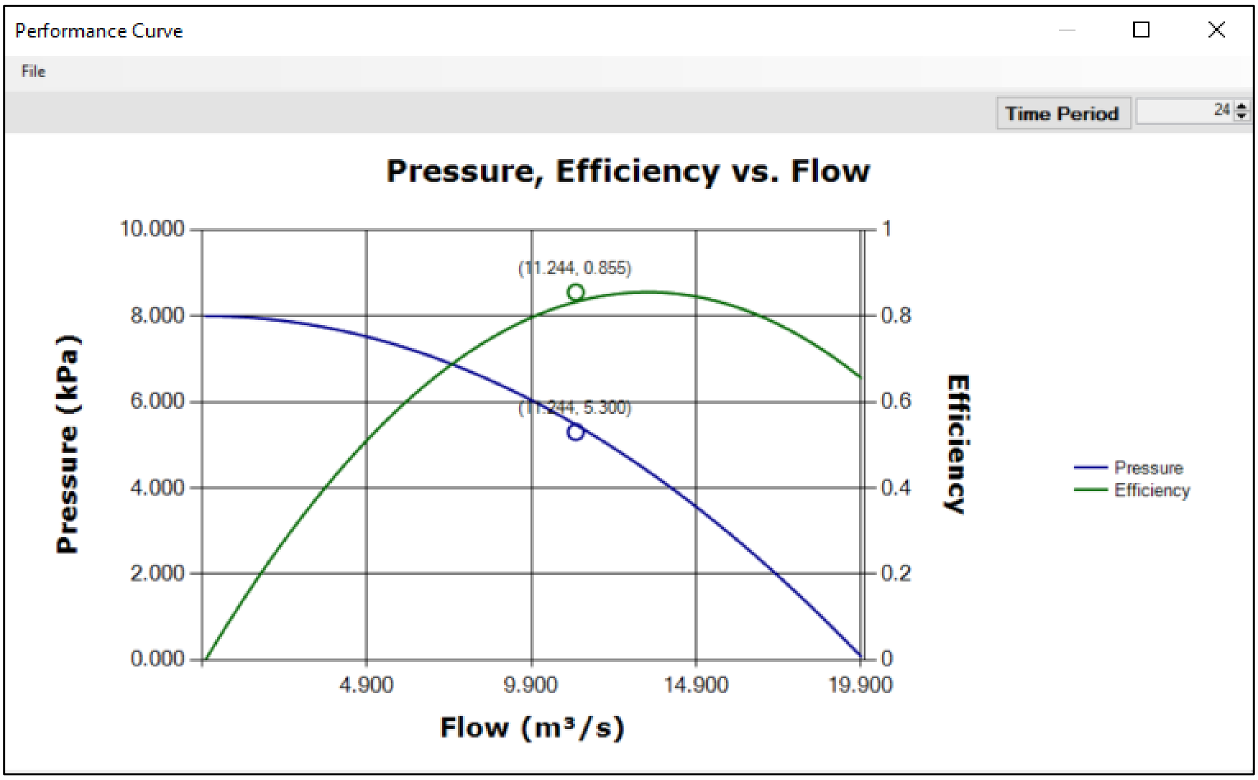

Figure 2-14: PTB fan performance curve output[14]

Figure 2-14 shows the point at which the fan is performing on the performance curve for the given pressure difference over the air pressure boundary. The fan is calibrated once it is performing on its performance curve for any pressure within its range. It is also important to verify that the power output of the fan matches the actual power output.

Cooling components

The calibration of cooling components, much like the calibration of fans, is achieved with a smaller simulation to ensure the correct performance of the component. The difference in working with cooling components is that they require air and water inputs. This implies the use of water and air pressure boundaries, pipes, mass flows, and nodes. Figure 2-15 illustrates the simulation setup that is used to calibrate cooling components.

[14] Screenshot taken by author – PTB fan performance curve.

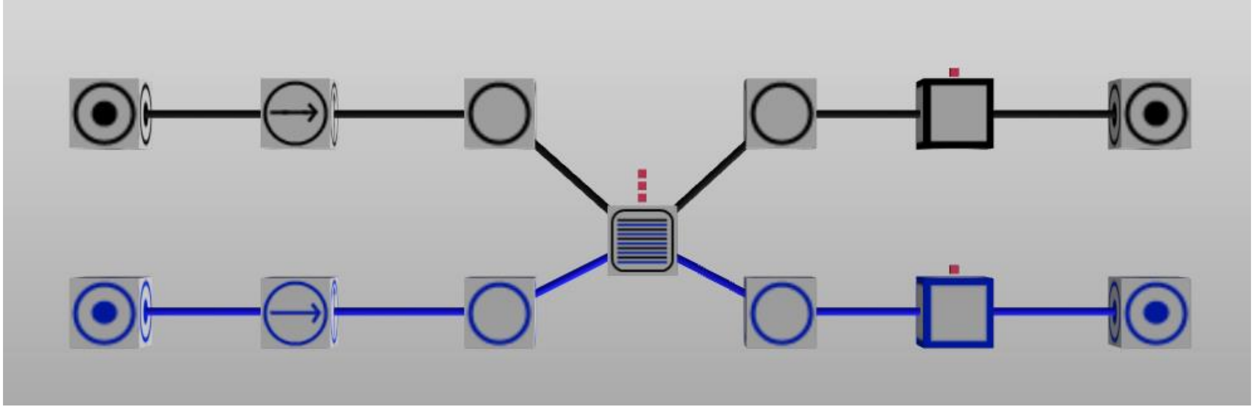

Figure 2-15: PTB cooling component calibration[15]

Figure 2-15 shows the use of air and water components to provide the necessary flow through the air-water heat exchanger. Similar setups can be used for water air cooling towers. The difference between the two components is that the water-air cooling tower simulates direct contact heat exchangers and water-air heat exchangers simulate indirect contact heat exchangers.

The water and air mass flow components are used to specify the required mass flow through the heat exchanger. This component has only one input and will provide the specified mass flow regardless of the pressure difference between the two pressure boundaries.

The air and water pressure boundaries are used to specify the inlet conditions of the heat exchanger. The air pressure boundary inputs are done in the same manner as for the fan calibration simulation. The water pressure boundary has different inputs but is still like the air pressure boundary. Figure 2-16 illustrates the inputs required for the water pressure boundary.

[15] Screenshot taken by author – PTB cooling component calibration.

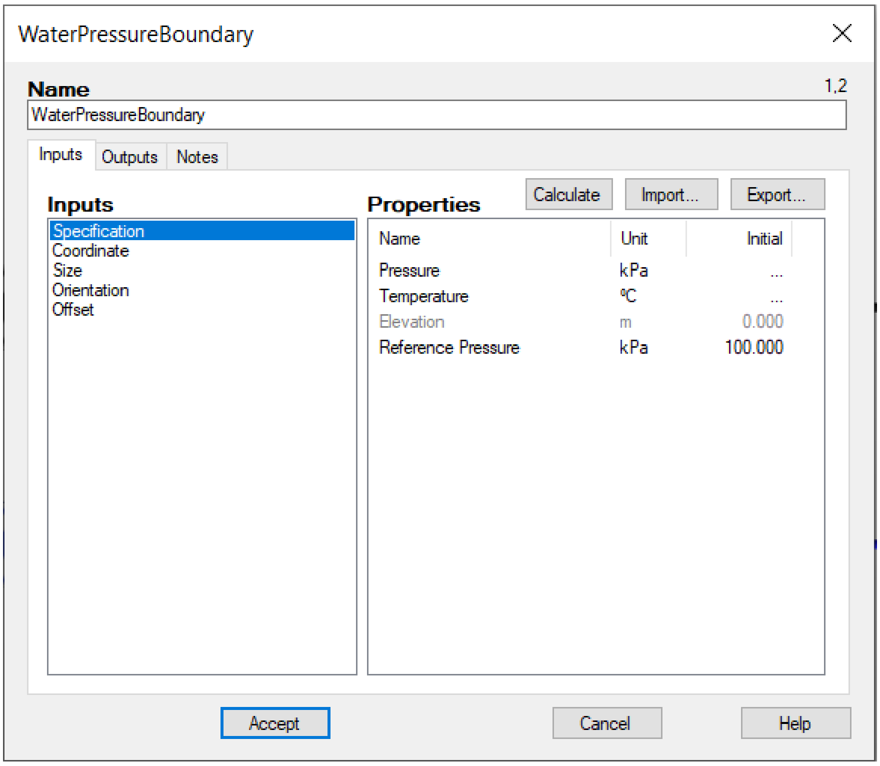

Figure 2-16: PTB water pressure boundary inputs[16]

Figure 2-16 shows that the water pressure boundary component requires a pressure and temperature input. This enables the inlet conditions of the heat exchanger to be specified. The cooling component then requires the specification of a unit area (UA) of heat transfer. It also requires the specification of the air and water mass flow. PTB has a built-in calculation that calculates the UA value of the heat exchanger. Figure 2-17 illustrates the required inputs to calculate the UA value of a heat exchanger.

[16] Screenshot taken by author – PTB inputs.

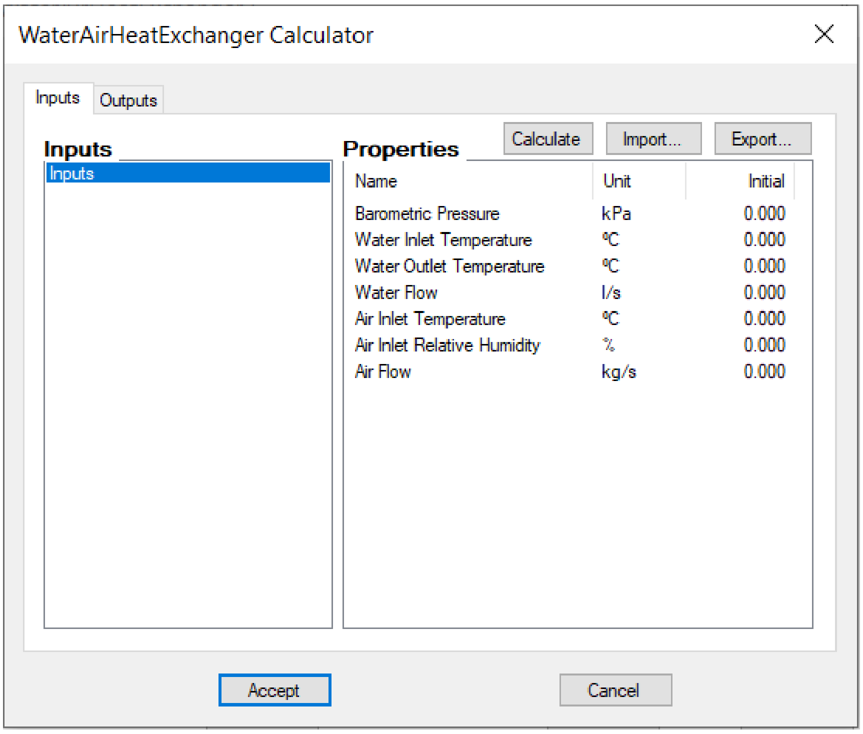

Figure 2-17: PTB built-in UA value calculator inputs[17]

Figure 2-17 show that the inputs required to calculate the UA value are barometric pressure, water inlet and outlet temperature, water flow, air inlet and outlet temperature, and airflow. This enables PTB to accurately calculate the required UA value to achieve the change in water and temperature for the given flows. The cooling component is calibrated when it achieves the required cooling duty under its design specifications.

Airways

The calibration of the airways is achieved by using the audit information that was obtained. The airflow through the air tunnels can be calibrated with the use of the calibration control component in PTB. This, however, is only done as a last resort. Figure 2-18 illustrates the different outputs that can be controlled with the use of calibration control.

[17] Screenshot taken by author – PTB inputs.

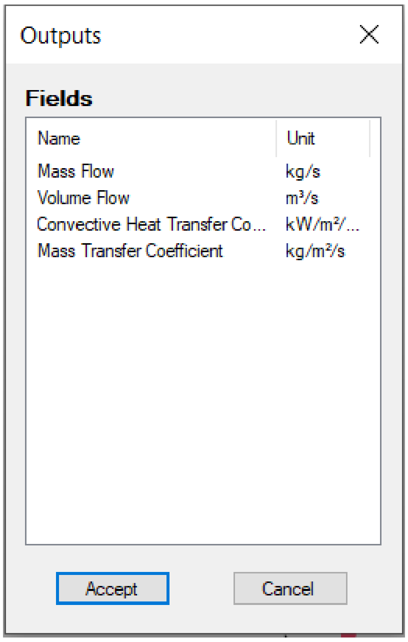

Figure 2-18: PTB calibration control component's outputs[18]

Figure 2-18 show that the mass flow, volume flow, convective heat transfer coefficient, and mass transfer coefficient can be calibrated with the use of this component. This is achieved by changing the properties of the air tunnel. The properties that can be chosen to achieve this is:

- Mass/volume flow – Door fraction
- Convective heat transfer/mass transfer coefficient – Rock area factor, wet area fraction, and cooling factor control.

The next step in haulage calibration is to thermally calibrate the haulages. Figure 2-19 illustrates the various inputs required to calibrate the thermal characteristics of the haulage.

[18] Screenshot taken by author – PTB inputs.

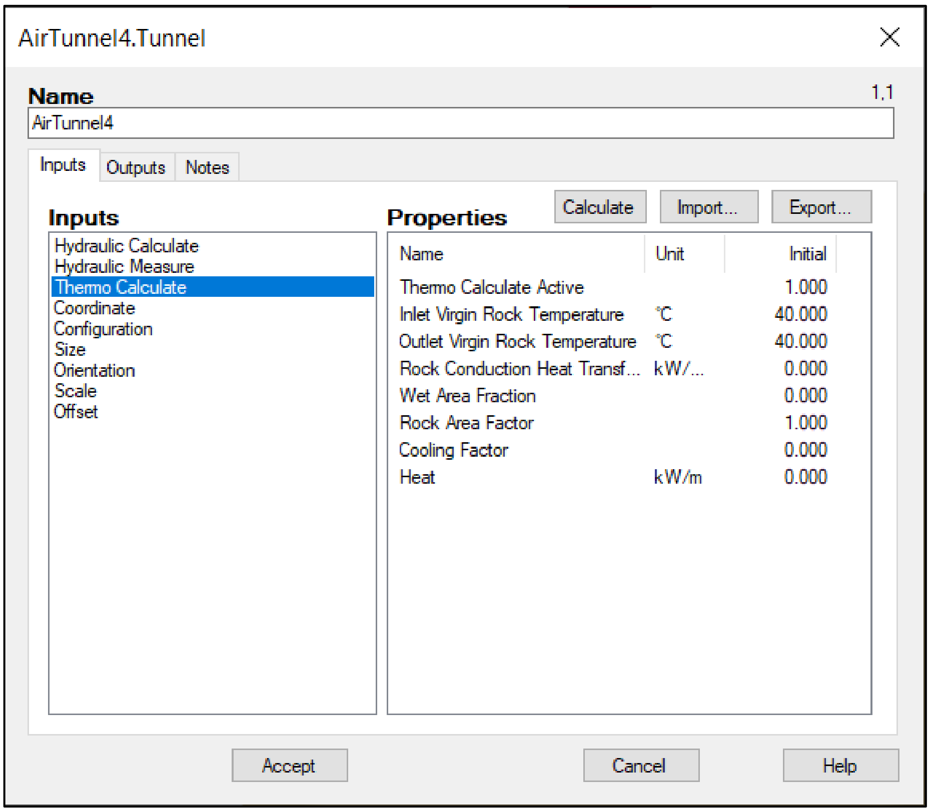

Figure 2-19: PTB air tunnel thermal calibration inputs[19]

Figure 2-19 shows the thermal calculation inputs used in PTB to characterise underground haulage. It is important to ensure that the thermal calculation is active by providing the standard input of 1. The rest of the inputs should then be provided for each haulage. The VRT values can be obtained from the planning department

The wet area fraction is used to simulate water accumulation within the haulage and the heat is provided in kW/m. The heat is calculated by using the information of equipment locations and specifications. This includes pumps, electrical equipment, vehicles, and all other artificial heat sources. The rock conduction heat transfer coefficient is determined with the use of a built-in calculator in PTB. Figure 2-20 illustrates the inputs required for the calculation of the rock conduction heat transfer coefficient.

[19] Screenshot taken by author – PTB inputs.

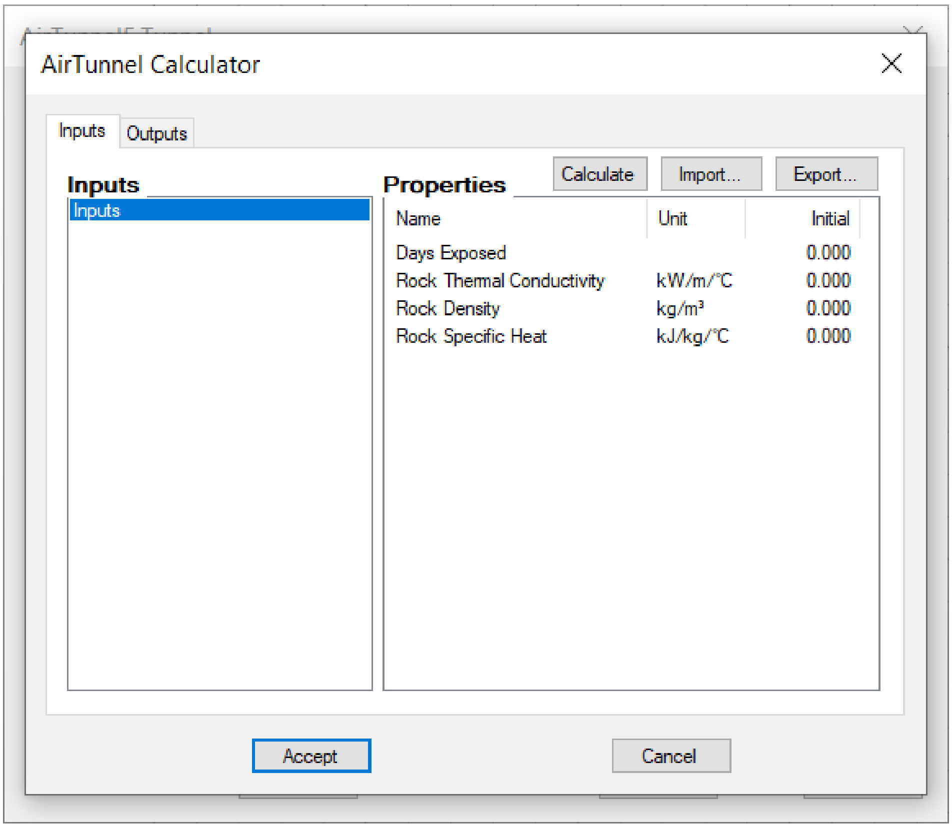

Figure 2-20: PTB built-in rock conduction heat transfer coefficient calculator[20]

Figure 2-20 shows the inputs to calculate the rock conduction heat transfer coefficient. These inputs are different to each rock type and the number of days that the rock has been exposed to the air.

Verification

The verification of whether a digital twin is calibrated is done by comparing the calibrated model outputs with the actual audit data. The model is assumed to be calibrated once the simulated values are all within 5% of the actual values. The nodes and tunnels that are to be used to evaluate the accuracy of the model will vary from mine to mine, but there is a list of locations that should be used to verify the model which is:

- Surface fan pressure, airflow quantity, motor power and efficiency.
- Intake and return shaft airflow quantities and temperature.
- Level intake air temperature, quantity, pressure, and relative humidity.

[20] Screenshot taken by author – PTB inputs.

- Half-level intake air temperature, quantity, pressure, and relative humidity.
- Cross-cut intake air temperature, quantity, pressure, and relative humidity.
- Booster fan pressure, airflow quantity, motor power and efficiency.
- Primary, secondary, and tertiary cooling infrastructure performance.

2.2.4 Problem identification

The use of a digital twin to identify problems within a system is still a new concept. The technique that will be used in this study is to compare the various key performance indicators (KPIs) in the calibrated ventilation models to the design specifications of the system. The deviations of the calibrated model, when compared to the design specifications of the system, is an indication of where the problems occur within the system.

The amount of KPIs in each ventilation network will differ, but there are various KPIs that will remain constant in every ventilation network. Table 2-1 outlines the KPIs of a typical ventilation network.

Table 2-1: KPIs of a typical ventilation network

Ventilation fans	• Fan pressure • Airflow quantity • Efficiency
Cooling components	• Inlet and outlet temperatures • Airflow rate • Cooling duty
Intake and return airways	• Air temperature • Airflow • Flow direction

Table 2-1 shows that it is imperative that the calibrated model be as accurate as possible to be able to conclude where the problem areas are. It is important to understand the implications of the values of each of these KPIs. This means that an understanding of over performance and underperformance should be achieved when evaluating the difference in the values of each of these KPIs.

The first component and its KPIs to be discussed is ventilation fans. The evaluation process starts with a better understanding of the performance curve of a fan. Figure 2-21 illustrates the various fan characteristic curves.

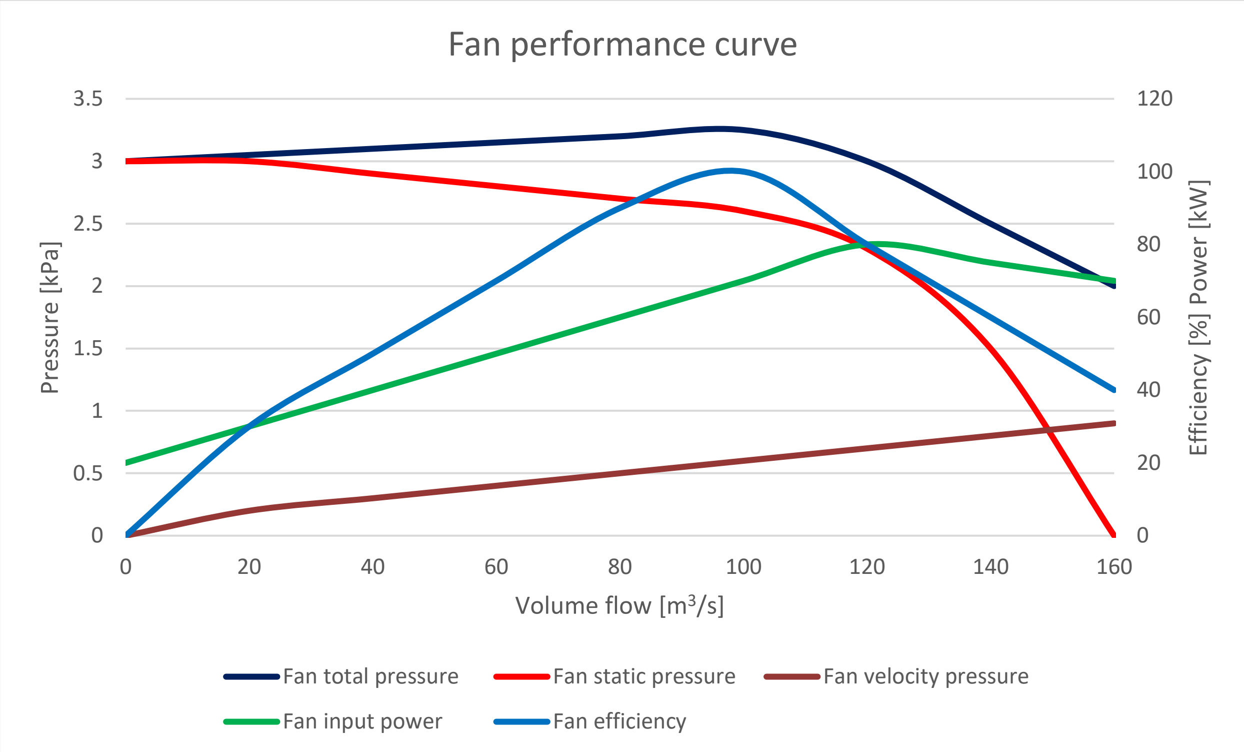

Figure 2-21: Typical fan characteristic curves

Figure 2-21 shows an example of a fan characteristic curve which includes the fan static pressure, total pressure, efficiency, input power, and velocity pressure. There is a peak in the fan efficiency, total pressure, and static pressure curves. This is important because this means that there is an optimum operation point of a fan. Although, this is not necessarily where the fan will be operating because this safeguards the fan from stalling when a system change occurs.

Therefore, when planning a ventilation network, the correct fan must be chosen to deliver a certain volume flow at a specific pressure. If this is done correctly then it can be assumed that when a fan is not operating as designed, there must be a problem within the ventilation network.

The evaluation of a fan's performance will require an understanding of what could cause a fan to perform differently from what it is designed to do. This is usually due to an increase or decrease in the system resistance. Figure 2-22 illustrates a typical underground parallel fan configuration.

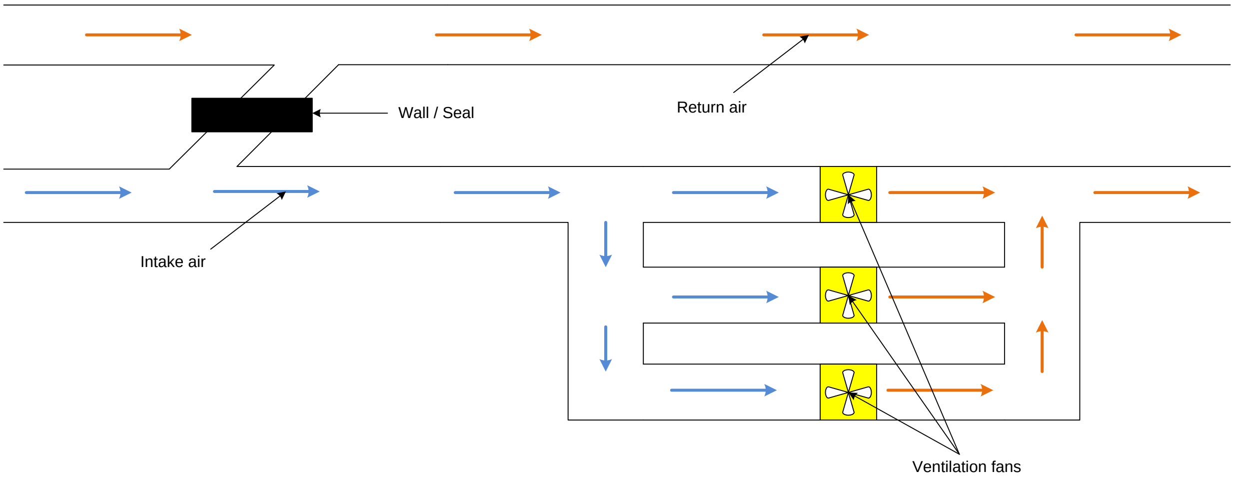

Figure 2-22: Typical parallel fan configuration

Figure 2-22 shows three ventilation fans placed in parallel with a single intake airway supplying air and a twin haulage parallel which is used as a RAW. This figure will be used to describe what could cause a fan's total and static pressure to increase and decrease. The fan pressure will increase if there is an increase in the system resistance either before or after the fan location. Figure 2-23 illustrates where the possible restrictions are to increase the fan pressure.

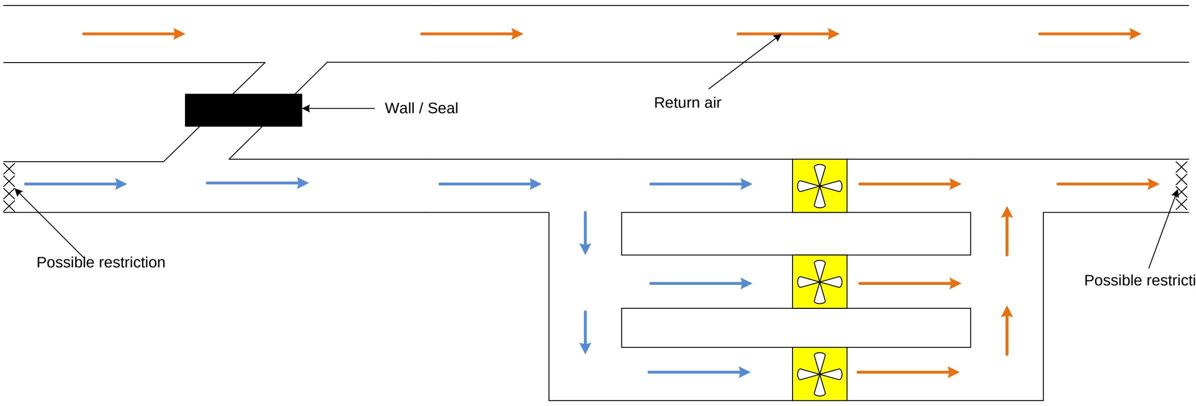

Figure 2-23: Illustration of what could cause an increase in fan pressure

Figure 2-23 shows that there is a change in the system resistance either before or after the fans, or sometimes both. The decrease in the system resistance will cause the operating pressure of the fan to decrease. This is most likely caused by air short-circuiting into the system due to a seal that is broken. Figure 2-24 illustrates what will happen if a seal is broken in the haulages before the fans.

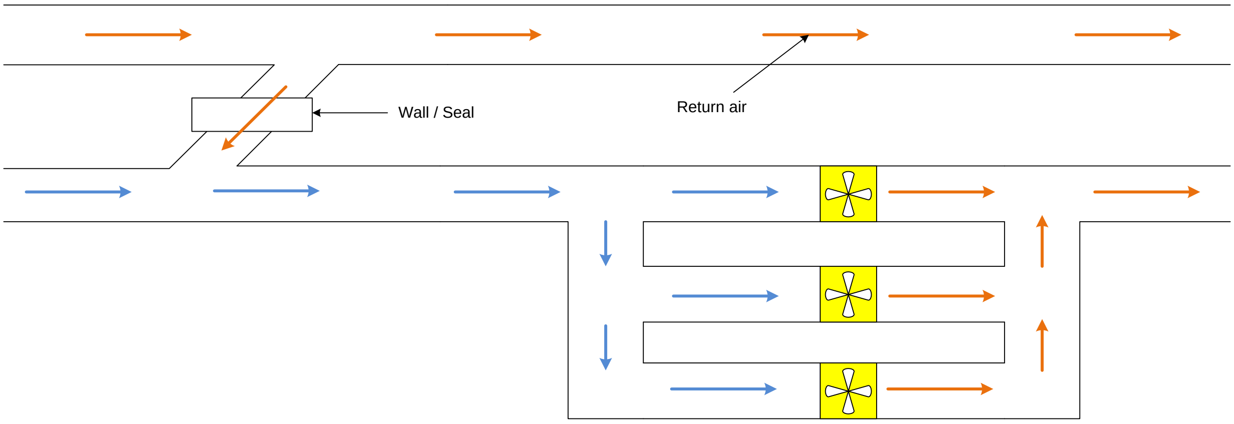

Figure 2-24: Illustration of what could cause a fan pressure to decrease

Figure 2-24 shows that when a seal is broken before the fan, the air will short circuit towards the fans and decrease the system resistance. This changes the operation point of the fans to lower pressure.

The next component to evaluate is the performance of the cooling equipment. It is important to know that the performance of the cooling equipment is dependent on the inlet temperature and flow rate of the cooling fluid and air. The measurement of the performance of a cooling component is done by calculating the heat transfer rate of the component. Equation 1 is used to calculate the heat transfer rate of the cooling component on the waterside.

$$\dot{Q}_w = \dot{m}_w C_p (T_{in} - T_{out}) \quad (1)$$

Where

$\dot{Q}_w$ = Heat transfer of the waterside of the cooling component (kW)

$\dot{m}_w$ = Mass flow of water (kg/s)

C_p = Specific pressure of water (kJ/kg·K)

T_{in} = The inlet temperature of water (°C)

T_{out} = The outlet temperature of water (°C)

The calculation of the heat transfer rate of air is different than that of the waterside. Equation 2 is used to calculate the heat transfer rate on the airside.

$$\dot{Q}_a = \dot{m}_a(h_{in} - h_{out}) \quad (2)$$

Where

$\dot{Q}_a$ = Heat transfer of the airside of the cooling component (kW)

$\dot{m}_a$ = Mass flow of air (kg/s)

h_{in} = The inlet enthalpy of air (kJ/kg)

h_{out} = The outlet enthalpy of air (kJ/kg)

This means that the evaluation of a cooling component should be done by comparing the cooling duty of either the air or waterside to the designed cooling duty. This will indicate the performance of the cooling component. The cause of the reduction in performance of a cooling component could be due to the airflow and inlet air temperature not being according to the design specifications.

The cause of an increase in inlet temperature or reduction in airflow can be identified by evaluating the performance of the intake and RAW. This entails the comparison between the design and actual airflow, temperature, and direction. Various occurrences can affect this, such as:

- leakages through seals,
- fans that are switched off or perform inefficiently,
- New restrictions that are added to the system, and
- The expansion of the mine,

The evaluation of the mine is a tedious process, but with the help of an accurate calibrated digital twin, it is sped up significantly. This section indicated what the main causes are in the deviations between the calibrated digital twin and the design specification of the system.

2.2.5 Simulate solutions

Simulating various scenarios to derive a solution to the problem that was identified within the ventilation network is one of the key advantages to having a digital twin of the mine ventilation network. This provides the opportunity to illustrate more than one solution to the relevant stakeholders and the benefits and losses could be compared and a decision could be made.

The simulation of a possible solution is an iterative process where various changes are implemented and tested using the digital twin. The solution will depend on the problem and each problem will be different than others. There are however basic principles that could be applied to help speed up this process.

- Restricting/stopping airflow will cause more air to flow to the other surrounding areas due to less air flowing through the changing area and will increase the overall system resistance.
- Opening stoppings/restrictions will cause less air to flow to the surrounding areas due to more air flowing through the area that is changed and will reduce the overall system resistance.
- Try to stay away from adding additional infrastructure and first work with the infrastructure available.
- Fans will increase the flow through an area, but it is important to note that they will add heat to the system and increase the pressure on the discharge side of the fan.
- It is, however, always important to simulate realistic solutions and to keep in mind what is the future of the mine. This is achieved with constant communication of what is simulated with the ventilation department and the relevant stakeholders.
- It is also important to re-evaluate the entire system when a solution to the problem is obtained. This is to ensure that none of the other sections within the ventilation network is negatively influenced by the solution.

The results of the simulated solution should then be compiled and the main KPI’s should be used to communicate what the improvement will be of the system. The solution is optimised if all the main KPIs are improved upon and there are no negative effects when the solution is implemented on the system.

2.2.6 Report findings

The next step of the process is to report the findings on what was achieved when simulating various solutions to the problem. It is important to always report multiple viable solutions if possible. The reports should be detailed and outline the various implications when a solution is implemented by illustrating the improvement on the main KPIs.

It should also be noted that when a solution to a problem is reported, a viable step-by-step plan of implementing the solution should be presented to provide clarity on the relevant stakeholder on what the improvement will be on the system as well as how it can be implemented.

It is then the responsibility of the relevant stakeholders of the mine to approve one of the proposed solutions. This will ensure that everybody is informed of what the next steps are and how the solution will be implemented.

It should also be noted that this could be a tedious process since the stakeholders will have various questions and will request certain changes that are to be looked at in the proposed solutions. These changes should be looked at, but it is important to ensure that the solution that is to be implemented, is still improving the overall system and will solve the identified problem.

2.2.7 Implement solutions

The implementation of the proposed solution is the most important step in improving the ventilation network. It is important to ensure that the solution is implemented exactly as it was intended to reduce the chance of possibly influencing the system negatively. Constant monitoring and verification of the improvement of the project are critical.

It is important to help with formulating the plan with step-by-step instructions of how the improvement should be implemented. This will ensure that the project is implemented correctly and that the expected results are obtained. There are instances where scenarios must be simulated to help with the planning of the project, for example, the simulation of a scenario to effectively enter an area with high temperatures.

This is when a system change must be made to help with the implementation of the project. Then it is important to ensure that the system is changed back to the original configuration once the project has been implemented.

This is where the value of having an accurate digital twin is once again emphasised. The digital twin will help simulate scenarios in which the health and safety of the mine personnel are ensured.

This adds the added benefit of cost avoidance as the system can be altered beforehand to test whether the proposed plan will work before making any actual changes to the system.

The final step after the solution has been implemented is to ensure that all the expected results were achieved and that the solution was implemented correctly. This is where a full audit of the area is conducted and the results from the simulation are validated. The success of the project is then quantified and reported to the relevant stakeholders.

2.2.8 Maintain models

The final important step is to always update the digital twin as the mine expands and changes. Recall from section 1.2 of this study that the ventilation network is dynamic and complex because it is always changing, expanding, and extending deeper below the surface. It is therefore imperative that the digital twin remains up to date with the expansion of the ventilation network.

The above measures ensure that the digital twin remains an accurate representation of how the actual system is performing. It is important to communicate with the relevant mine personnel who are responsible for the plans of the ventilation network. Figure 2-25 illustrates an example of how plans are built into the digital twin.

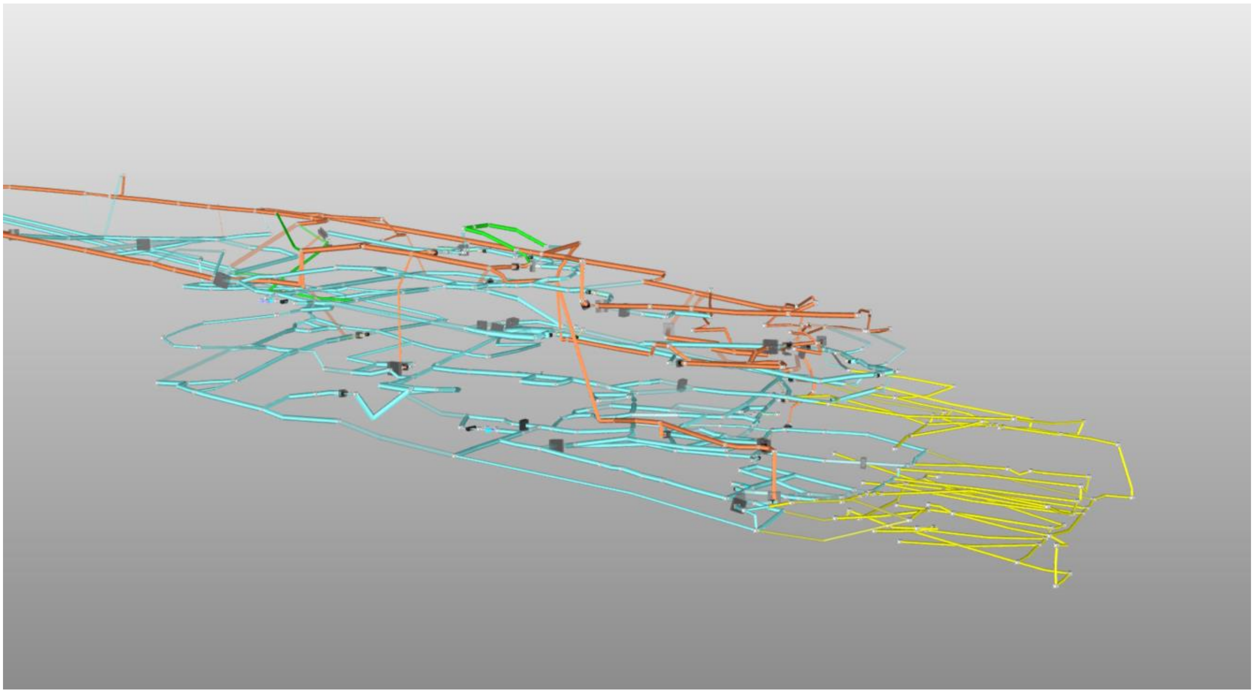

Figure 2-25: Example of how plans are built-in beforehand

Figure 2-25 shows how the plans are built-in. The blue and orange lines represent the actual haulages that are currently being used and the yellow lines represent what is being planned to be mined in the future. These plans are to be built beforehand in PTB and be sized and calibrated as the areas are developed.

It is also important to remain up to date with unexpected changes that are happening to the system. These changes must be made to the digital twin to ensure that it remains calibrated and up to date. This why regular audits must also be conducted of the ventilation system to ensure that there are no unplanned changes to the system and its performance. This will ensure that when new ventilation problems are identified that accurate solutions could be provided to the relevant stakeholders.

2.3 Summary

The methodology that was derived and used in this study was explained in more detail through illustrations and descriptions. This is a generic overview of the method that can be applied to any deep level mine ventilation network. Figure 2-26 illustrates a summary of the first four steps which are taken to develop a calibrated digital twin.

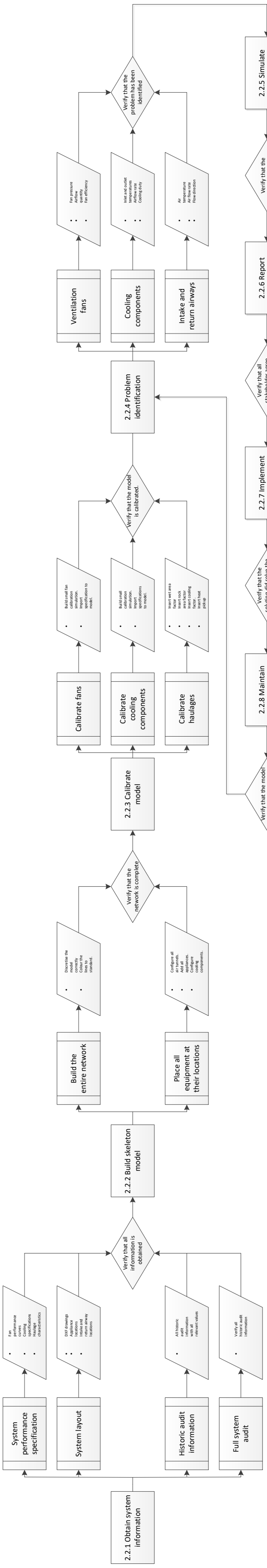

Figure 2-26: Method to develop an accurate calibrated digital twin

Figure 2-26 shows a breakdown of each of the steps that are taken towards building a calibrated digital twin. This process can be used to develop an accurate digital twin of an underground mine ventilation system. The process also describes how the model can be utilised to identify and solve problems within the system. This means that the process addressed the objectives of this study.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Preamble

This chapter evaluates the methodology that is described in Chapter 2 and then tests the methodology using a case study. The background of the mine that is used in the case study is provided. The process of how the digital twin was developed it then discussed followed by an in-depth discussion of how the system was evaluated and what problems were identified.

The results of the simulated solution to the problem are discussed and the key results highlighted, followed by a discussion of the post-implementation measurements to validate the results and quantification of the overall improvement in the system.

3.2 Case study

The gold mine the serves as the case study was originally developed as a conventional narrow-reef deep-level gold mine. The mining areas in the mine were mined out and closed off, after which a decline was developed to access gold resources. The mine was converted to a mechanised mine which is adapted for “massive mining”. The current depth of the mine is exceeding 3 km with new plans to mine even deeper.

This presented a wide array of challenges to the ventilation department to safely ventilate the new ore body. The mining activity that is currently taking place is situated roughly 8 km from the main intake shaft of the mine. There is one axial extraction fan on the surface which is responsible for extracting all the return air from the mine. The location of this fan is roughly 13 km from the nearest return point of the mine.

The mine utilises underground refrigeration to help to reduce the heat resulting from the surrounding rock and mining activities. The refrigeration system consists of fridge plants that supply chilled water to the mine for mining activities as well as six bulk air cooling towers (BACs) which help cool the intake air of the mine. This refrigeration system is situated 2.5 km from the furthest working place, which adds to the challenge of supplying cool air to the mine.

The method used to extract the ore involves dump trucks and conveyor belts. These vehicles are diesel-powered and emit large quantities of heat when operating. Figure 3-1 illustrates the layout of the mine’s ventilation network.

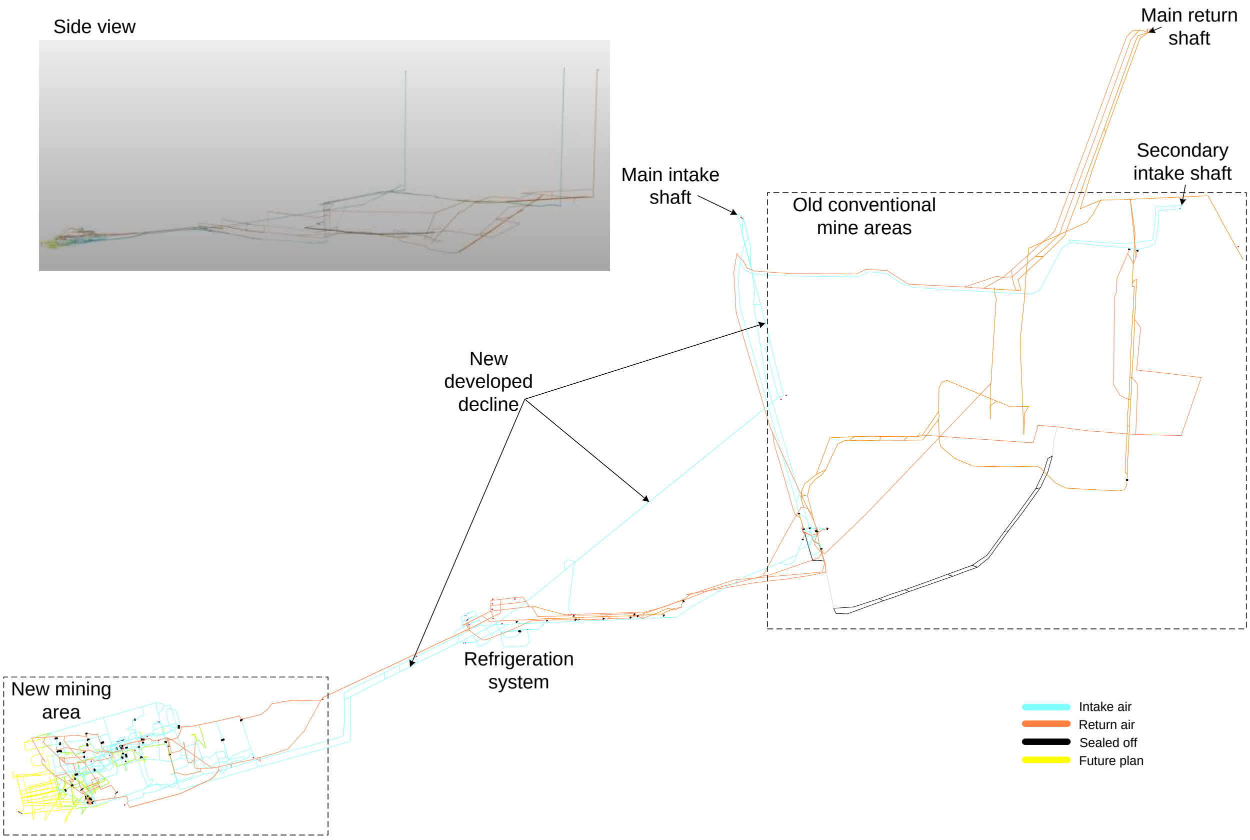

Figure 3-1: Layout of the ventilation network

Figure 3-1 shows the layout of the overall ventilation system. The locations of the main and secondary intake shafts as well as the return shaft are highlighted to show the locational challenge of ventilating the new mining area. The blue line illustrates the intake airways and the orange lines the RAWs. The yellow lines show the future mining plans for the mine from which it can be seen that the mine is developing further away from the intake and return shafts.

It is evident that the challenges of ventilating this mine will only increase and that there is a need to help mitigate some of these challenges. The other challenge that the mine faces is that it still utilises the old conventional mine areas as RAWs. These areas are sealed off and are inaccessible due to the high temperatures of the return air.

This emphasises the need for the mine to have an accurate digital twin of the ventilation system which can be used to help evaluate the performance of the system. This will help with the identification of ventilation problems within the system which were previously unknown. The reasons mentioned make this mine an ideal case study for the testing of the methodology provided in Chapter 2.

3.2.1 Digital twin development

The development of the digital twin of the ventilation network for the mine used in this study was completed with the use of the method discussed in Chapter 2.

Obtain information

The information on the system was gathered from the mine personnel to help with the understanding of the system. There are 22 booster fans in a tight circuit within the mining areas referred to as the mining block. Appendix F illustrates the locations of all the fans in the mine. There are also four 250-kW fans located at the refrigeration system which provides airflow of 65 m^3/s over each of the condensers. These fans are also used as the main booster fans underground. These four fans are in a series configuration with the 22 fans located in the mining block.

It was therefore imperative to obtain the performance curves of these fans. All the performance curves were obtained and can be found in Appendix G. This information will then be used to calibrate all the ventilation fans.

Furthermore, information was gathered as to which cooling components are located within the system. There are four open-spray BACs located close to the refrigeration system and two more located within the mining block. The design specifications of the BACs were therefore obtained and used to calibrate the cooling components within the system.

The next information to be obtained is all the DXF files of all the areas within the ventilation network. This information can be seen in Appendix F. These files can be used in PTB to build the layout of the entire system. It is also important to determine which areas within the mine are intake airways and which areas are RAWs.

The historic audit information was gathered from the ventilation department. This information was then verified by conducting a full ventilation audit of the mine. The audit information used to calibrate the digital twin can be seen in Appendix F.

The building of the skeleton

The building of the skeleton model in PTB is achieved by building the model in discretised nodes as described in section 2.2.2 of this study. The model in this study is built out of more than 2 500 discretised nodes and components. This is due to the complexity and scale of the system. Figure 3-2 illustrates an example of the nodes used to build the skeleton.

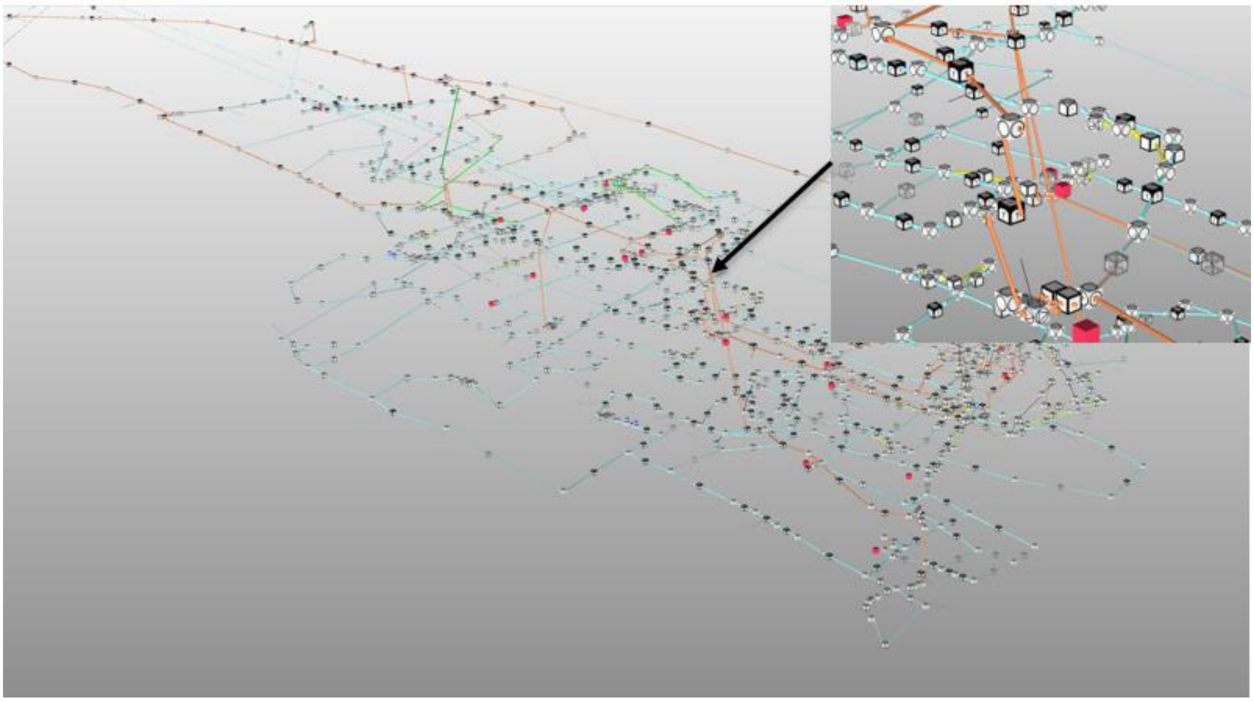

Figure 3-2: Discretised nodes used to build the skeleton of the model

Figure 3-2 shows that many nodes are used to build the ventilation network in PTB and illustrates the complexity of the system. The entire model was then built with the use of the DXF files that were obtained, and all the components were inserted in their various locations. Figure 3-3 illustrates the skeleton model of the entire ventilation network evaluated in this study.

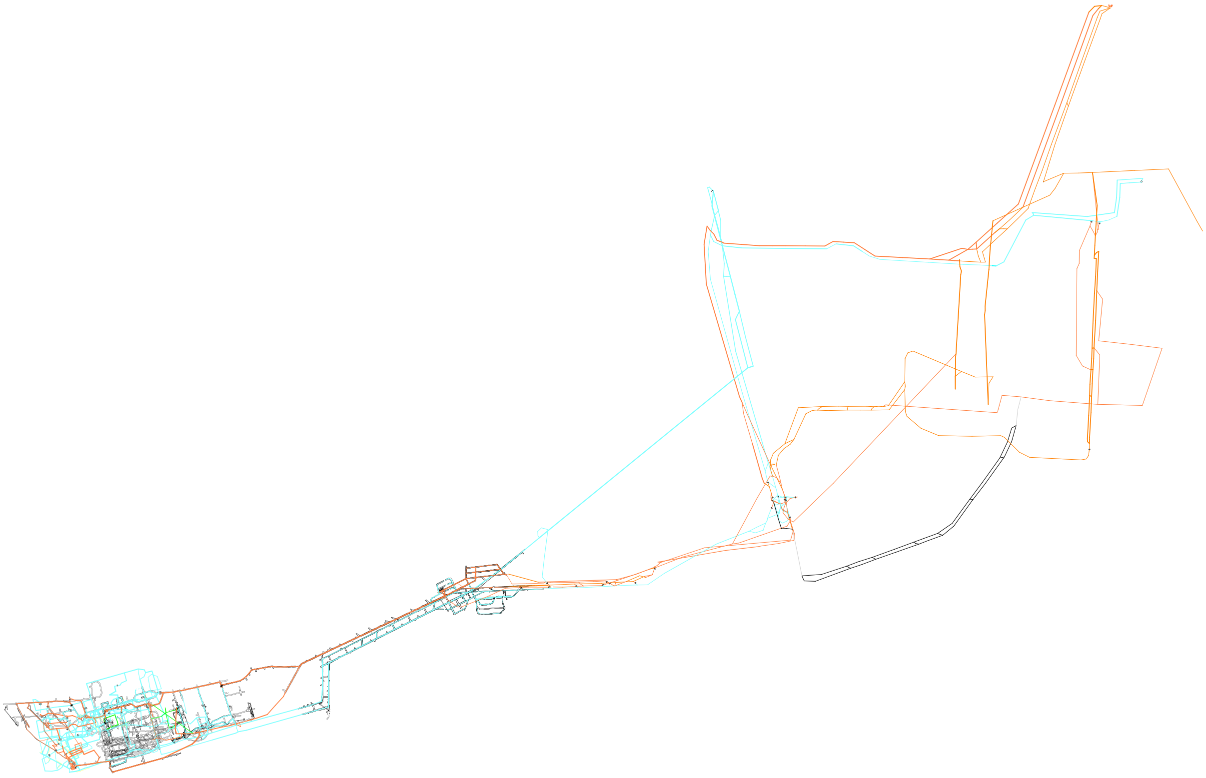

Figure 3-3: The skeleton of the ventilation network as seen from above

Figure 3-3 shows the entire ventilation network of the underground mine that will be evaluated in this study. The haulage sizes, VRTs, and ages of the haulages are inserted. The VRT of the haulages was determined from the depth of the haulage and the rock conduction heat transfer rate was determined from the age of the haulage. The internal standard for the colours of the haulages was used in this case study.

Calibrated model

The skeleton model was then calibrated to reflect the performance of the system by following the steps as described in section 2.2.3. Next, the model has calibrated the digital twin and verified to be calibrated to an accuracy within 5% of the actual measurements taken during the ventilation survey of the mine. It was necessary to use calibration controllers in some areas since there were instances where restrictions were present in the airways. Table 3-1 compares the actual measurements of the main KPIs of the system to the simulated values.

Table 3-1: Comparison between the main KPI's of the system

KPI	Actual measured values	Simulated values	Accuracy (%)
Surface fan pressure (kPa)	3.09	3.11	99.35
Main booster fan 1 pressure (kPa)	5.13	4.94	96.30
Main booster fan 2 pressure (kPa)	5.04	4.94	98.02
Main booster fan 3 pressure (kPa)	5.05	4.95	98.02
Main booster fan 4 pressure (kPa)	5.08	4.94	97.24
Total intake airflow (kg/s)	188.01	184.35	98.05
Total return airflow (kg/s)	188.01	184.35	98.05

Table 3-1 indicates that the model is calibrated to within 5% of the actual measurements. It can therefore be assumed that the model is calibrated to reflect the actual performance of the system.

3.2.2 Problem identification

The evaluation of the ventilation network began with the comparison of the pressures of all the ventilation fans within the system with their respective design specifications. Figure 3-4 illustrates the comparison between the calibrated fan pressures and their respective design specifications.

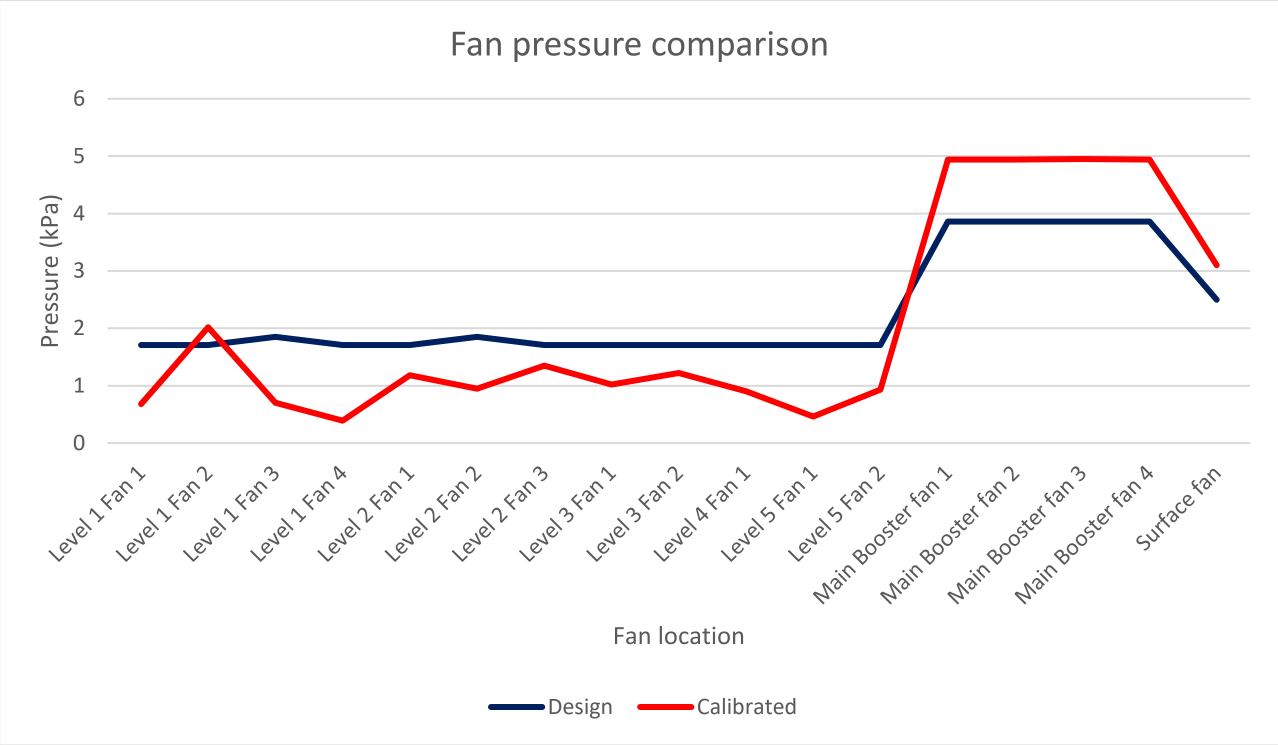

Figure 3-4: Calibrated fan pressure comparison to design specifications

Figure 3-4 shows that there is a clear difference between the calibrated and design pressures of the fans within the system. The most concerning difference is on the four main booster fans. This is a clear indication that there are restrictions in the areas behind the fans.

The areas behind the fans are the main RAWs of the mine which passes through the old conventional mine airways as shown in Figure 3-1. This means that these areas must be investigated to identify and reduce the restrictions within the airways. This is, however, impossible due to the hot condenser air that is flowing through these areas. The temperature within these areas exceed 40 °C wet bulb and is therefore above the legal limit as described in the Mine Health and Safety Act [23].

The possible improvement of the system when addressing these issues was then quantified with the use of the calibrated digital twin. Table 3-2 provides a breakdown of the possible improvements to the system.

Table 3-2: Improvements to the system according to the digital twin

KPI	Initial measurements	Simulated improved values	Total improvement
Surface fan pressure (kPa)	3.1	2.8	0.3
Main booster fan 1 pressure (kPa)	4.9	4.8	0.1
Main booster fan 2 pressure (kPa)	4.9	4.7	0.1
Main booster fan 3 pressure (kPa)	4.9	4.7	0.1
Main booster fan 4 pressure (kPa)	4.9	4.7	0.1
Total intake airflow (kg/s)	184	197	13
Total return airflow (kg/s)	184	197	13

Table 3-2 shows that there will be an overall improvement to the ventilation system. The pressure of all the main booster fans, as well as the surface fan, will decrease. This is due to the reduction in the system resistance when the restrictions are removed. These findings were then used to motivate the importance of entering these areas and reducing the restrictions.

3.2.3 Simulation of solution

The problem of entering these areas is caused by the design of the ventilation system. Figure 3-5 illustrates the locations of the areas that are to be investigated.

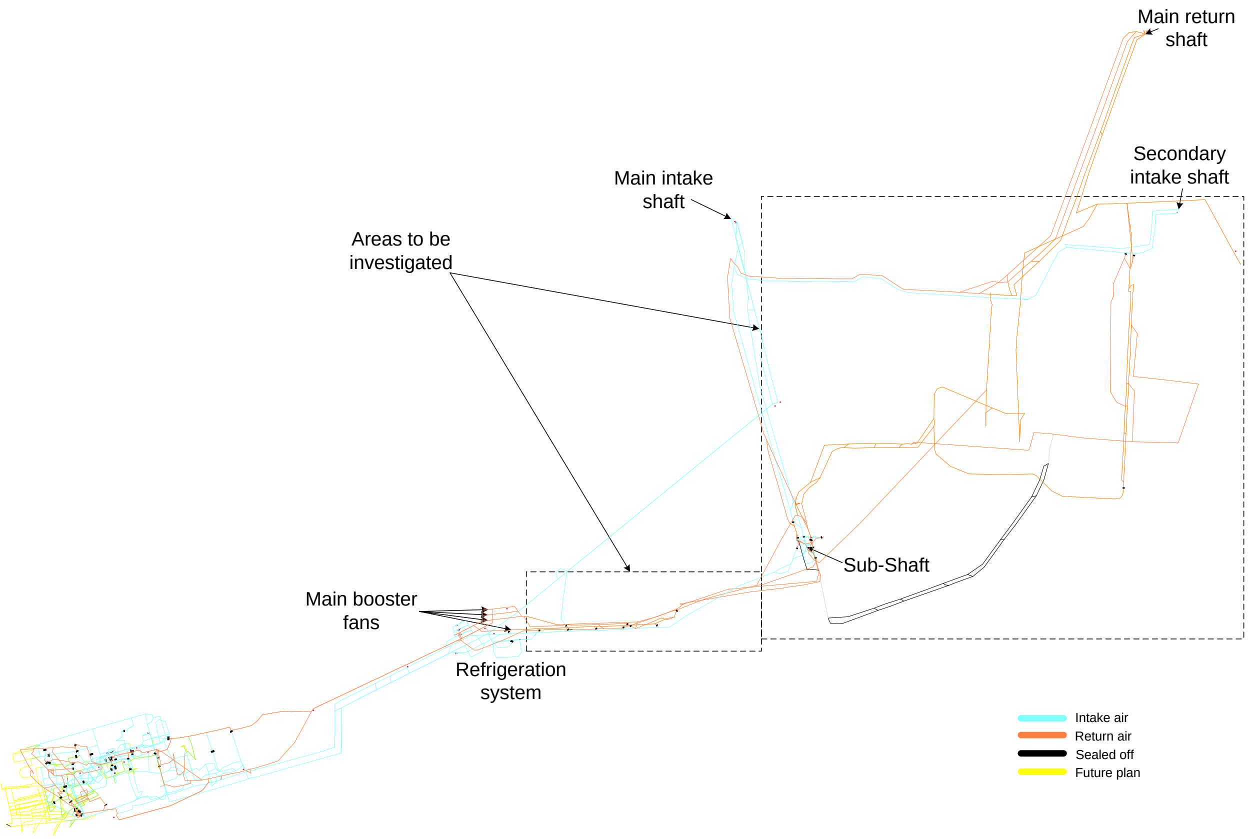

Figure 3-5: Location of the areas that should be investigated

Figure 3-5 shows that the problem with reducing the restrictions in the RAW is due to the high temperatures in these areas caused by the hot air flowing from the condensers. The other issue that is causing these high temperatures is the heat pickup from the mining activities in the mining block. The consultation with the mine personnel led to the testing of an initiative of diverting fresh cool air into these old areas.

This initiative was tested using the digital twin of the ventilation system. The initiative starts by short-circuiting air to the main booster fans and excluding the mining block heat pickup. Figure 3-6 illustrates the short-circuiting of air to the main booster fans.

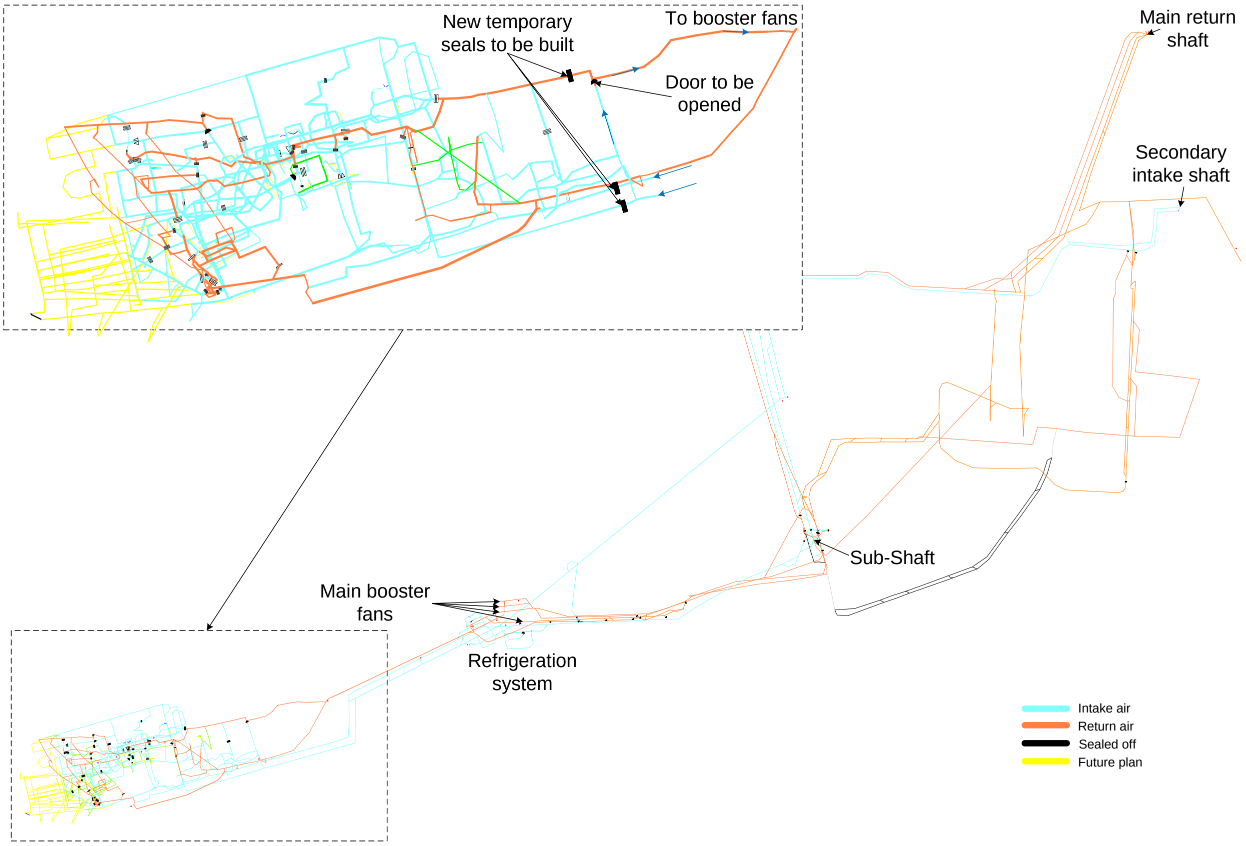

Figure 3-6: Short-circuiting of air to the main booster fans

Figure 3-6 shows that three temporary seals will have to be built and that the door that is the entrance to the RAW should be opened. This will cause all the intake air to bypass the mining block. The heat pickup will then be removed from the equation and cold fresh air will flow to the four main booster fans. The next step that was tested was switching off the refrigeration system. Figure 3-7 illustrates the location and layout of the refrigeration system.

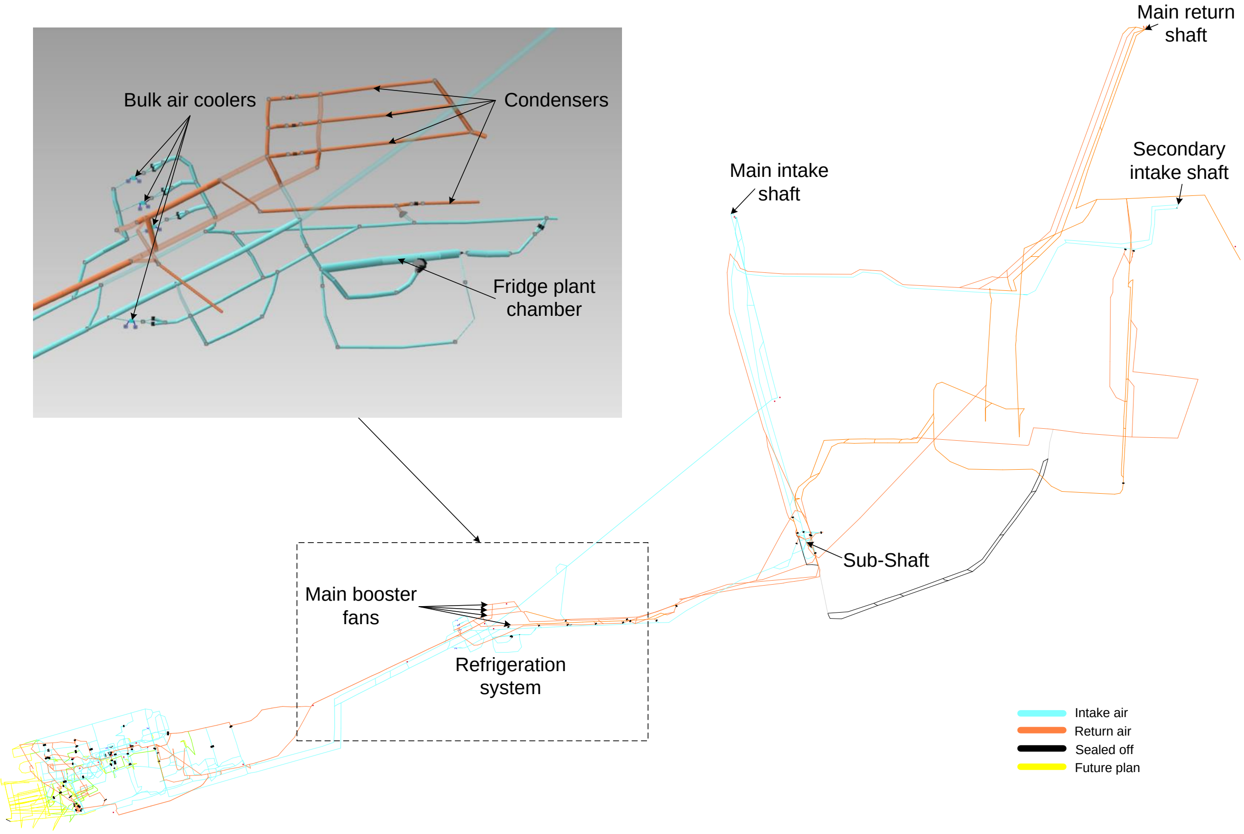

Figure 3-7: Refrigeration system location and layout

Figure 3-7 show the locations of all the components in the refrigeration system. The entire refrigeration system will be switched off for the scenario which will mean that the heat from the condensers will be eliminated from the ventilation system. The final step will be to short circuit fresh air through the sub-shaft to the old areas of the mine. Figure 3-8 illustrates the method of short-circuiting air through the sub-shaft of the mine.

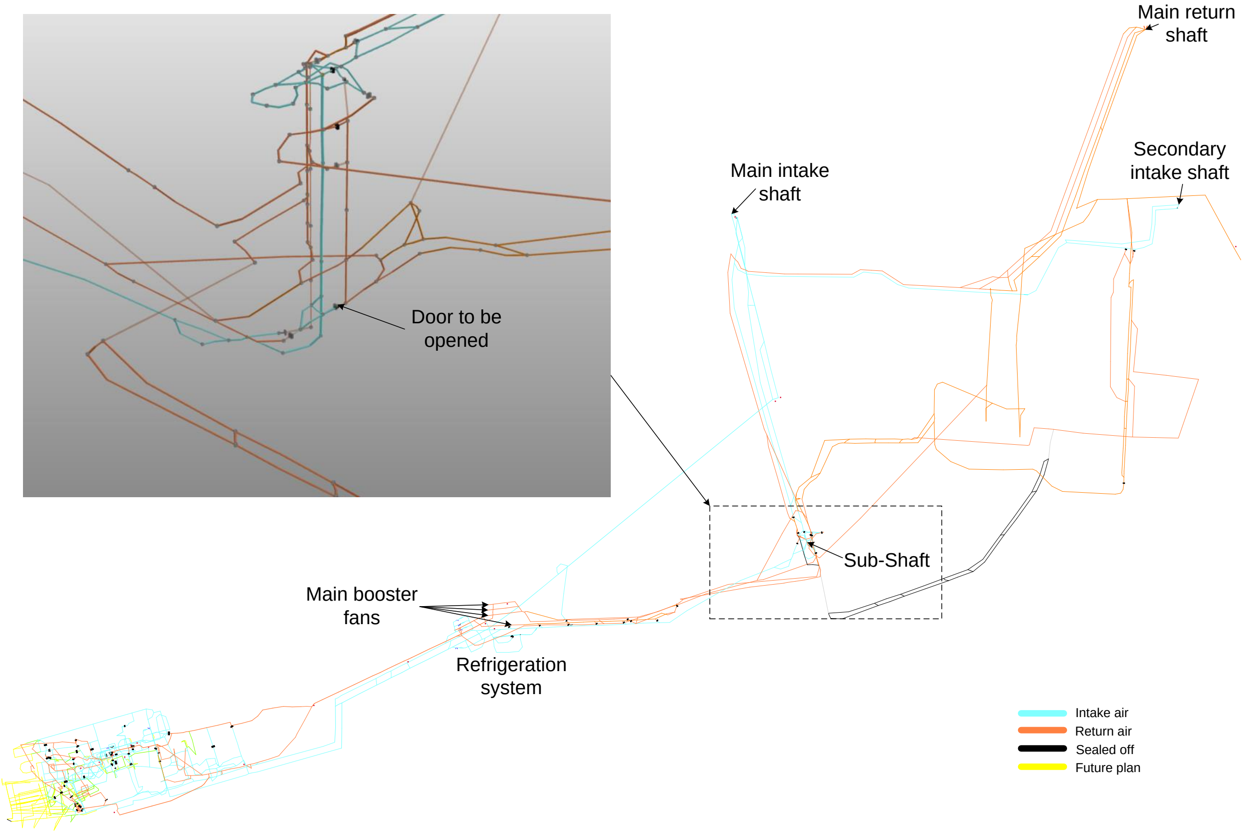

Figure 3-8: The short-circuiting of air through the sub-shaft

Figure 3-8 shows the door that should be opened to enable fresh air to flow into the areas that should be investigated. This will lower the temperature of the area and increase the amount of fresh air. This initiative was simulated with the use of the digital twin and it was found that the temperatures were reduced within legal limits after 36 hours. Figure 3-9 illustrates the overall initiative.

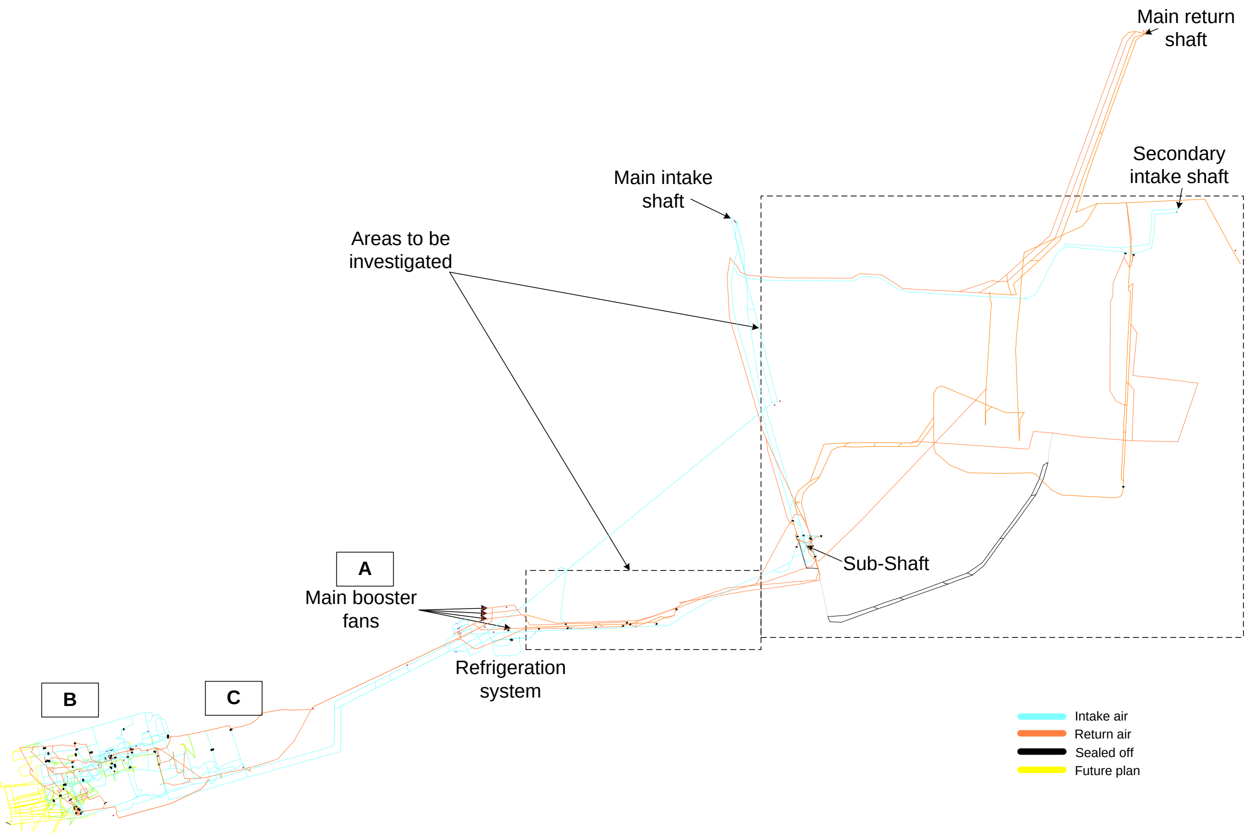

Figure 3-9: Simulated initiative

Figure 3-9 shows the configuration of the initiative that was tested using the digital twin of the ventilation network. To summarise, the initiative is the following:

A. All refrigeration systems are to be switched off, which means that there will be no hot condenser air flowing through the areas that are to be investigated.
B. All mining activities are to be stopped and the flow of air through the mining block is to be sealed off so that it is short-circuited through the four main booster fans.
C. Fresh air will be short-circuited through the sub-shaft directly into the old areas.

3.2.4 Implementation

The suggested solution was approved by all relevant stakeholders and the planning commenced. The success of the initiative will be dependent on the various changes that are to be made to the system. It was determined that a high-pressure door will have to be installed on the levels at the sub-shaft that are to be evaluated to ensure that the fresh air can be flushed through the areas that are to be investigated.

It was then decided that the areas that are to be investigated be divided into four different zones. Each zone will be allocated with two Mines rescue teams to ensure the safety of the personnel. This is the legal requirement for the Mines rescue teams as it enables them to have one team investigating and a second on standby to help in the event of an accident. Figure 3-10 illustrates the zones that were identified to be investigated.

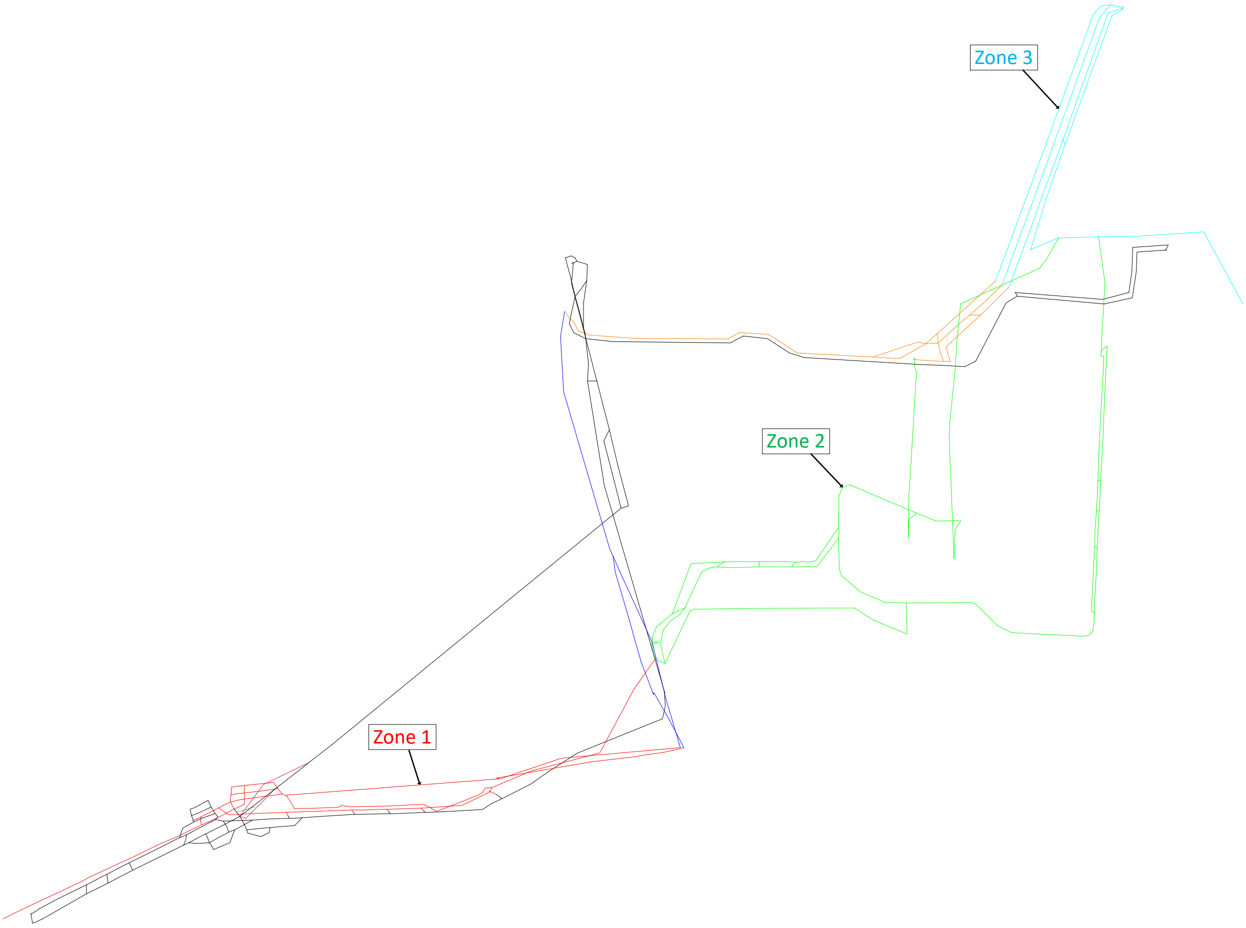

Figure 3-10: The zones that are to be investigated

Figure 3-10 show the four zones which were investigated and detailed layouts of each of these zones were given to the various teams so that they could mark the finding at the relevant locations. Appendix I shows the layouts that were given to the personnel. It is also important to note that before the investigations commenced that there were already known restrictions within these areas. This enabled the proto team to know where to investigate first so that no time is wasted in these dangerous areas.

The known restrictions were:

- A wall located downstream from the four main booster fans.

- Fall of grounds located in Zone 1 and 3.
- Water and mud accumulation in Zone 2.

The initiative was then implemented over the Easter weekend of 2019 to allow for the stoppage of mining activities. The detailed plan for the investigation can be seen in Appendix H. In Summary, the sequence of events for the investigation was as follow:

1. On Thursday 18 April 2019:
    a. All mining activity was stopped at 18:00.
    b. All fans located in the mining block were switched off except for four fans which helped with the recirculation of air through the mining block and reduced the chance of gas build-up.
    c. The entire refrigeration system was switched off and the four main booster fans were kept running.
    d. The relevant seals were installed, and doors were opened to allow the short circuit of air through the main booster fans and the sub-shaft.
2. On Friday 19 April 2019:
    a. Pressure measurements were taken of the main booster fans as well as the quantity that is short-circuited.
    b. Two Mines rescue teams went to install pumps in the water accumulation in Zone 2 and to do an inspection of the area.
3. On Saturday 20 April 2019:
    a. Two Mines rescue teams entered the area Zone 1 from the main booster fan side to inspect the raise borehole leading to the upper level and to identify the fall of grounds.
    b. Two teams entered the same level but from the sub-shaft side to identify any restrictions in the airway.
    c. Two Mines rescue teams entered the level above this level from the main decline to inspect the wall that is known to be behind the main booster fans and to remove it with the use of explosives.
4. On Sunday 21 April 2019:
    a. Five Mines rescue teams were sent to Zone 3 to identify and reduce restrictions.
    b. The wall inspected on Saturday was fully removed.

The sequence of events went as planned and the investigation was a success. The detailed findings by the various proto teams can be found in Appendix I. The summary of the main findings is the following:

- Falls of ground water accumulation, and old pipes restricting the airways of Zone 2. These restrictions were reduced.
- A large fall of ground was identified in Zone 1 as well as a water plug in the raise bore hole to the upper levels.
- The known wall was blasted but could not be removed completely in one day. This was finished the next day with a second blast.
- Falls of ground were identified and reduced in Zone 3.

3.2.5 Results discussion

The discussion of the improvement to the system is imperative to quantify the success of the investigation into the RAWs of the mine. The changes made to the system by reducing the restrictions in the airways should have an impact on the overall performance of the system.

Table 3-2 provided a prediction of the improvement of the system when reducing these restrictions, and it is important to validate that this was indeed the case. Therefore, the actual measurements were taken after the investigations, and from this, the actual performance improvement was quantified. Table 3-3 compares the simulated values from the digital twin to the actual measurements.

Table 3-3: Comparison between actual and simulated values

KPI	Simulated value	Actual measured values	Accuracy (%)
Surface fan pressure (kPa)	2.8	2.8	100
Main booster fan 1 pressure (kPa)	4.8	4.7	98
Main booster fan 2 pressure (kPa)	4.7	4.6	98
Main booster fan 3 pressure (kPa)	4.7	4.6	98
Main booster fan 4 pressure (kPa)	4.7	4.6	98

Total intake airflow (kg/s)	197	205	96
Total return airflow (kg/s)	197	205	96

Table 3-3 shows the accuracy of the digital twin in predicting and quantifying the improvements to a ventilation network. This is an indication that the digital twin can be used to accurately predict the improvement in a ventilation network by implementing changes to the digital twin.

This case study proved effective enough to test the methodology derived in this study. The methodology was implemented, and an accurately calibrated digital twin of the ventilation system was built. The scenario that was simulated to enable the mine personnel to enter previously inaccessible areas proved successful and validated the benefit of having a calibrated digital twin of a ventilation system. The digital twin was also able to predict changes in the ventilation system with a 96% accuracy when compared to actual measurements.

The ventilation system was improved and the operating static pressure of all four main booster fans was reduced; this means that the booster fans will exhaust more air through the mining block. The increase in quantity through the mining block was measured to be 205 kg/s, which is within 3.9% of the predicted improvement. There is a difference in the actual results and simulated results since the number of restrictions reduced had to be estimated beforehand with the information available. This means that more restrictions were reduced than estimated when simulating the results.

The case study is, however, an example of how a digital twin of a deep-level mine ventilation system can be used to identify and solve complex mine ventilation problems.

3.3 Validation

The validation that the objectives of the study have been met is critical to the success of the dissertation. Therefore, to summarise the success of obtaining the objectives, the following can be said:

- This case study proved that the developed methodology for building accurate digital twins of deep-level mine ventilation networks is effective.
- The technique designed to evaluate a ventilation network by using a digital twin to identify problems within the system was proven to be successful.

- The implementation of the proposed project that was simulated in the case study did improve the ventilation network.
- The changes made to the actual system were implemented in the digital twin and the plans for the life of mine were built. This will ensure that the digital twin remains up to date and that it can accurately simulate more scenarios in the future.

The methodology can now be used in the industry to help develop various digital twins of the underground ventilation systems. These digital twins can then be applied to help optimise the ventilation system to help improve the working conditions of the people underground.

3.4 Conclusion

The case study used in this dissertation was a prime example of what the value of a calibrated digital twin of an underground mine ventilation system could be. The investigation into the old areas of the mine would not have been possible without the use of the calibrated digital twin. The digital twin enabled the mine personnel to test a scenario with which they could enter the areas safely without endangering any mine personnel.

The investigation proved successful and all involved personnel was able to return safely with new information on the condition of these old areas. The identified restrictions were reduced as far as possible and a wall behind the main booster fans was removed. This caused an increase in the overall performance of the ventilation system and this has proven the value of a calibrated digital twin.

The case study also showed that the digital twin can predict the performance of the system with an accuracy of 96%. This indicates that when other initiatives are simulated to improve the system, the results will reflect what the actual system performance will be.

CHAPTER 4: CONCLUSION

4.1 Overview

The depths of deep-level gold mines are increasing every year. This means that the average VRTs of the working areas are also increasing. This combined with the complexity of underground mine ventilation systems contributes to the inability to effectively optimise mine ventilation systems.

The present approach of evaluating ventilation systems is inefficient and outdated. Therefore, there is a need to derive a method to effectively develop and utilise a calibrated digital twin to help solve complex ventilation problems. This will optimise the system and improve the environmental conditions for the people working underground. Therefore, the objectives of this study were to:

- Develop a methodology for building accurate digital twins of a deep-level mine ventilation network.
- Design a technique to evaluate a ventilation network by using a digital twin to identify problems within the system.
- Improve the ventilation network by implementing the digital twin.
- Provide a method for maintaining a digital twin to continuously represent the performance of the actual system.

The method developed in this study comprehensibly described the development of a calibrated digital twin. The method further expanded on the utilisation of the digital twin and how it is used to evaluate and optimise the ventilation system. This method was then applied to a case study where an accurate calibrated digital twin was developed. The digital twin was then used to evaluate the mine ventilation system and problems were identified where the system resistance caused the pressure of the surface fan and four main booster fans to increase.

This led to the conclusion that the main RAW system was restricted. The issue raised was that these areas were inaccessible due to high temperatures and poor ground conditions. This led to the initiative of using the calibrated digital twin to simulate a scenario in which these areas could be accessed.

The scenario that was simulated included the stopping of all mining activities, isolation of the mining block, switching off of all refrigeration systems so that the hot condenser air was no longer discharged into these areas, and the short-circuiting of fresh air through the sub-shaft into these areas. The possible improvement of the system by reducing the restriction in the airways was simulated and used as a motivation to conduct the investigation.

The investigation was conducted over the Easter weekend of 2019 to enable the stopping of all mining activities. The planned sequence of events was carried out and the relevant areas were investigated. The mines rescue teams entered the areas and identified various falls of grounds and flooding as expected. The fall of grounds was reduced as much as possible and submersible pumps were installed in the flooded areas. The wall downstream from the four main booster fans were removed as planned after two attempts.

The investigation proved to be successful and everything went according to plan. The improvement to the performance of the ventilation system had to be verified and measurements of the main KPIs were taken. The actual improvements proved to be within 5% of the predicted improvement from the digital twin.

This case study is proof of the value of having a calibrated digital twin of a mine ventilation system. The digital twin was calibrated to within 5% of the actual performance of the system and was utilised to solve a complex ventilation problem. The digital twin was then used to identify the problem areas within the system. It was able to simulate a method of entering previously inaccessible areas of the system and to predict the possible improvement to the system performance as a motivation to carry out the investigation.

The plans of the mine and the changes to the system were implemented to the calibrated digital twin. This means that the model can be maintained and kept up to date to ensure that all the simulations of different improvements will remain accurate. This means that all the objectives of this study were addressed and were proved effective for solving and optimising a complex mine ventilation system.

The study proved successful and all objectives were achieved. This means that the methodology derived in this study can now be applied to different ventilation systems to build calibrated digital twins. These digital twins can then be utilised to help optimise the underground environment for the people working underground.

4.2 Recommendations

The issues encountered in the case study of this dissertation was that it was challenging to obtain trusted audit information of the system. Additionally, where ventilation audits were carried out over different days, the mass balance of the flow of air through the mine did not match up. This is due to the dynamic nature of the mine ventilation system. It is therefore recommended that the full system ventilation audit be carried out on one day.

The next recommendation is that more problems now be identified within the same system that was evaluated in the case study. This will enable the further optimisation of the system and will help the system to perform as it was designed to perform.

The case study, although it proved successful, is only one mine ventilation system. This means that this method should be tested on other mine ventilation systems to test the validity of the method. The method could also be expanded and altered so that it can be applied to any of the complex systems related to deep-level mining such as compressed air and refrigeration systems.

The final recommendation is to apply the method to fully integrate mine ventilation and refrigeration systems. This will increase the scope of problem identification and the optimisation of the system. This will optimise the planning of the cooling infrastructure and ventilation as the mine is developed further.

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A. Appendix A: Heat sources underground

Geothermal

The further development of the mines as they go deeper leads to an increase in the virgin rock temperatures (VRTs) [8]. The world's deepest mine is in South Africa's Carletonville gold deposit where they are mining at a depth of 4000m. The VRT at this depth ranges to a temperature as high as 70°C [8]. The high-temperature rock releases large amounts of thermal energy into the air using conduction and convection [8]. This gradually increases the air temperature within the roadways and working areas [8]. The equation used to calculate the heat transfer between the rock and the air is [8]:

$$\dot{Q}_r = K_\tau UL(T_{VRT} - T) \quad (3)$$

$$K_\tau = \frac{1.163}{\left(\frac{1}{9.6v_a}\right) + 0.0441} \quad (4)$$

where,

$\dot{Q}_r$ = Heat transfer of surrounding rock (kW)

K_τ = The heat transfer coefficient between a rock and air (kW/m^2·°C)

U = The perimeter of the haulage (m)

L = The length of the haulage (m)

T_{VRT} = The average virgin rock temperature (°C)

T = The average air temperature (°C)

v_a = The average air velocity (m/s)

This equation is however for the ideal case where the walls of the haulage are completely dry. In real life, the evaporation of the moisture will absorb some of the heat to generate heat and moisture exchange [8]. That is the reason why the latent heat exchange between the air flowing through the haulage and the evaporation of the water must be calculated as well. The heat exchanged can be calculated with [8]:

$$\dot{Q}_w = \beta A P_c (P_s - P_v) \quad (5)$$

$$\beta = 0.0846 + 0.0262 v_a \quad (6)$$

$$P_c = \frac{101.325}{P_a} \quad (7)$$

where,

$\dot{Q}_w$ = Heat transfer between water and air (kW)

β = Latent heat exchange coefficient (J/s·N)

A = Heat dissipation surface area of water (m^2)

P_c = The pressure correction factor

P_s = Saturated steam pressure the water(kPa)

P_v = Partial vapor pressure of the water in the air (kPa)

P_a = The atmospheric pressure of the air (kPa)

The transportation of the newly mined ore has an impact on the surrounding air temperature. The ore is in direct contact with the air and the heat from the ore is absorbed by the air. The increased surface area of the rock means that the heat transfer is faster than that of the unmined ore. The equation that is used to determine the heat transfer between the air and the newly mined ore is [8]:

$$\dot{Q}_{ore} = 0.0024L^{0.8}(T_{ore} - T)\dot{m}_{ore}C_{ore} \quad (8)$$

where,

$\dot{Q}_{ore}$ = Heating transfer between the ore and air (kW)

T_{ore} = Average temperature of the ore (°C)

$\dot{m}_{ore}$ = Ore transport capacity (kg/s)

C_{ore} = Ore specific heat capacity (kJ/kg·°C)

Auto compression

The ventilation of an underground mine starts with fresh air flowing down the main intake shaft. This change in depth as the air flows down the shaft causes the air to compress as it flows deeper into the mine. This compression of the air causes the air to release heat into the environment. The air temperature will increase by 1°C for every 102m change in depth under adiabatic conditions. There is however an exchange in moisture and heat between the sidewalls of the shaft and the air under normal circumstances [8].

Electromechanical equipment

The use of electromechanical equipment in these areas increases with the rise in mechanization in underground mining [8]. The exothermic heat that is produced by this equipment is a major heat source in the underground environment [8]. The equation that is used to determine the amount of heat that is generated by an electromechanical machine is [8]:

$$\dot{Q}_d = \sum \varphi \, N_d \tag{9}$$

where,

$\dot{Q}_d$	= Heating transfer between electromechanical equipment and air (kW)
φ	= Heat dissipation coefficient
N_d	= Total power of all electrical equipment (kW)

Diesel engines

Some underground mines make use of vehicles with diesel engines for certain tasks. These engines convert a portion of the heat input and use it as mechanical power. The rest of the heat is directly emitted into the air. The term of useful work is also used to describe the mechanical power of a diesel vehicle [35]. Useful work is when a vehicle is working on an incline against gravity and non-useful work is when the vehicle is travelling horizontally. When non-useful work is being conducted then all the heat is dissipated into the air [35] This is also true for when the vehicle is stationary [35].

The total heat dissipation is therefore equal to the total heat input. The total heat dissipation can be determined by the product of the mass of the fuel and its calorie value. There are however exceptions to this such as trucks and LHD vehicles which transport ore against gravity and are doing large amounts of mechanical work. The bulk of the heat input is however still dissipated into the air [35].

Compressed air

Compressed air is a safe and convenient source of energy in comparison to other sources. It is used in most underground mines for drilling, loading, and as a source of fresh air in emergency refuge bays. Compressed air produces a steady flow of heat that is dissipated into the air [35].

The difference between the use of compressed air in comparison to electrically powered machines is that the exhaust air enters ventilation air. The air provided mechanical work to the compressed air machine, which means that the exhaust air has a lower enthalpy than the intake air. This means that the exhaust air is colder than the ventilation air and constitutes a negative heat load [35]. This is only true for the exhaust ends of the compressed air line since the local underground compressor will discharge heat into the air.

Heat from people

The amount of heat that a human body transfers into the atmosphere does not have a major impact but it does however form part of the overall heat load in the mine. The amount of heat that is dissipated by people working in mines depends on the number of people that are working and the type of work that is being done. The typical figure for the heat that is added to the system by a human body is as follows [35].

- 90 to 115 W for a person that is resting
- 200W for a person doing light work
- 275 W for a person with a moderate work rate
- 470 W for a person doing hard work

Explosives

There are large amounts of heat that are transferred into the air when explosives are used in development. The heat from the explosives is transferred to the rock and is released over long periods. The heat that is transferred into the air depends on the type of explosion and varies between 3 800 and 4 500 kJ/kg [35].

B. Appendix B: Ventilation surveys

This appendix serves as a summary of what a ventilation survey of a mine ventilation network entails. A detailed description of the procedure can be found in Chapter 6 of the Subsurface ventilation engineering book written by Malcolm J. McPherson [10].

Ventilation survey

The ventilation survey starts with the measurement of the quantity of air flowing through the mine. The airflow quantity is quantified by determining the average air velocity through the airway and multiplying it by the cross-sectional area of the haulage [10].

$$Q = v_a A_h \quad (10)$$

Where,

Q = Quantity of airflow (m^3/s)

v_a = The average air velocity (m/s)

A_h = Cross-sectional area of haulage (m^2)

This quantifies the airflow through a haulage. There are however many different techniques to measure the average air velocity. The first measurement that will be focused on is the measurement of the airflow velocity [10]. Various instruments are used to measure the air velocity such as [10]:

- Rotating vane anemometer
- Swinging vane anemometer
- Vortex-shedding anemometer
- Hot-body anemometers
- Smoke tubes
- Pitot-static tubes
- Tracer gases

However, the most common instruments that are used for measuring the airflow velocities in haulages are the rotating vane anemometers. The rotating vane anemometer measures the flow when an airstream flows through the instrument and exerts a force on the angled vanes. The causes the vanes to rotate at an angular velocity that is proportional to the air velocity. A clutch and gear arrangement couples the vanes to a digital counter or a circular dial. This then displays a reading in meters [10].

The vane anemometer is always used in conjunction with a stopwatch. The stopwatch is started when the measurements start and end when the measurement is completed. The time displayed on the stopwatch and the anemometer reading is then used to calculate the air velocity [10].

$$v_a = \frac{L_r}{t} \tag{11}$$

Where,

v_a	= The average air velocity (m/s)
L_t	= The rotating vane anemometer reading (m)
t	= Time duration of measurement (seconds)

Various techniques can be utilised when using the rotating vane anemometer. The most common technique used is moving traverses. This requires the anemometer to be attached to a rod of at least 1.5m long [10].

The method starts with the observer facing into the airflow and holding the rod in front of him/her. The dial on the vane should be facing in the direction of the observer. The dial is then zeroed by a switch once the vane is turning at a constant velocity. A second observer will use the stopwatch to measure the duration of the measurement. Both observers then start their respective measurements at the same time [10].

The path of the traverse method should be the same for every measurement. Figure B-1 illustrates the path of the traverse method [10].

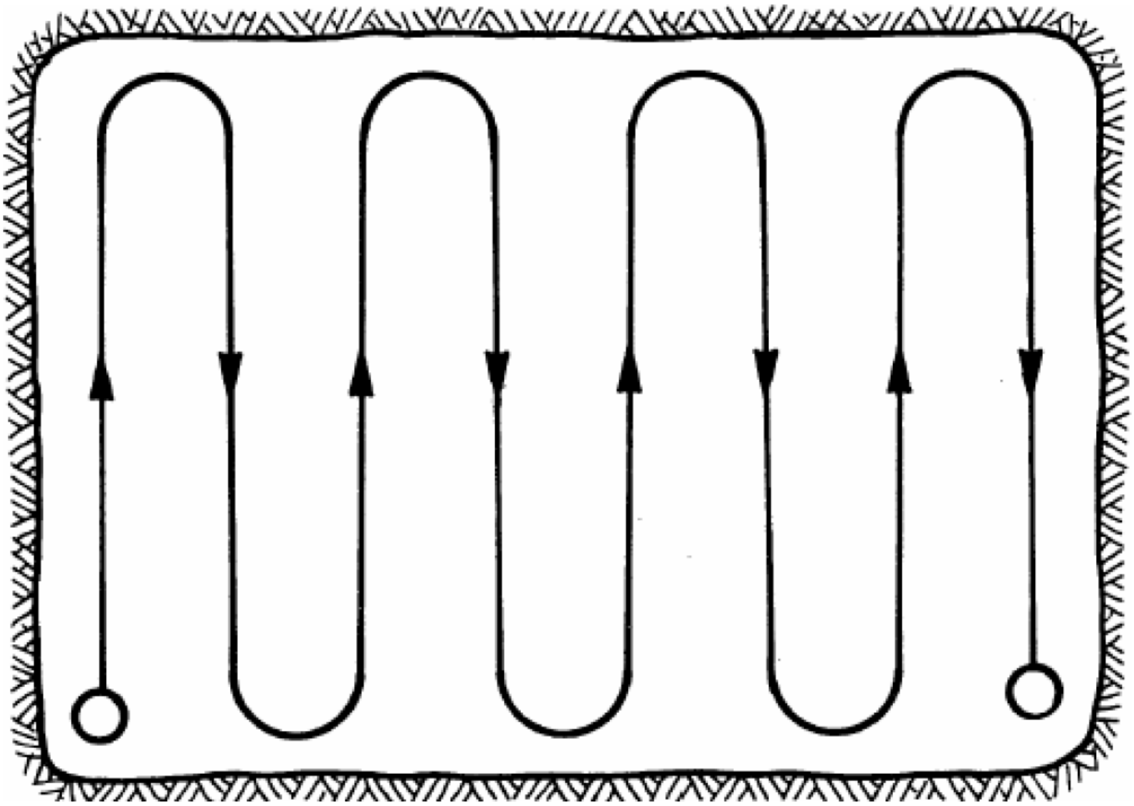


Figure B-1: Path of the traverse method [10]

Figure B-1 shows that the traverse method covers the entire haulage so that the average air velocity is accurately measured. This method should be repeated until three readings agree to within ±5%. It is also important to choose the measurement location carefully so that there is the least number of factors that influence the measurement. Factors that can influence a measurement are [10]:

- Leakage paths (Crosscuts)
- Unstable ground conditions
- Obstructions in the airways

There is another method of using the vane anemometer. This method is the fixed-point measurement method. This method is mostly used for the measurement of air velocity through a duct or a ventilation fan. This method is done by holding the anemometer at the centre of the duct/fan and keeping it fixed at that point. The value obtained from this reading is then multiplied by a correction factor of 0.8 [10].

The cross-sectional area of a haulage can be measured with various techniques, but the most common technique that is used is taping. This is where the observer uses a measuring tape to measure the width and height of the haulage. New instruments such as a laser distance meter have been used in the past couple of years to replace the use of a measuring tape [10].

The next step in the ventilation survey is the pressure and temperature survey. This is where the barometric pressure, dry bulb temperature, and wet bulb temperature is measured. The barometric pressure is measured with a barometer and the temperature is measured with a whirling hygrometer [10].

The whirling hygrometer can measure both dry and wet bulb temperatures [10]. Therefore, it is ideal in ventilation surveys. Figure B-2 illustrates the different components in a whirling hygrometer.

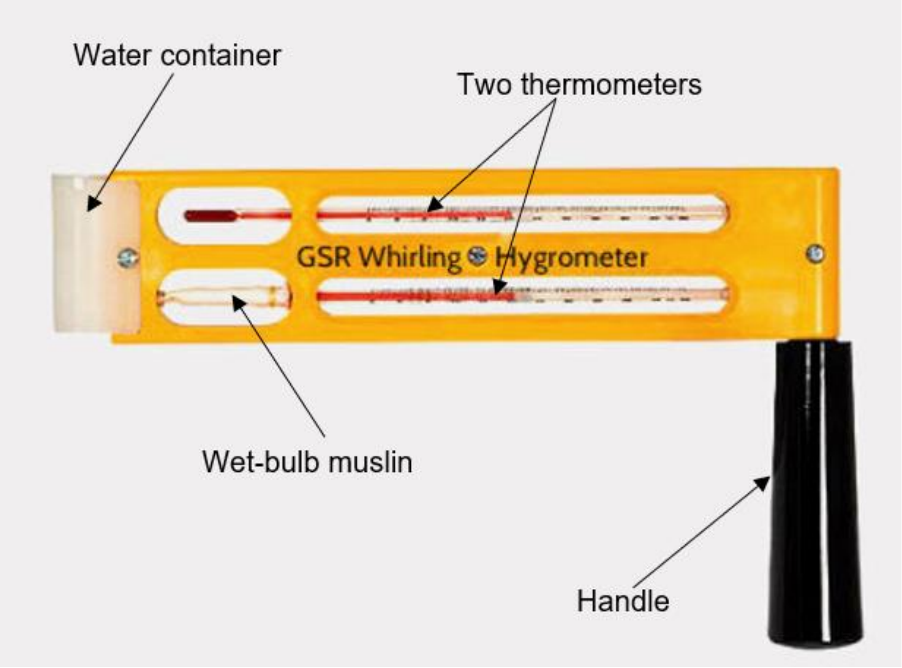


Figure B-2: The whirling hygrometer [47]

Figure B-2 shows the layout of the whirling hygrometer. The instrument is used by filling the water container with water. This will keep the wet-bulb muslin wet and enable the measurement of the wet-bulb temperature. The whirling is operated by holding it by its handle with one hand and swinging it at a constant velocity for 20 seconds in the direction of the airflow. The temperature of the air must then be written down as soon as possible to ensure an accurate reading [10].

C.Appendix C: Ventilation system evaluation

The evaluation of a ventilation system is done by analysing the ventilation network. Ventilation network analysis is a term that refers to a family of techniques that are used to determine certain parameters within the ventilation system such as [10]:

- The interactive behaviour between airflows within connected haulages.
- The resistances within haulages.
- The prediction of the distribution of air within the complete integrated network.
- The required combination of fans within the network to produce the required airflow.

The practical methods used in the analysis of a complex ventilation network limit the number of acceptable alternative ways to quantify these values. However, the techniques that are used are useful to determine multiple solutions that are to be investigated [10]. These methods that are used are known as the fundamentals of ventilation network analysis [10]. This appendix will serve as a summary of these fundamentals and the methods to solving ventilation networks.

The first fundamental method to analysing ventilation networks is Kirchoff's laws. Kirchoff's first law states that the mass flow entering a junction equals the flow that leaves the junction. This derives the equation [10]:

$$\sum_{i} \dot{m}_a = 0 \tag{12}$$

Where,

$\dot{m}_a$ = Mass flows entering the junction (kg/s)

i = Junction name (-)

The mass flow can be calculated by using the following equation [10]:

$$\dot{m} = \rho Q \tag{13}$$

Where,

$\dot{m}_a$ = Mass flows entering the junction (kg/s)

ρ = Air density (kg/m^3)

Q = Quantity of airflow (m^3/s)

This law provides the opportunity to validate the accuracy of the airflow measurement around a certain junction [10]. Kirchoff's second law states that the sum of all pressure drops around a closed path should be equal to zero [10]. This law takes the effect of fans and ventilation pressures into account. This can be calculated by using the following steady flow equation for a single airway [10].

$$\frac{\Delta v_a^2}{2} + \Delta Z g + W = \int V\, dP + F \tag{14}$$

Where,

v_a = air velocity (m/s)

Z = Height above datum (m)

g = Gravitational acceleration (m/s^2)

W = Input of work by the fan (J/kg)

V = Specific volume of air (m^3/kg)

P = Barometric pressure (Pa)

F = Work done against friction (J/kg)

This equation could be simplified if we consider that it is used to evaluate a closed path. This means that the change in elevation ΔZ is equal to zero and the sum of the changes in kinetic energy, Δv_a, is also equal to zero. The equation can then be shown for the closed path, p, as [10]:

$$\sum_{p}\int V\,dP + \sum_{p}[F - W] = 0 \tag{15}$$

Where the summation of $-\int V\,dP$ terms equate to the natural ventilation energy, NVE, that is originated from the addition of thermal energy to the air. Therefore, the equation could be simplified further to [10]:

$$\sum[F - W] - NVE = 0 \tag{16}$$

These terms can now be converted to pressure units by multiplying each term with the density of the air, ρ. The equation is then written as [10]:

$$\sum[\rho F - \rho W] - \rho NVE = 0 \tag{17}$$

Where,

ρF = Frictional pressure drop, P_f, (Pa)

ρW = Total pressure increase across a fan, P_{fan}, (Pa)

ρNVE = Natural ventilation pressure, NVP, (Pa)

From this we have the simplified equation which is known as Kirchoff's second law which is written as [10]:

$$\sum[P_f - P_{fan}] - NVP = 0 \tag{18}$$

The next law that is considered one of the fundamentals of ventilation network analysis is the square law which was derived from the Chezy Darcy relationship. The traditional form of the square law is written as [10]:

$$P_f = RQ^2 \tag{19}$$

Where,

P_f = Frictional pressure drop (Pa)

R = Atkinson resistance (kg/m^7)

Q = Quantity of airflow (m^3/s)

The square law is used to determine the frictional pressure drop within a haulage. The solving of equivalent resistances within a system with the use of the square law differs when connecting airways are found in a series or a parallel configuration. Figure C-1 illustrates the series configuration of various resistances in a haulage [10].

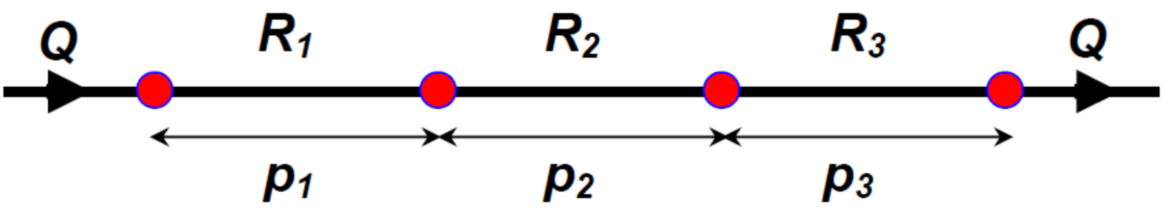


Figure C-1: Resistances in series [10]

Figure C-1 will be referred to when explaining the calculation of the equivalent resistance of resistances in series. When evaluating the configuration, we can state that [10]:

$$P_1 = R_1 Q^2 \tag{20}$$

$$P_2 = R_2 Q^2 \tag{21}$$

$$P_3 = R_3 Q^2 \tag{22}$$

Where,

$P_{1,2,3}$ = Frictional pressure drops (Pa)

$R_{1,2,3}$ = Atkinson resistances (kg/m^7)

Q = Quantity of airflow (m^3/s)

Then we can state that for a series circuit the equivalent resistance equates to [10]:

$$P_{eq} = (P_1 + P_2 + P_3) = (R_1 + R_2 + R_3)Q^2 \tag{23}$$

P_{eq} is the equivalent resistance of the circuit and can be simplified to [10]:

$$P_{eq} = R_{series}Q^2 \tag{24}$$

Where,

$$R_{series} = R_1 + R_2 + R_3 \tag{25}$$

Therefore, the calculation of the equivalent resistance in series can be simplified as [10]:

$$R_{series} = \sum R \tag{26}$$

The calculation of the equivalent resistance of resistances that are connected in parallel differs from when they are connected in series. Figure C-2 illustrates the configuration of resistances connected in parallel [10].

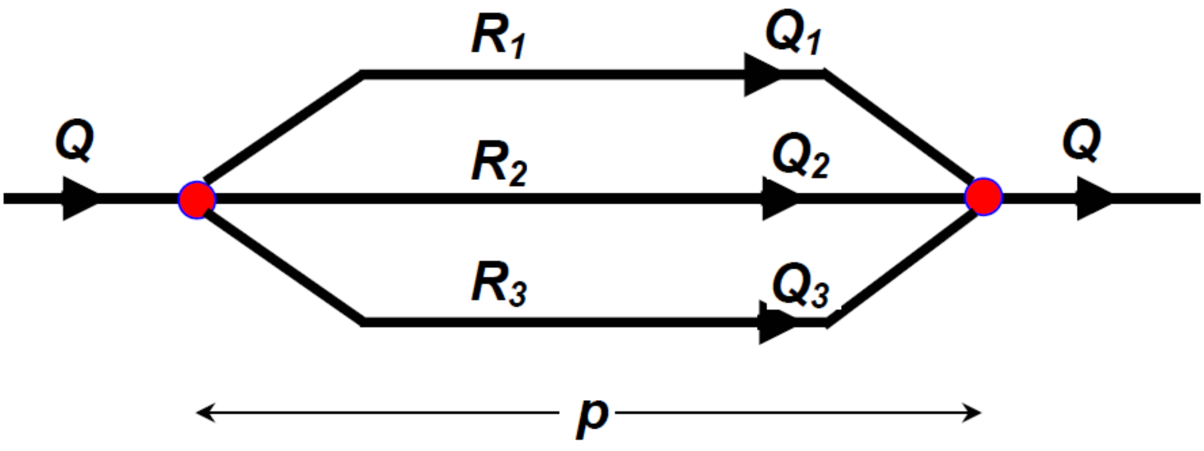


Figure C-2: Resistances in parallel [10]

Figure C-2 will be referred to when explaining the calculation of the equivalent resistance of a network with resistances connected in parallel [10]. When evaluating this configuration, we can state that [10]:

$$P_{eq} = R_1 Q_1^2 = R_2 Q_2^2 = R_3 Q_3^2 \tag{27}$$

Which gives [10]:

$$Q_1 = \sqrt{\frac{P_{eq}}{R_1}} \tag{28}$$

$$Q_2 = \sqrt{\frac{P_{eq}}{R_2}} \tag{29}$$

$$Q_3 = \sqrt{\frac{P_{eq}}{R_3}} \tag{30}$$

Combining the three flow we get [10]:

$$Q = Q_1 + Q_2 + Q_3 = \sqrt{P_{eq}}\left(\frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + \frac{1}{\sqrt{R_3}}\right) \tag{31}$$

This equation can be simplified to [10]:

$$Q = \frac{\sqrt{P_{eq}}}{\sqrt{R_{par}}} \tag{32}$$

Where R_{par} is the equivalent resistance of a parallel circuit. This equivalent resistance can therefore be calculated with [10]:

$$\frac{1}{\sqrt{R_{par}}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + \frac{1}{\sqrt{R_3}} \tag{33}$$

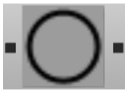
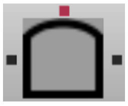
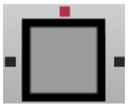
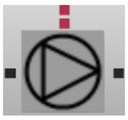
Which can be generalised to [10]:

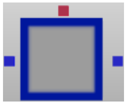
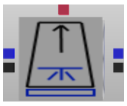
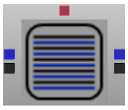
$$\frac{1}{\sqrt{R_{par}}} = \sum \frac{1}{\sqrt{R}} \tag{34}$$

The equations and methods described in this appendix is a summary of the practical methods and fundamentals used in the mining industry to analyse ventilation networks. The detailed breakdown of the application and examples of how it is applied can be further investigated by reading the book titled “Subsurface Ventilation Engineering” written by Malcolm J. McPherson [10].

D. Appendix D: PTB component descriptions

Table D-1: PTB component descriptions [46]

Component	Image	Function
Air pressure boundary		The air pressure boundary has constant user-specified pressures, temperatures, humidities for every period.
Air node		Air height (change in network elevation) and air volume are specified in air nodes. All the air network properties, pressure, temperature, density, etc. are calculated in the air nodes.
Air tunnel		The air tunnel component is used to simulate the thermohydraulic fundamentals of underground mine haulages, stopes, and shafts. Rock heat transfer and air pressure losses using the Atkinson friction factors are included.
Air pipe		The flow network pressure losses are calculated in the pipe component. The pipe component includes a variable valve fraction for flow or pressure control. Auto compression heat is also calculated in the pipe component.
Air fan		The fan component generates pressure differences in the flow network to induce airflow through the network. The fan component generates heat in the fluid due to inefficiencies and adiabatic compression.
Water pressure boundary		The water pressure boundary has constant user-specified pressures and temperatures for every period. This

		component is used where the network connects to other systems or sources.
Water node		Water height (change in network elevation) and water volume are specified in water nodes. All the water network properties, pressure, temperature, enthalpy, etc. are calculated in the water nodes.
Water pipe		The flow network pressure losses are calculated in the pipe component. The pipe component includes a variable valve fraction for flow or pressure control.
Water air cooling tower		The cooling tower is used to simulate a counter flow heat exchanger. It simulated the heat transfer between air and water as it flows through the cooling tower.
Water air heat exchanger		The water to the air heat exchanger is a counter flow indirect contact heat exchanger. The air is dehumidified when the inlet water temperature is below the air inlet dew point temperature.

E. Appendix E: Friction coefficients of haulages

Table E-1: Friction coefficients of different haulages [10]

Rectangular airways		
	Friction factor, k kg/m^3	Coefficient of friction, f (dimensionless)
Smooth concrete lined	0.004	0.0067
Shotcrete	0.0055	0.0092
Unlined with minor irregularities only	0.009	0.015
Girders on masonry or concrete walls	0.0095	0.0158
Unlined, typical conditions no major irregularities	0.012	0.02
Unlined, irregular sides	0.014	0.023
Unlined, rough, or irregular conditions	0.016	0.027
Girders on side props	0.019	0.032
Drift with rough sides, stepped floor, handrails	0.04	0.067
Steel arched airways		
	Friction factor, k kg/m^3	Coefficient of friction, f (dimensionless)
Smooth concrete all round	0.004	0.0067
Bricked between arches all round	0.006	0.01
Concrete slabs or timber lagging between flanges all round	0.0075	0.0125
Slabs or timber lagging between flanges to spring	0.009	0.015
Lagged behind arches	0.012	0.02
Arches poorly aligned, rough conditions	0.016	0.027
Metal mines		
	Friction factor, k kg/m^3	Coefficient of friction, f (dimensionless)
Arch-shaped level drifts, rock bolts, and mesh	0.01	0.017
Arch-shaped ramps, rock bolts, and mesh	0.014	0.023
Rectangular raise, un-timbered, rock bolts and mesh	0.013	0.022
Bored raise	0.005	0.008
Beltway	0.014	0.023
TBM drift	0.0045	0.0075
Coal mines: Rectangular entries roof-bolted		
	Friction factor, k kg/m^3	Coefficient of friction, f (dimensionless)
Intakes, clean conditions	0.009	0.015
Returns, some irregularities/ sloughing	0.01	0.017
Belt entries	0.005 to 0.011	0.0083 to 0.018
Cribbed entries	0.05 to 0.14	0.08 to 0.23
Shafts		

	Friction factor, k kg/m³	Coefficient of friction, f (dimensionless)
Smooth lined, unobstructed	0.003	0.005
Brick lined, unobstructed	0.004	0.0067
Concrete lined, rope guides, pipe fittings	0.0065	0.0108
Brick lined, rope guides, pipe fittings	0.0075	0.0125
Unlined, well-trimmed surface	0.01	0.0167
Unlined, major irregularities removed	0.012	0.02
Unlined, mesh bolted	0.014	0.023
Tubbing lined, no fittings	0.007 to 0.014	0.0012 to 0.023
Brick lined, two sides buntons	0.018	0.03
Two side buntons, each with a tie girder	0.022	0.037
Longwall face line with steel conveyor and powered supports		
	Friction factor, k kg/m³	Coefficient of friction, f (dimensionless)
Good conditions, smooth wall	0.035	0.058
Typical conditions, coal on conveyor	0.05	0.083
Rough conditions, uneven faceline	0.065	0.108
Ventilation ducting		
	Friction factor, k kg/m³	Coefficient of friction, f (dimensionless)
Collapsible fabric ducting (forcing systems only)	0.0037	0.0062
Flexible ducting with fully stretched spiral spring reinforcement	0.011	0.018
Fibreglass	0.0024	0.004
Spiral wound galvanized steel	0.0021	0.0035

F. Appendix F: Ventilation survey information

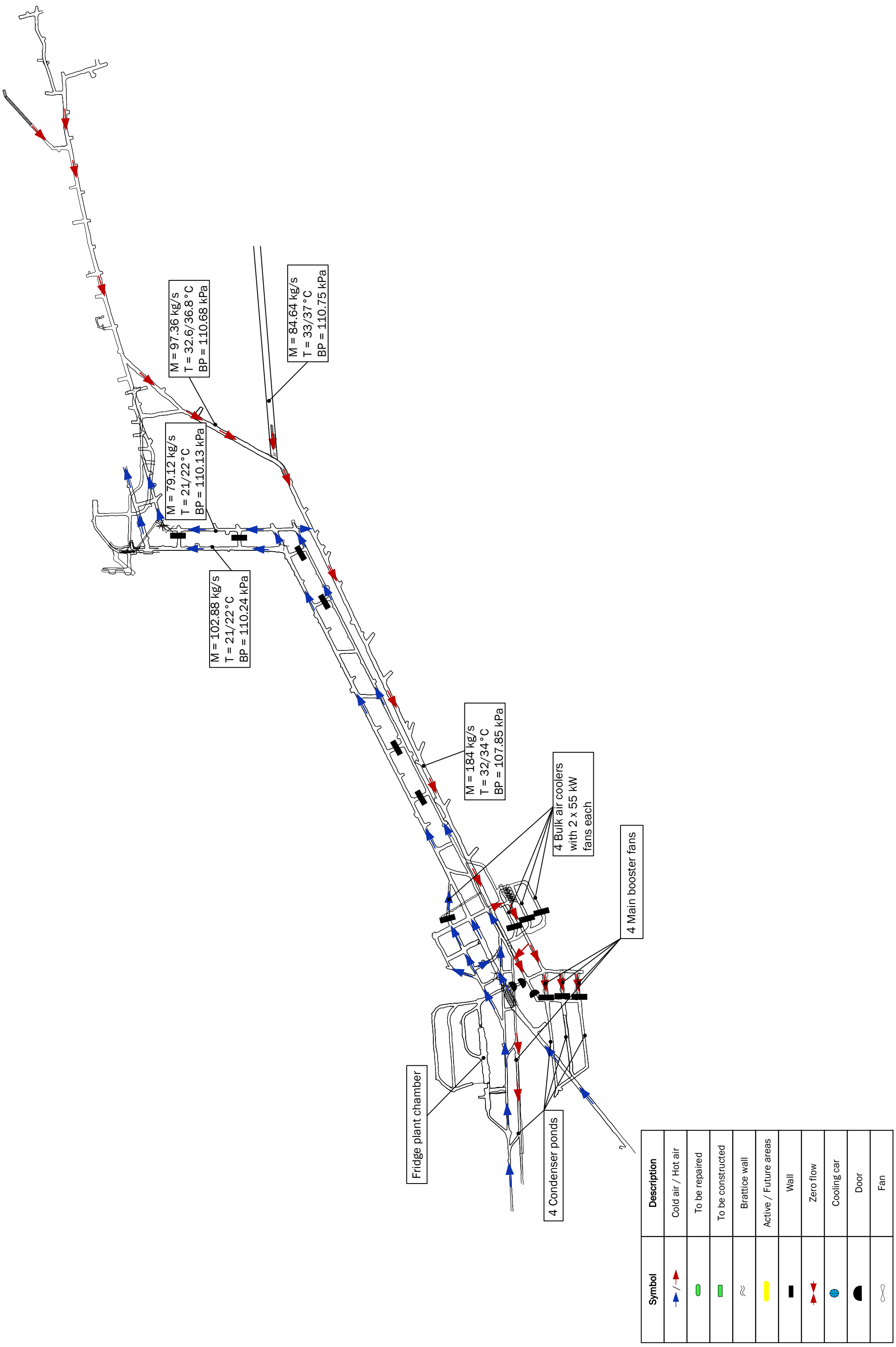


Figure F-1: Ventilation survey information for the main decline and refrigeration network

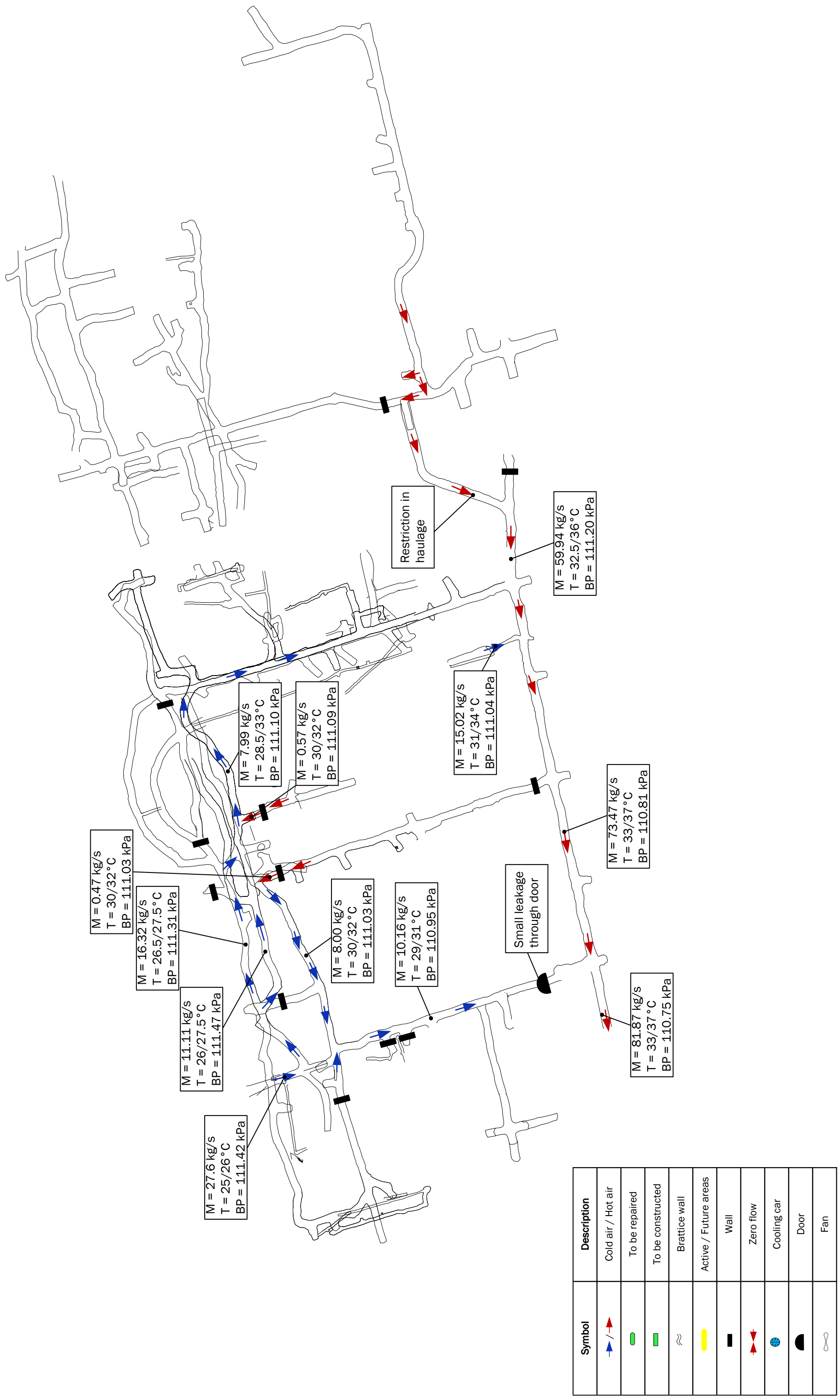


Figure F-2: Ventilation survey information for Level 1

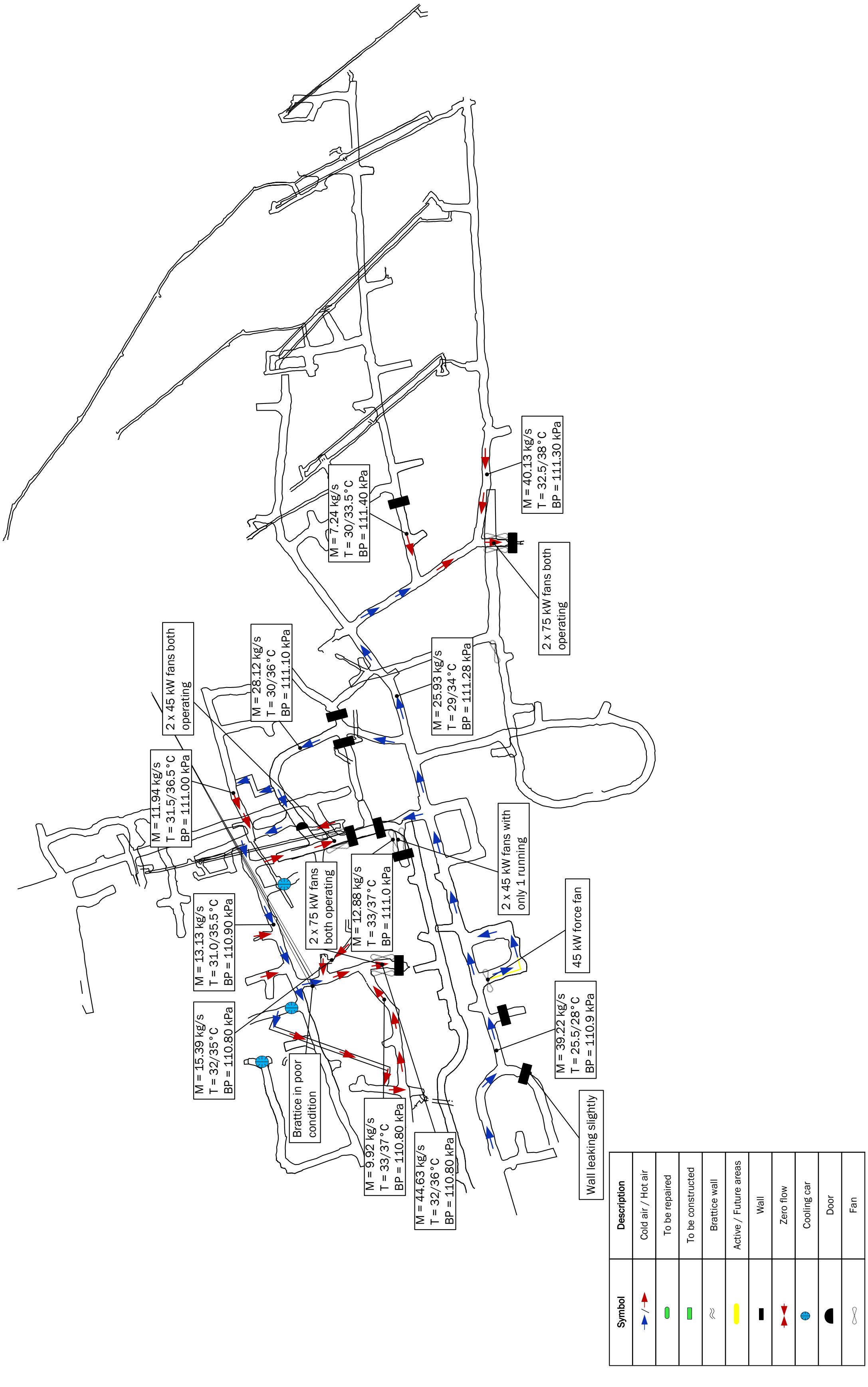


Figure F-3: Ventilation survey information for Level 2

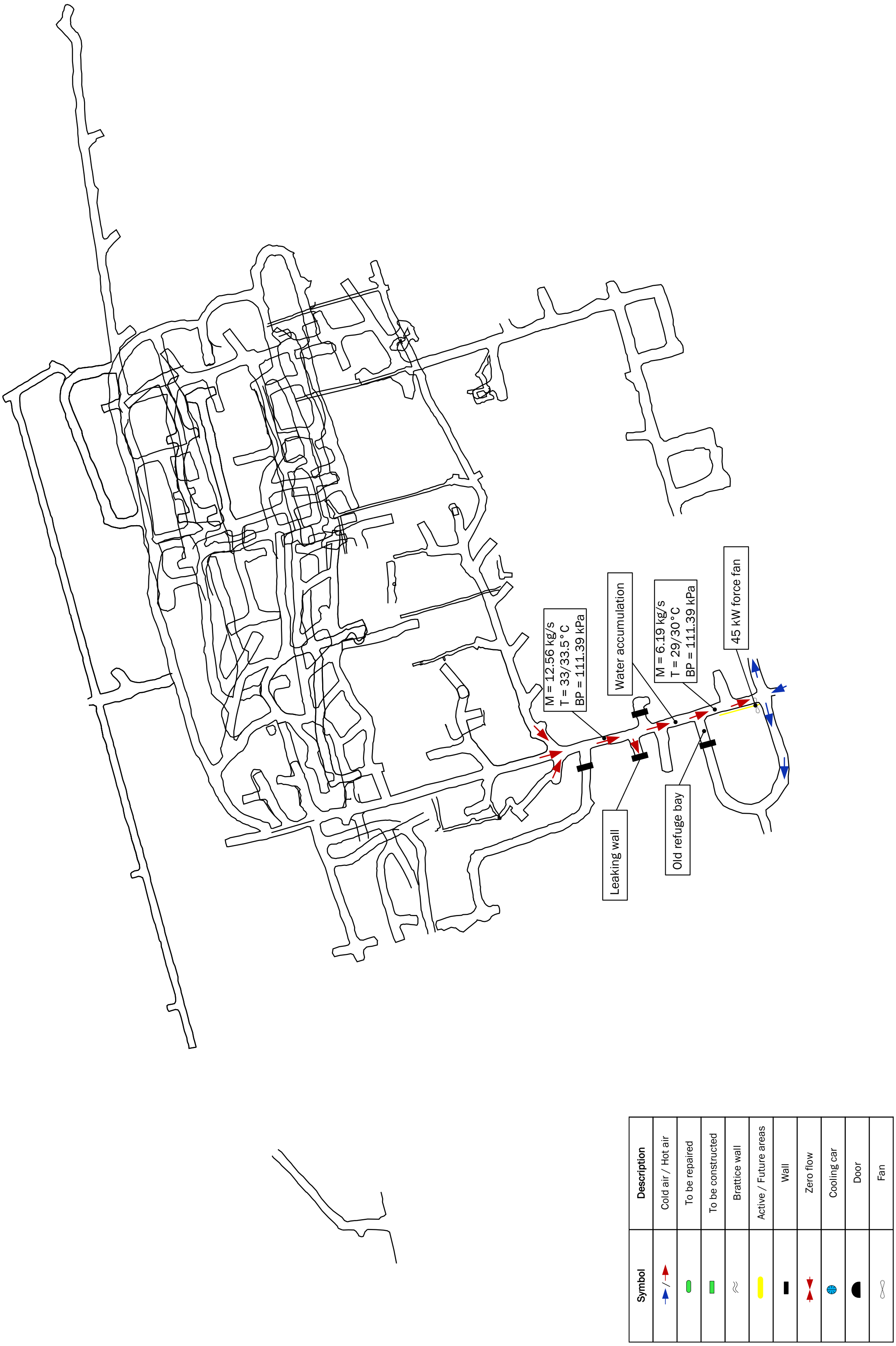


Figure F-4: Ventilation survey information for Level 3

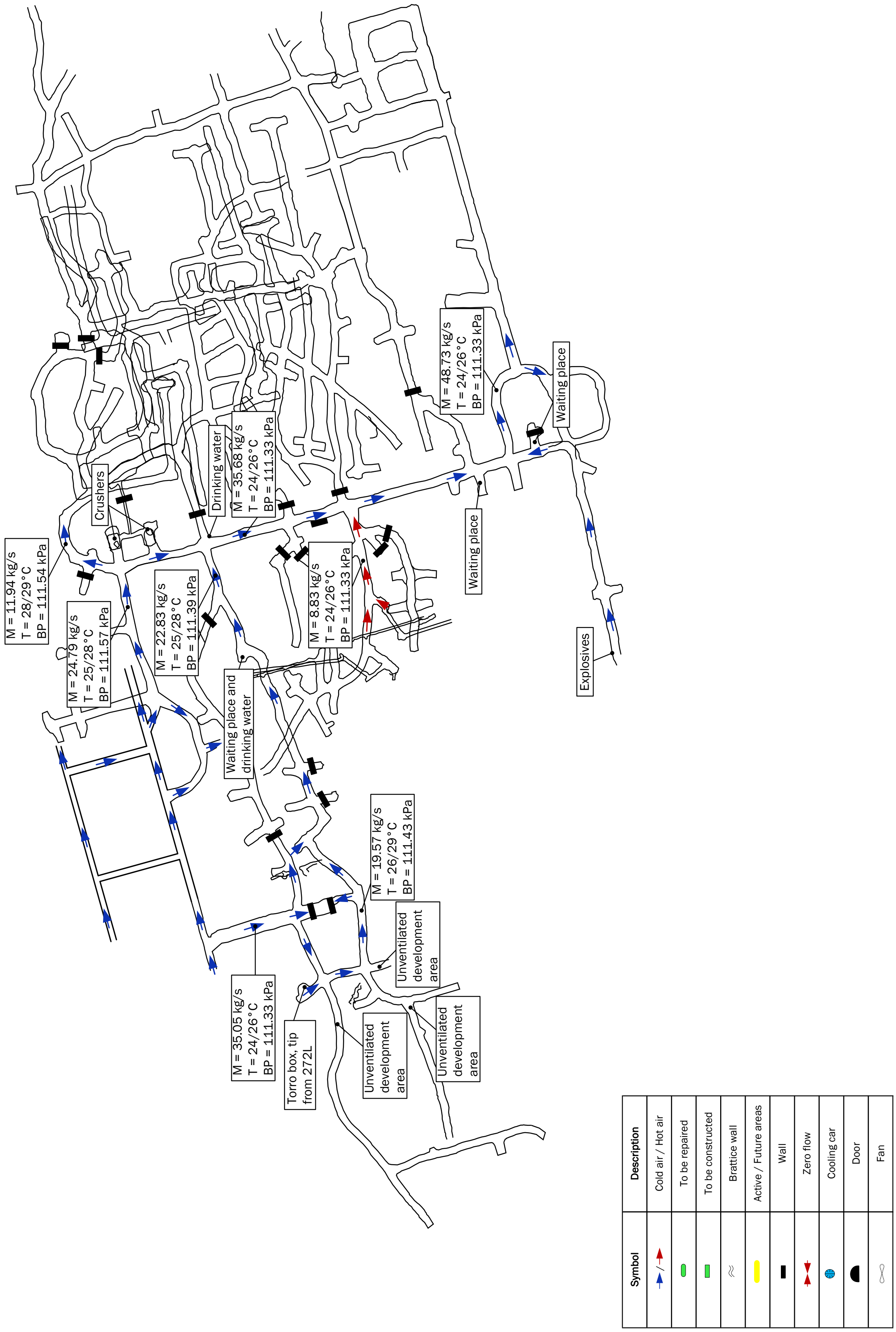


Figure F-5: Ventilation survey information for Level 4

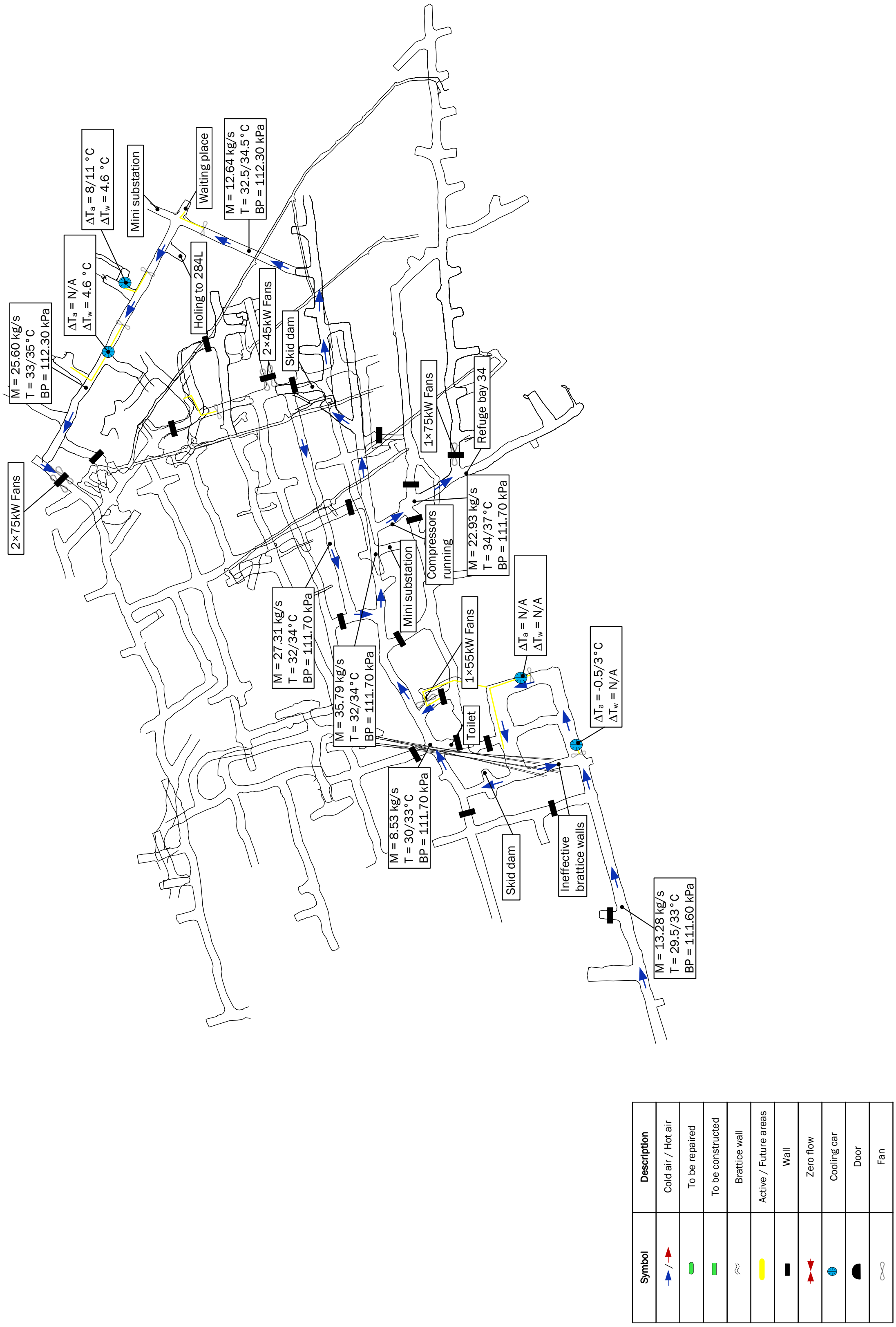


Figure F-6: Ventilation survey information for Level 5

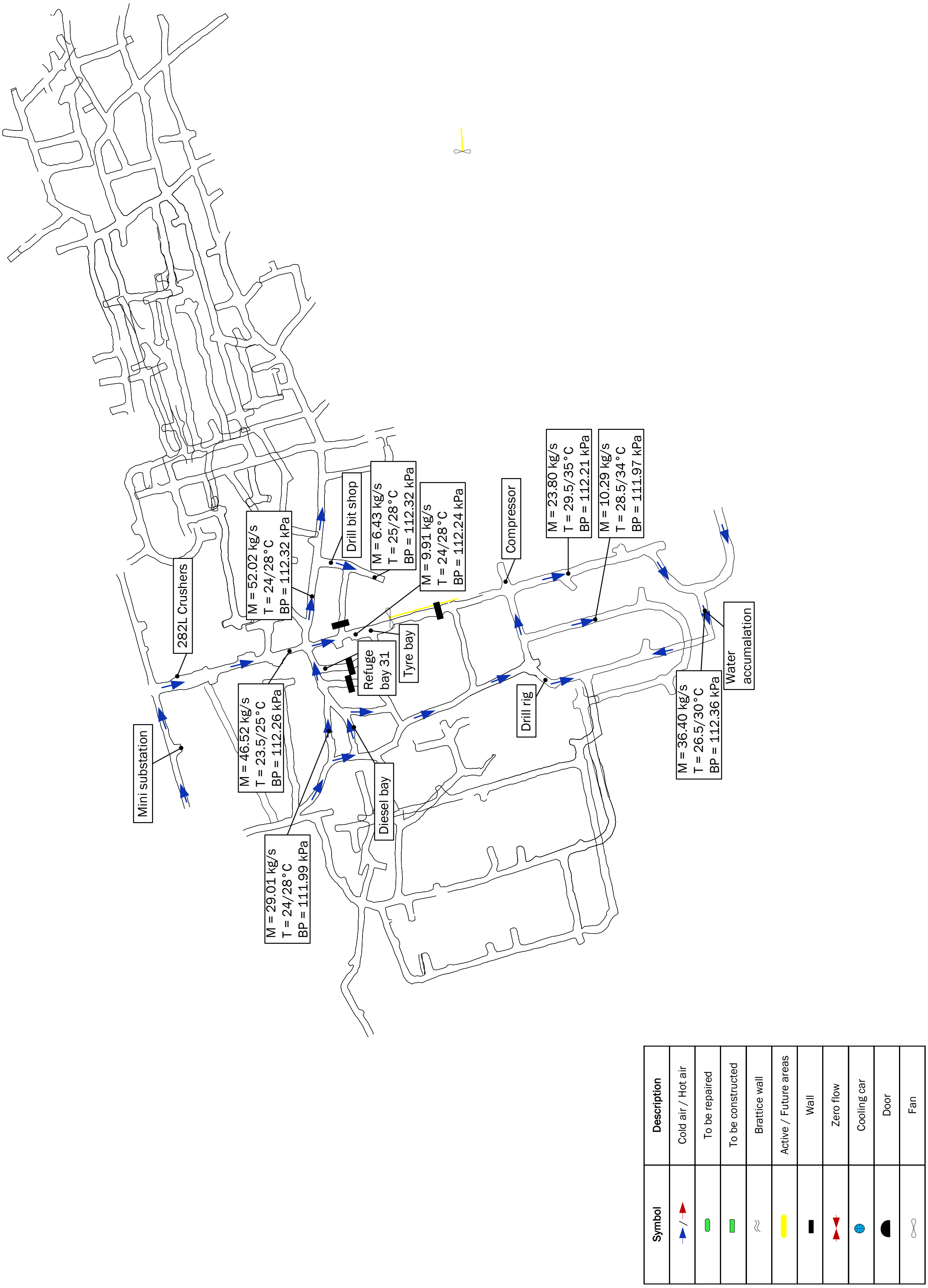


Figure F-7: Ventilation survey information for Level 6

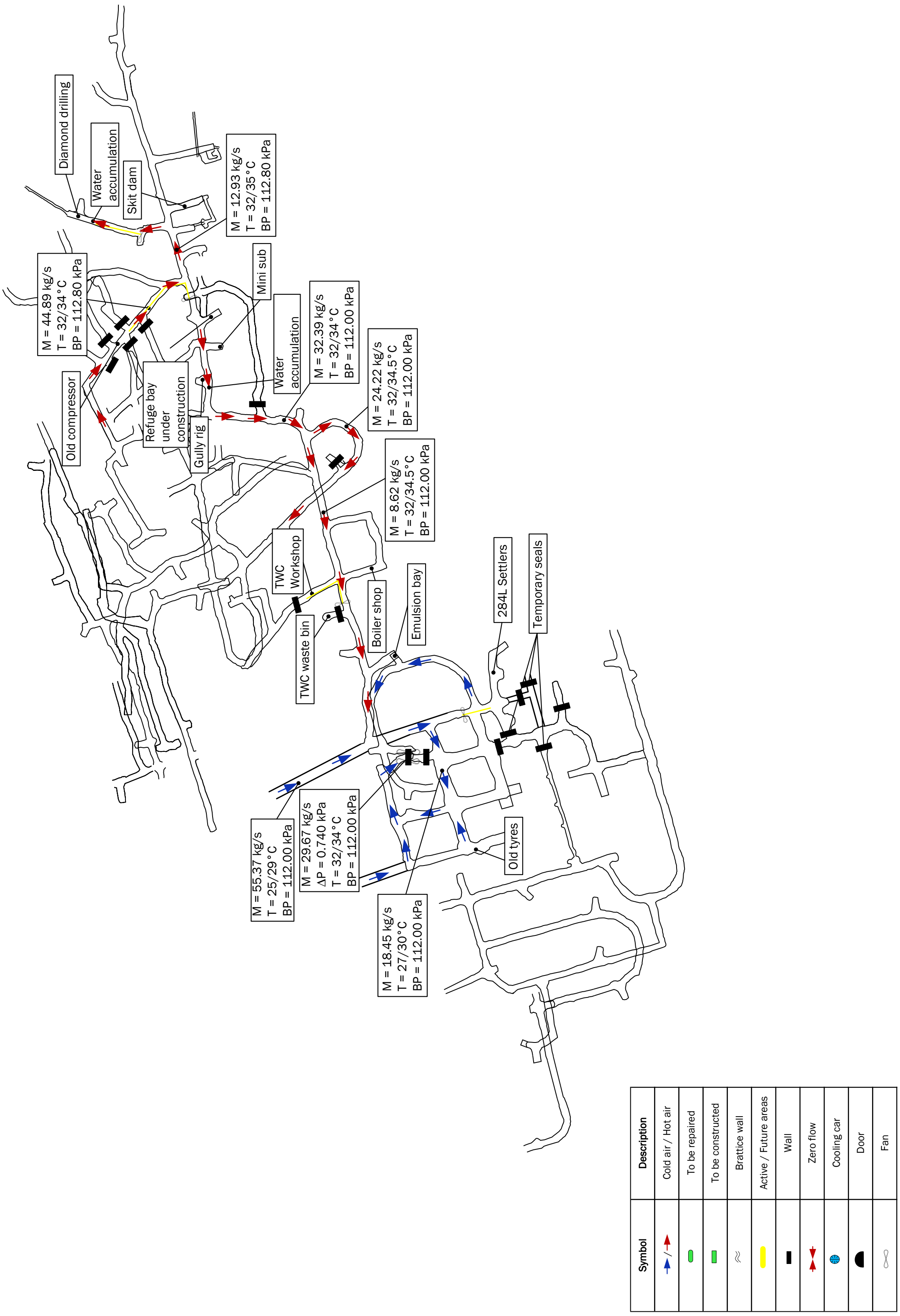


Figure F-8: Ventilation survey information for Level 7

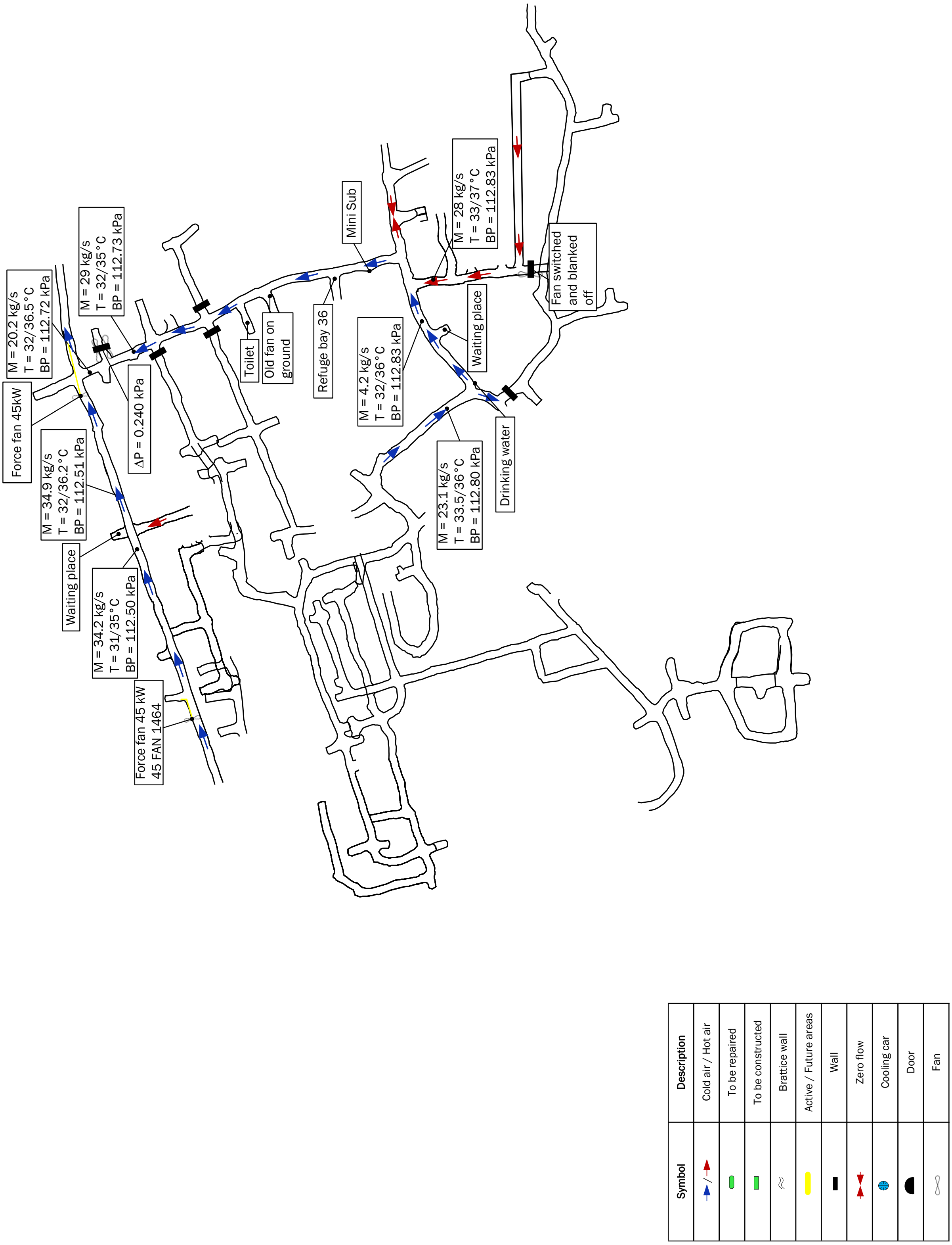


Figure F-9: Ventilation survey information for Level 8

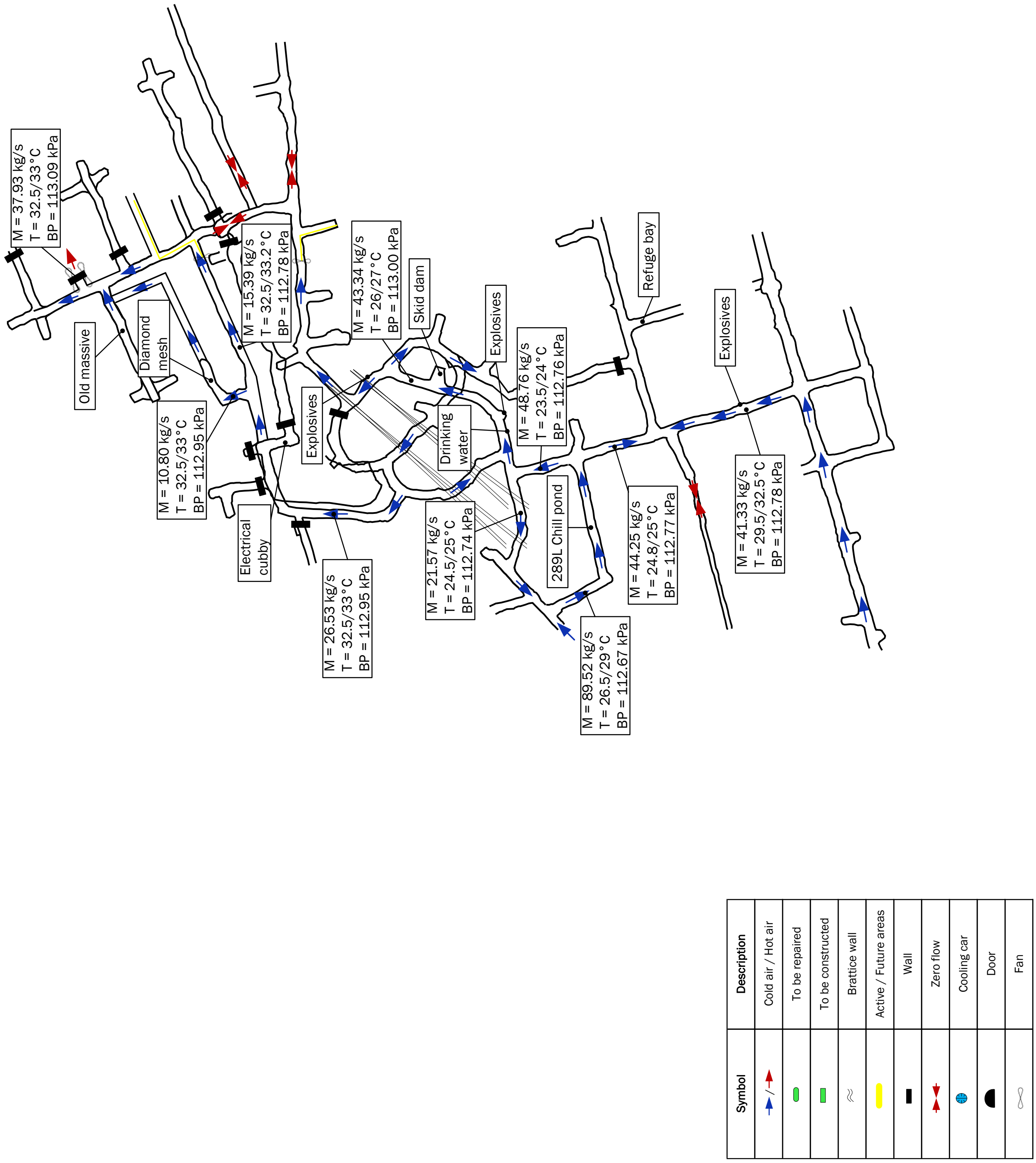


Figure F-10: Ventilation survey information for Level 9

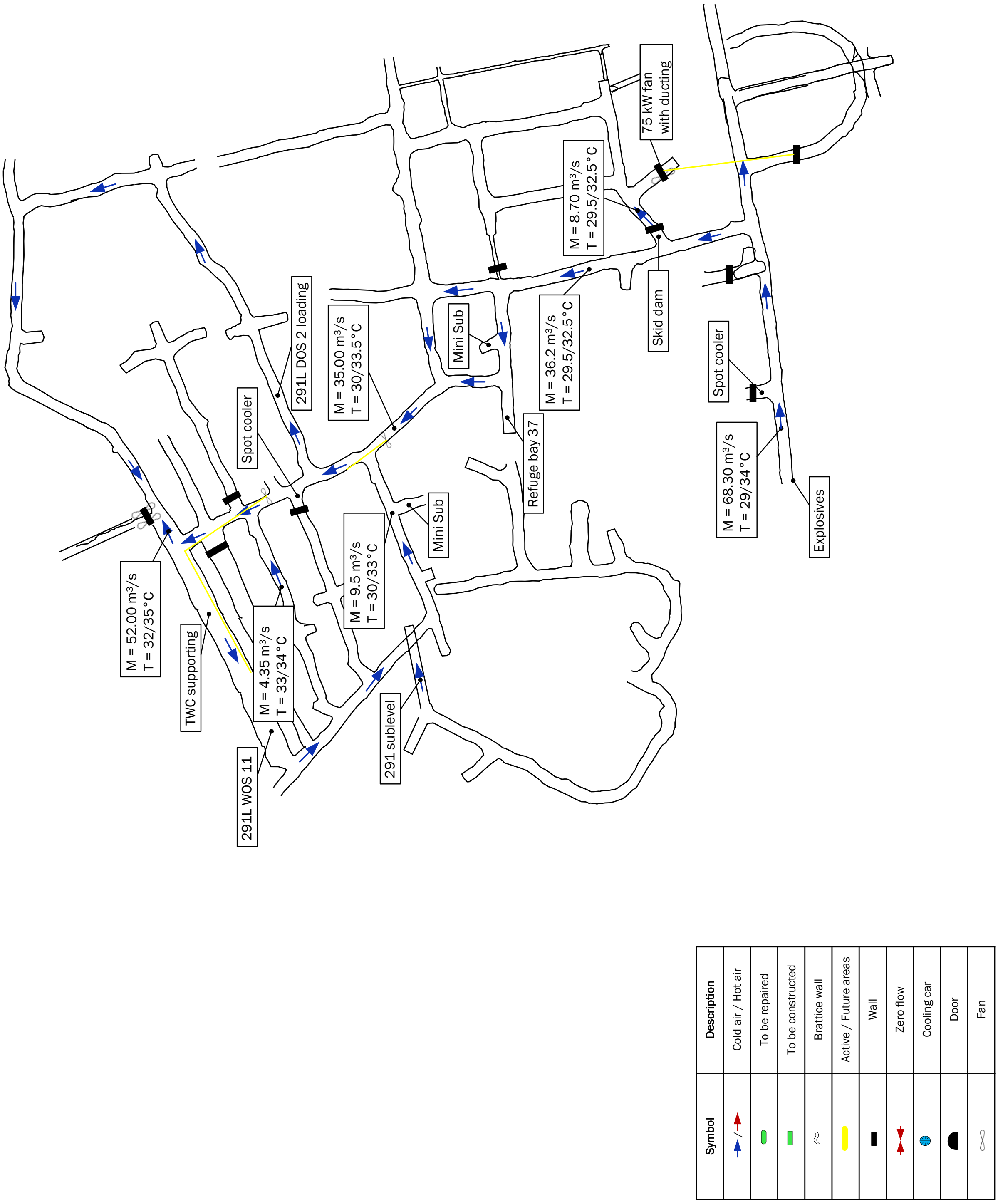


Figure F-11: Ventilation survey information for Level 10

G. Appendix G: Ventilation fans performance curves

75kW silenced axial flow fan

Table G-1: 75 kW (1220 mm) fan performance test report

Client: Harmony Gold mining company Limited	Tested with 0 Screens
Speed: 4PL – 525 Volt	Sound pressure level: 89.5 dB
Date received: 04/04/2018	Reporting density: 1.2 kg/m^3
Date tested: 25/04/2018	Barometric pressure: 84.5 kPa
Fan make: Axial flow	Wet-bulb temperature: 13°C
Fan size: 1220 mm diameter	Dry bulb temperature: 21°C

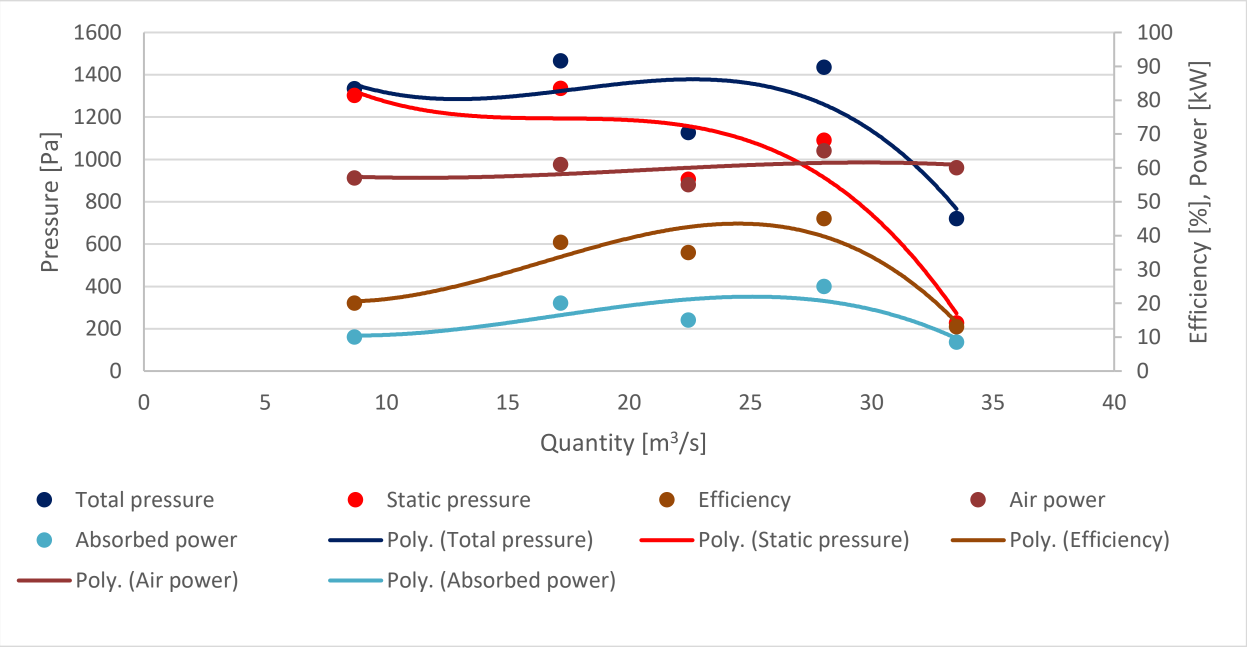


Figure G-1: 75 kW silenced fan (1220mm) performance curve

75kW silenced axial flow fan

Table G-2: 75 kW (1016 mm) fan performance test report

Client: Harmony Gold mining company Limited	Tested with 0 Screens
Speed: 2PL – 525 Volt	Sound pressure level: 99.9 dB
Date received: 04/04/2018	Reporting density: 1.2 kg/m^3
Date tested: 26/04/2018	Barometric pressure: 84.6 kPa
Fan make: Axial flow	Wet-bulb temperature: 14°C
Fan size: 1016 mm diameter	Dry bulb temperature: 19.5°C

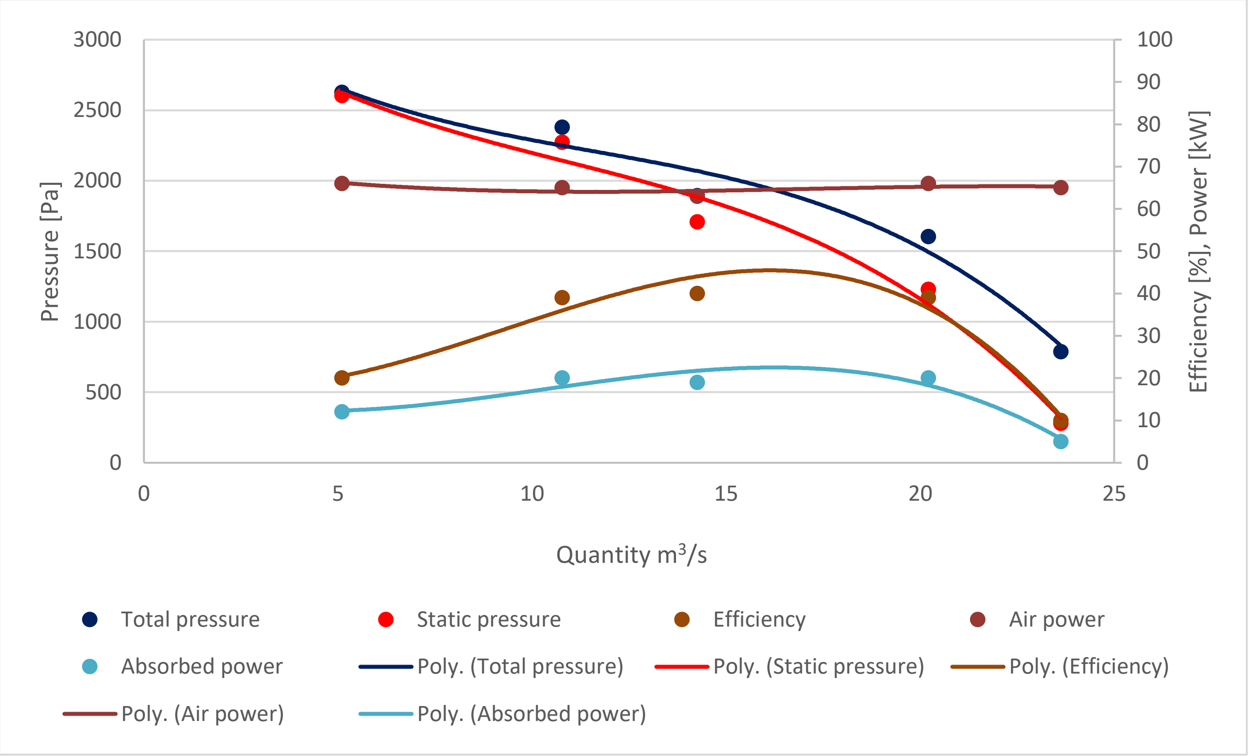


Figure G-2: 75 kW silenced fan (1016mm) performance curves

45kW silenced axial flow fan

Table G-3: 45 kW (760 mm) fan performance test report

Client: Harmony Gold mining company Limited	Tested with 0 Screens
Speed: 2PL – 525 Volt	Sound pressure level: 94.9 dB
Date received: 04/12/2017	Reporting density: 1.2 kg/m^3
Date tested: 14/02/2018	Barometric pressure: 84 kPa
Fan make: Axial flow	Wet-bulb temperature: 18.4°C
Fan size: 760 mm diameter	Dry bulb temperature: 29.5°C

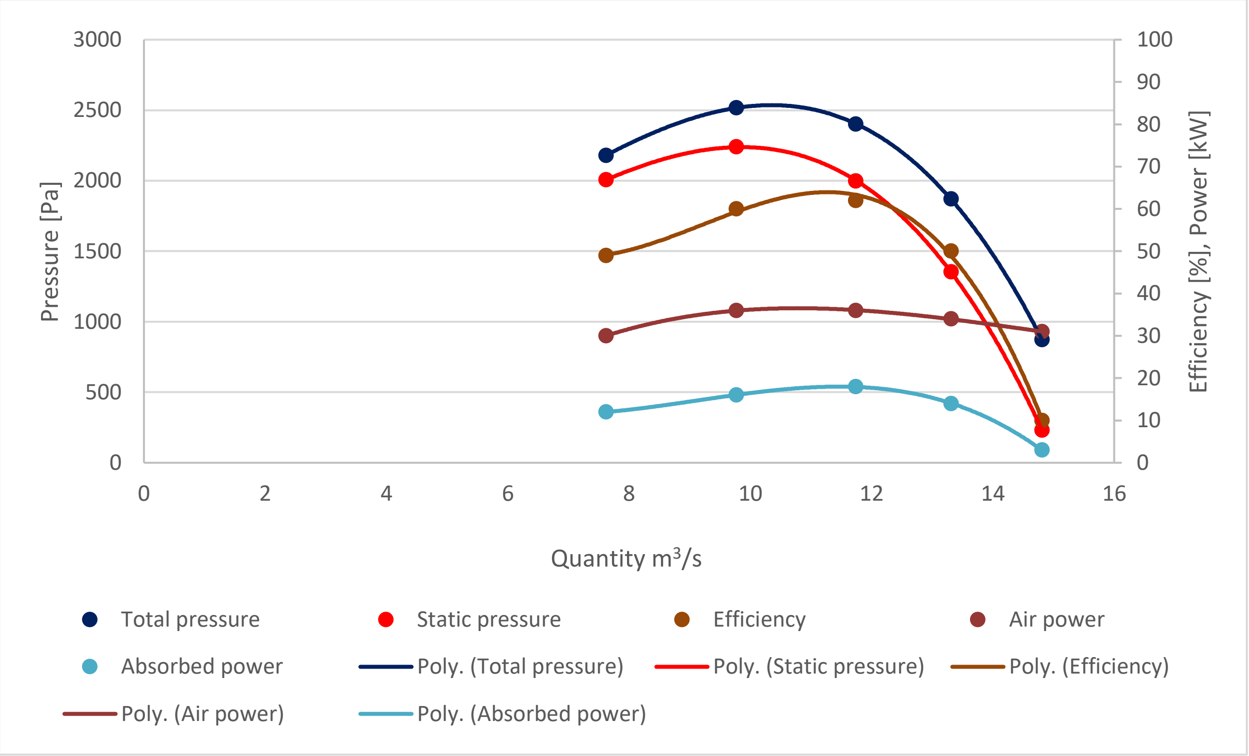


Figure G-3: 45 kW silenced fan (760 mm) performance curves

Surface fan

Fan characteristic curve

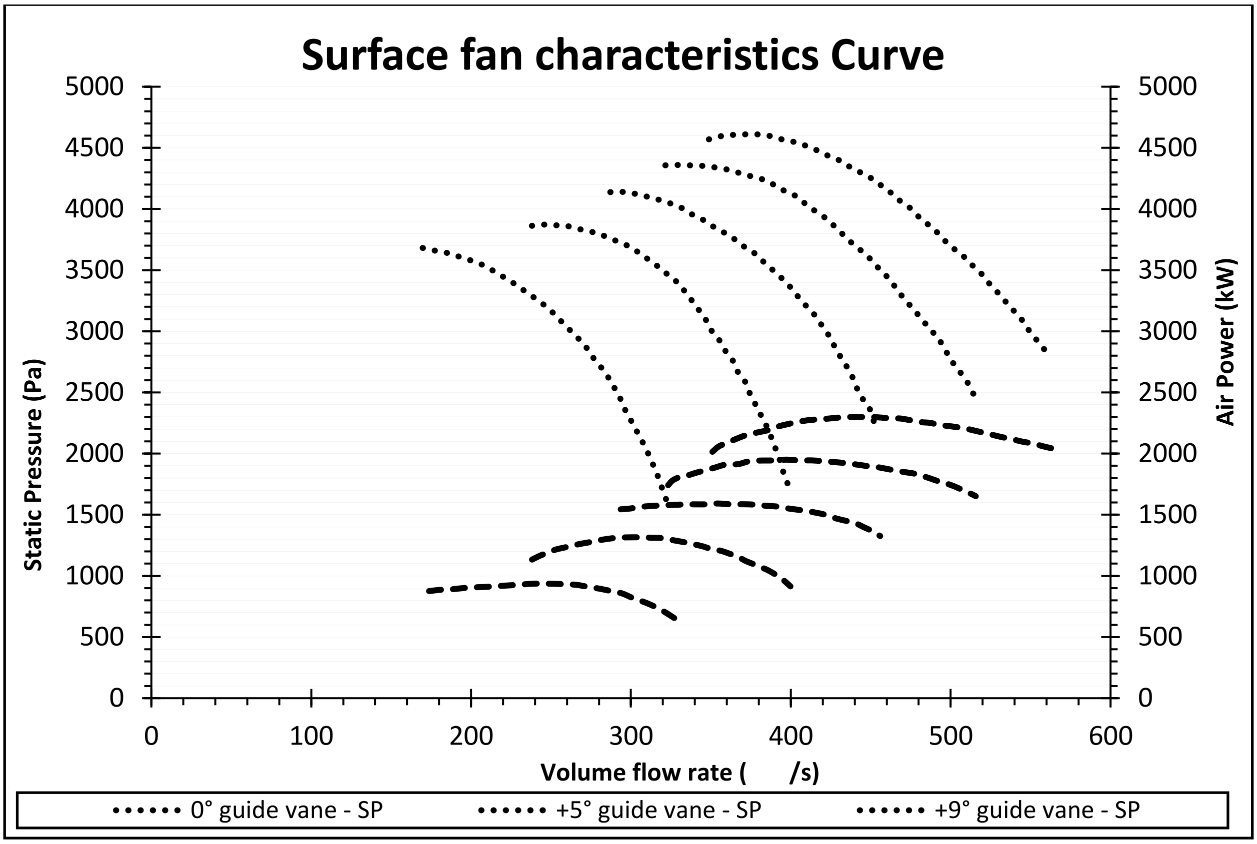


Figure G-4: Surface fan characteristic curve

Main booster fans

Fan performance test report

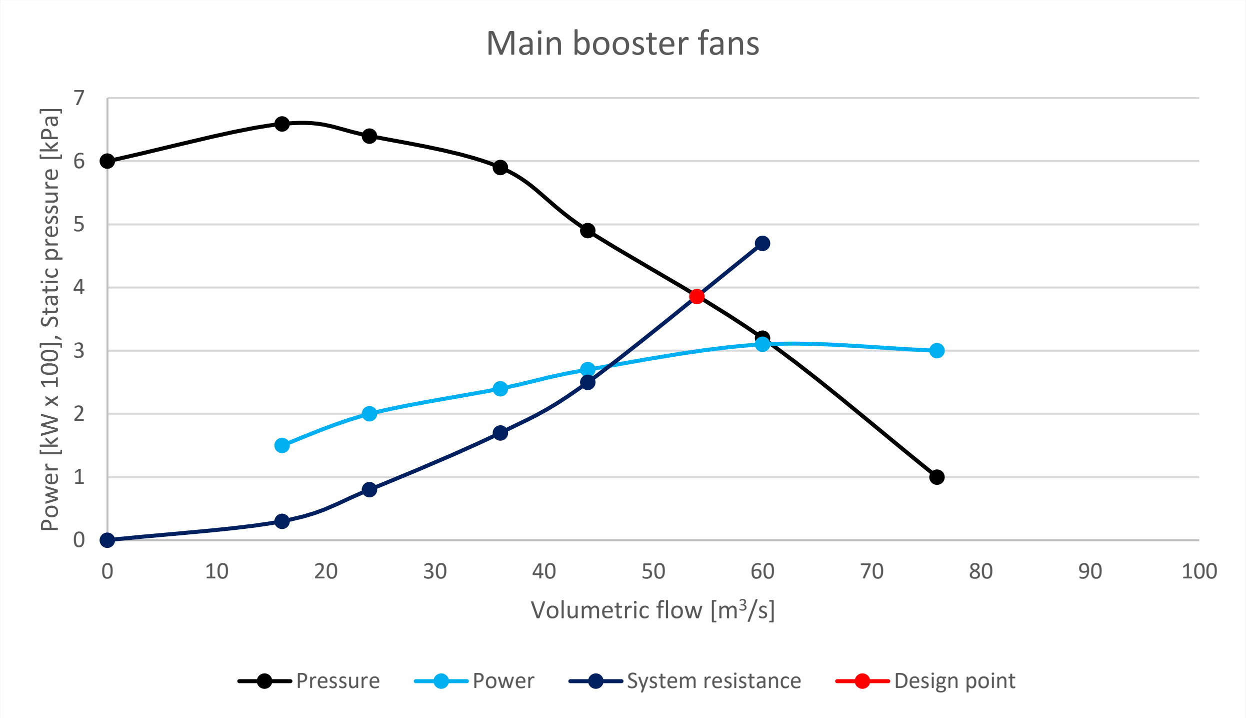


Figure G-5: Main booster fans performance curve

H. Appendix H: Detailed plan for the investigation

Table H-1: Pre-planning objectives

Investigate Second intake shaft								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
-	20/03/2019	Quantify air flowing to escape route.	1	Ventilation	ETA	20/03/2019	100%	✓
Verify fan running configuration								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
-	20/03/2019	Test effort of opening doors at main booster fans.	1	Engineering	ETA	25/03/2019	100%	✓
-	20/03/2019	Test effort of flushing air through sub shaft.	2	Engineering	ETA	25/03/2019	100%	✓
Drain Zone 1.1								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
1	18/03/2019	Place order for stainless steel valves and puddle pipe configuration.	1	Engineering	Mbusi	20/03/2019	100%	✓
1	18/03/2019	Transport the stainless steel valves and puddle pipe configurations to 62L and 65L.	2	Engineering	Mbusi	05/04/2019	100%	✓
1	18/03/2019	Drill holes in wall for draining.	3	Mining	ETA	08/04/2019	100%	✓
1	18/03/2019	Install puddle pipe and valve configuration.	4	Mining	ETA	08/04/2019	100%	✓
1	18/03/2019	Ensure water is directed to annex holes.	5	Mining	ETA	08/04/2019	100%	✓
1	18/03/2019	Dose water on shaft bottom to increase pH levels.	6	-	Jonathan	08/04/2019	100%	
1	18/03/2019	Monitor drainage flow.	7	Engineering	Mbusi	18/04/2019	100%	✓
Investigate water level at Zone 2								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
2	18/03/2019	Arrange proto team to investigate the start of water on 65L East.	1	Mining	Dorus	29/03/2019	100%	
2	18/03/2019	Determine dewatering pipe lengths required as well as pump specifications.	2	-	ETA	29/03/2019	100%	✓
2	18/03/2019	Place order for pipes and pumps as well as the guide couplings.	3	Engineering	Mbusi	04/04/2019	100%	✓
2	18/03/2019	Modify pumps to skid to enable easy transport.	4	Engineering	Mbusi	15/04/2019	100%	✓
2	18/03/2019	Deliver pumps and pipes	5	Engineering	Mbusi	16/04/2019	100%	✓
2	18/03/2019	Connect extension cable to fan for power supply to pumps.	6	Engineering	Mbusi	16/04/2019	100%	✓
2	18/03/2019	Connect pump to power supply.	7	Engineering	Mbusi	16/04/2019	100%	✓
Equip entry points with doors								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
3	18/03/2019	Survey door construction site for dimensions.	1	Ventilation	Johan	18/03/2019	100%	✓
3	18/03/2019	Obtain quotes and place order for doors and construction material.	2	Ventilation	Johan	29/03/2019	100%	✓
3	18/03/2019	Deliver to shaft	3	Ventilation	Johan	05/04/2019	100%	✓
3	18/03/2019	Transport doors to sub shaft levels	4	Engineering	Mbusi	08/04/2019	100%	✓
3	18/03/2019	Install doors and vent pipes	5	Ventilation	Johan	13/04/2019	100%	✓
3	18/03/2019	Install doors and vent pipes - F2:	5	Ventilation	Johan	19/04/2019	100%	✓
3	18/03/2019	Remove current walls (East) and ensure proper seal.	6	Ventilation	Johan	19/04/2019	100%	✓
Move fan on Zone 1.1								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
4	18/03/2019	Investigate location to move fan to.	1	Ventilation	Johan	19/03/2019	100%	✓
4	18/03/2019	Supply power source to new locations.	2	Engineering	Mbusi	04/04/2019	100%	✓
4	18/03/2019	Transport fan and ducting	3	Ventilation	Johan	22/03/2019	100%	
4	18/03/2019	Build wall, install fan and ducting	4	Ventilation	Johan	29/03/2019	100%	
4	18/03/2019	Switch current fan off and start newly installed fan.	5	Ventilation	Johan	19/04/2019	100%	
Areas to be investigated clearly marked								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
-	18/03/2019	Print detailed plans for each zone section.	1	Planning	Theunis	16/04/2019	100%	
Prototeam communications								
ID	**Date**	**Action**	**Priority**	**Department**	**Responsible person**	**Completion Date**	**Progress**	**Sign off**
-	18/03/2019	Communications to be established on each station	1	Engineering	Mbusi	14/04/2019	100%	✓
-	18/03/2019	Contact MRS for back-up prototeams	2	Mining	Dorus	05/04/2019	100%	

Table H-2: Bill of quantities to be ordered

ID	Quantity	Description	Responsible person	Date ordered	Date delivered	Progress	Sign off
-	6	High pressure doors	Johan	02/04/2019	04/04/2019	100%	✓
-	6	Low pressure doors (Opposite flow)	Johan	02/04/2019	04/04/2019	100%	✓
-	2	Stainless steel pumps	Mbusi	05/04/2019	-	100%	✓
-	2	Fire hose 1.5km (100m length, 4in or 8in)	Mbusi	05/04/2019	-	100%	✓
-	2	Connecting flanges to pumps	Mbusi	04/04/2019	-	100%	✓
-	2	Mobile winches	Mbusi	05/04/2019	-	100%	✓
-	X ton	Additional lime for dosing	Jonathan	28/03/2019	-	100%	
-	20 bundles	Vsheeting	Theunis	27/03/2019	27/03/2019	100%	
-	20 boxes	Vercifoam	Theunis	28/03/2019	28/03/2019	100%	
-	10	m16 Props	Theunis	28/03/2019	28/03/2019	100%	
-	15	760mm pipes (regulators)	Johan	25/03/2019	28/03/2019	100%	
-	6	760 flanges for regulators	Johan	25/03/2019	28/03/2019	100%	

Table H-3: Sequence of events presented to the mine

18/04/2019 18:00	
Stop all mining activities	
ID	**Action**
-	All mining must be stopped and employees withdrawn from the mining block.
-	All electrical supply to mining block must be stopped including the mining block fans.
-	l refrigeration plants needs to be stopped along with the condenser ponds and chill ponc
-	Only Booster fan 1 and 4 should be running
19/04/2019 18:00	
Investigate condenser ponds	
ID	**Action**
5	Inspect condition of each condenser ponds.
5	Clean obvious restrictions and replace faulty nozzles.
Investigate Zone 1	
Proto team 1	
ID	**Action**
6	vestigate condenser 1 RAW from condenser pond on 67L up to the raise connected to 6
6	Verify if any clear obstructions are evident and if water build-up is present.
Proto team 2	
ID	**Action**
7	Enter ventilation door on 65L at 1C# and closes doors once inside.
7	Walk towards 255L condenser ponds and inspect all raise bore holes as well.
Proto team 3	
ID	**Action**
8	Enter ventilation door on 62L at 1C# and closes doors once inside.
8	Walk towards 255L condenser ponds and inspect all raise bore holes as well.
Proto team 4	
ID	**Action**
9	Enter ventilation door on 60L at 1C# and closes doors once inside.
9	Walk towards 255L condenser ponds and inspect all raise bore holes as well.
20/04/2019 06:00	
Stop 255L and open 1C#	
ID	**Action**
-	Open doors at 1C# on 60L, 62L, 65L and 67L.
-	Stop booster fan 1 to 4 at 255L
-	Regulate air to ensure sufficient intake quantity on 60L, 62L,65L and 67L
-	Wait 12 hours for effective cooling.
20/04/2019 18:00	
Investigate Zone 2	
Proto team 1	
ID	**Action**
10	Investigate 67L from 1C# toward 2A and 2B declines.
10	Dewater any water build-up toward 1C#.
Proto team 2	
ID	**Action**
11	Investigate 65L from 1C# toward 2A and 2B declines.
11	Inspect all raise bore holes.
11	Dewater any water build-up toward 1C#.
Proto team 3	
ID	**Action**
12	Enter from top of 2A and 2B decline shaft and proceed towards 65L.
Investigate Zone 3	
Proto team 4 & 5	
ID	**Action**
13	Investigate 52L RAW between 2# towards 5# surface fan.
13	Verify air from 3#.
13	Clear all fall of grounds.
21/04/2019 06:00	
Start all mining activities	
ID	**Action**
-	All electrical supply to mining block must be restarted including the mining block fans.
-	ll refrigeration plants needs to be started along with the condenser ponds and chill pond
-	All Booster fans should be switched on.
22/04/2019 - 30/04/2019	
Verify that changes in the RAW improved the ventilation system	

I. Appendix I: Detailed findings during the investigation

Friday 19 April

The Mines rescue teams entered Zone 2 and made their way to the area where mud and water accumulation is expected. The temperature was within acceptable parameters, but the conditions in the airways were dangerous. Figure I-1 illustrates an example of the condition of the airways leading to water accumulation.

Figure I-1: Condition of airways in Zone 2

Figure I-1 show that there were falls of grounds and old pipes encountered. These restrictions were reduced when it was safe to do so. The team was however able to reach the water accumulation. Figure I-2 illustrates the depth of the water accumulation in the airway.

Figure I-2: Water accumulation in Zone 2

Figure I-2 show that there was water accumulation as expected. The Mines rescue team then installed pumps to help reduce the water accumulation. The Mines rescue team then made their way back to safety and reported their findings.

Saturday 20 April

Two Mines rescue teams made their way into Zone 1 behind the main booster fans to identify possible fall of grounds and to inspect the raise borehole to the upper level. The raise borehole was located at the end of the haulage and along the way they identified a large fall of ground. Figure I-3 illustrates the fall of ground that was identified.

Figure I-3: Fall of ground in Zone 1 behind the main booster fans

Figure I-3 shows the large fall of ground. The Mines rescue team then reduced the fall of the ground as much as possible to reduce the restriction in the airway. The Mines rescue team then continued and reached the raise borehole. Figure I-4 illustrates the condition of the raise borehole to the upper level.

Figure I-4: Water plug identified in a raise borehole

Figure I-4 shows that a water plug has formed in the raise borehole. This occurs when the booster fan is unable to blow the water droplets from the condenser ponds up the raise borehole. The water starts to accumulate and plug the entire raise borehole. This can only be removed by stopping the fans that are connected to the raise borehole. This, however, will not stop the water plug from forming again and should therefore be done at regular intervals.

The other four Mines rescue teams entered the level above them to inspect the wall that is known to be there and the condition of the airway. Two Mines rescue teams entered from the decline on the one side of the airway and they were tasked to remove the wall. Figure I-5 illustrates the hole that was blasted in the wall.

Figure I-5: Hole blasted in the wall

Figure I-5 shows that the entire wall was not removed. This meant that the Mines rescue team would have to return the following day to remove the wall. The other two Mines rescue teams then entered from the sub-shaft side of the airway and began inspecting the condition of the airway. They were unable to identify any clear restrictions and made their way back to safety.

Sunday 21 April

The Mines rescue team that could not remove the wall the previous day went back to finish the job. Figure I-6 illustrates that the wall was removed completely on this day.

Figure I-6: Wall entirely removed

Figure I-6 shows the wall was removed, which would have an impact on the reduction of restrictions in the airways. The remaining Mines rescue teams then investigated Zone 3 which lead to the main surface fan ventilation shaft. They inspected all the airways and only found a few small falls of grounds and reduced them as much as they could.

Monday 22 April

All mining activities were resumed, and normal operation commenced. Overall, the weekend was a success, and all areas were investigated. The scenario that was simulated using the digital twin performed as expected and is proof of the value of having a calibrated digital twin of a ventilation network.

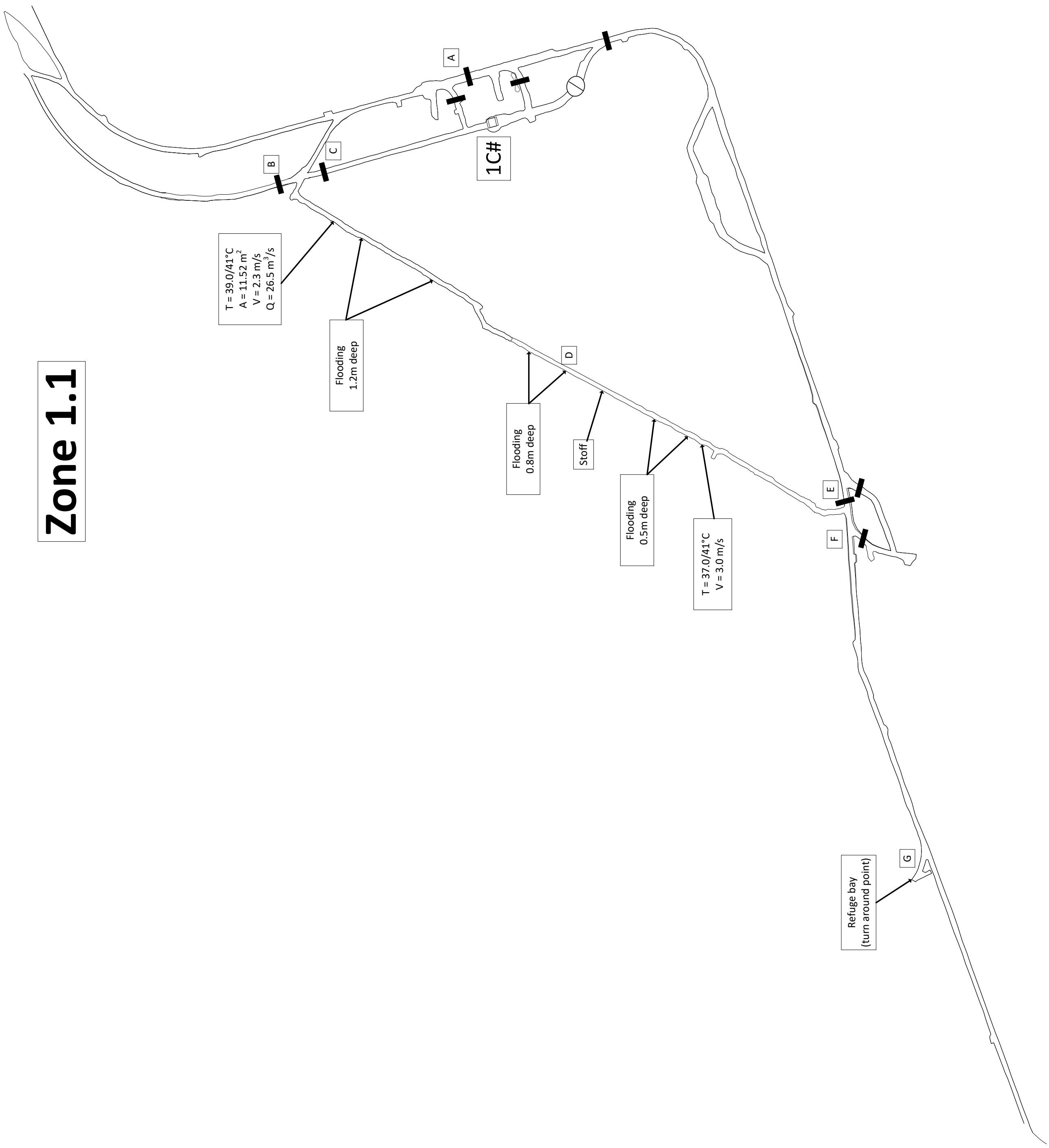


Figure I-7: Zone 1.1 detailed findings section 1

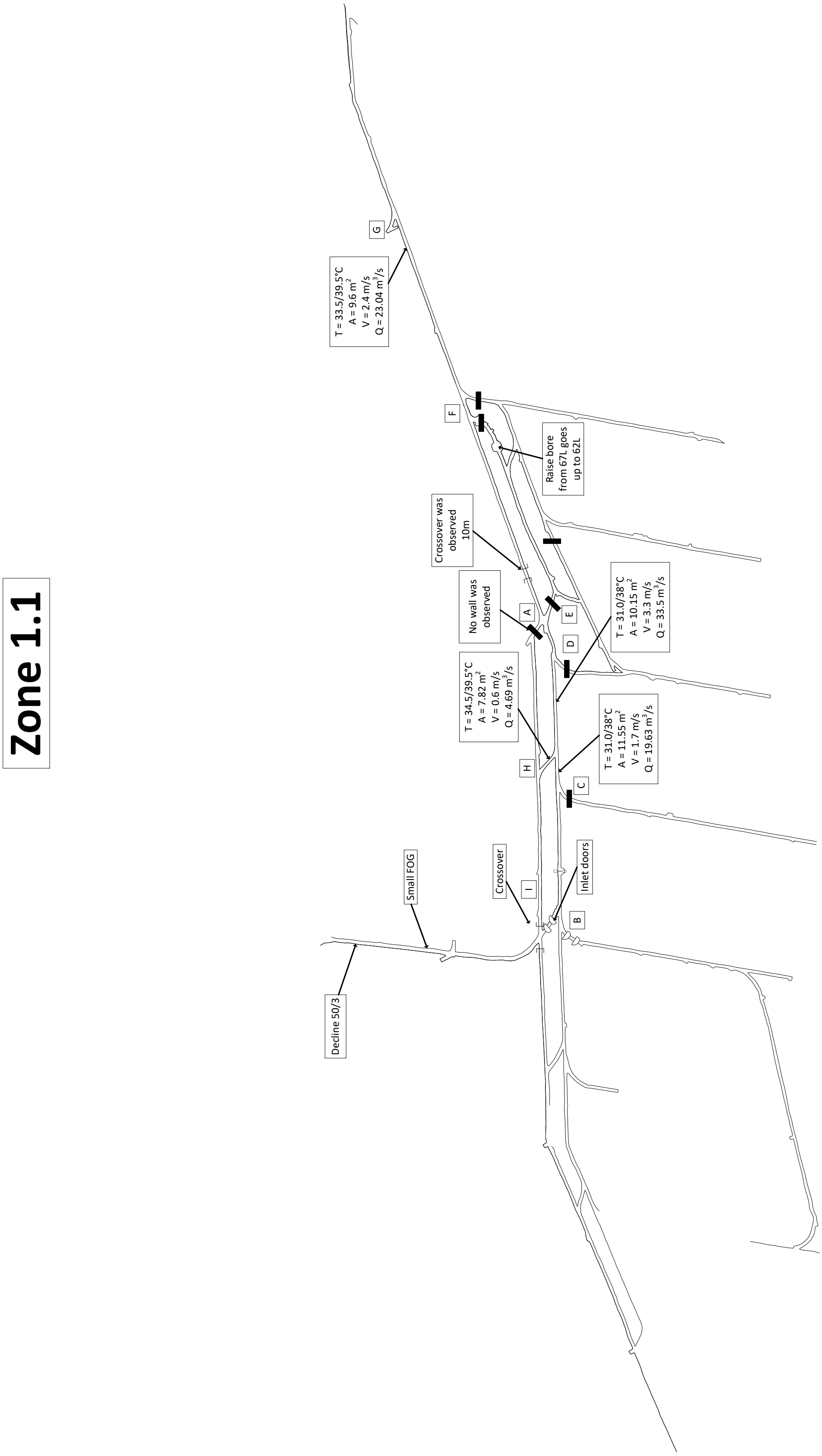


Figure I-8: Zone 1.1 detailed findings section 2

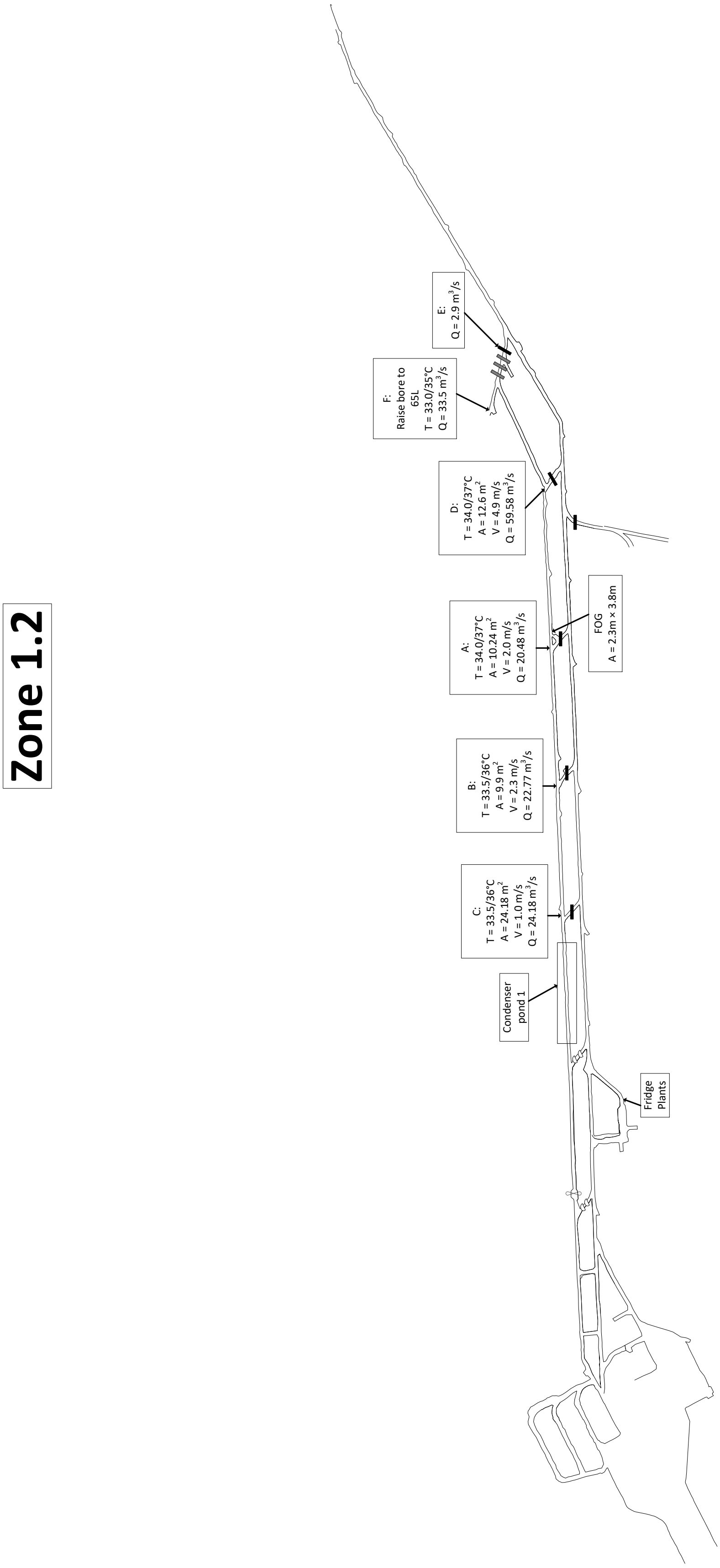


Figure I-9: Zone 1.2 detailed findings

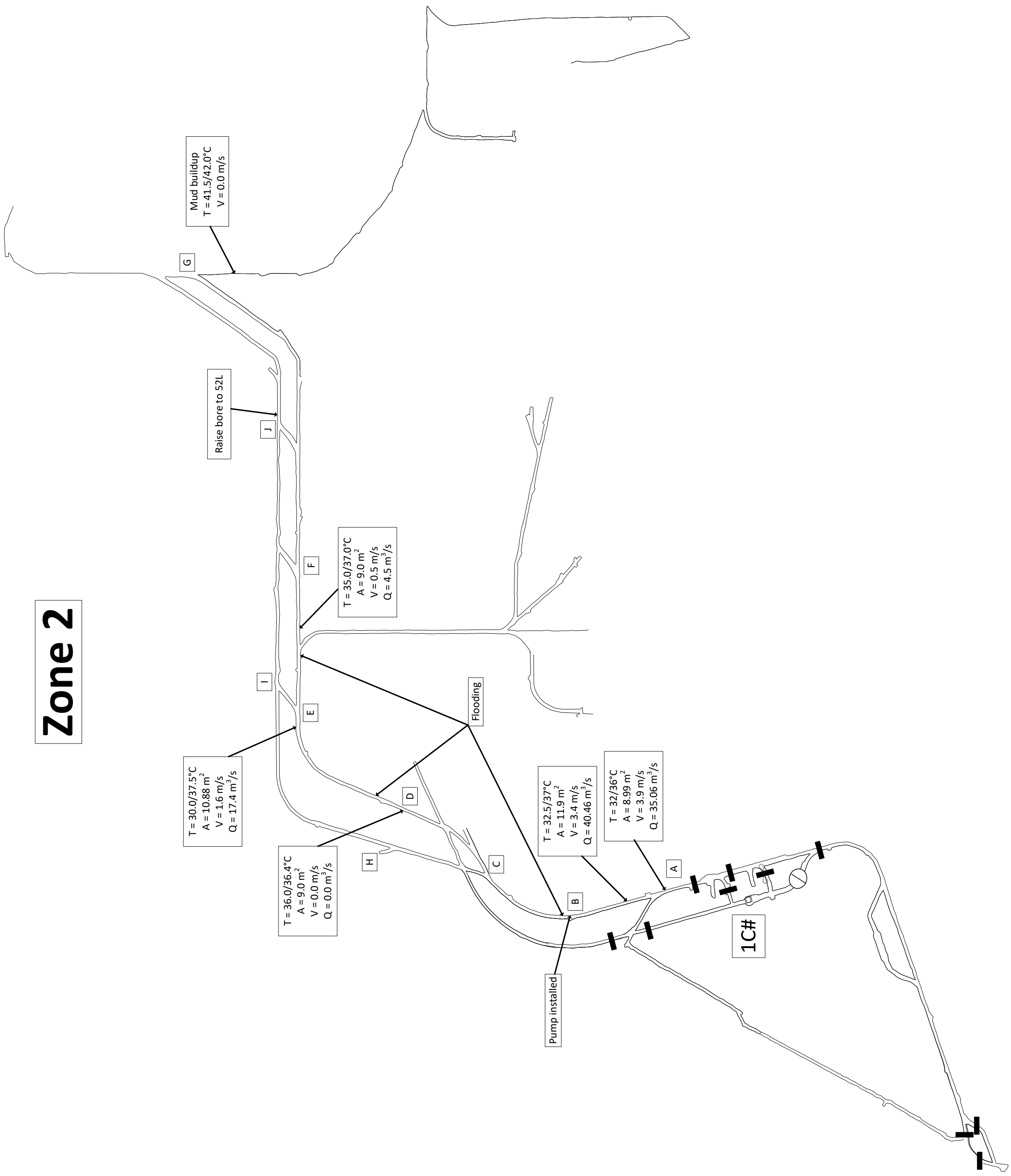


Figure I-10: Zone 2 detailed findings

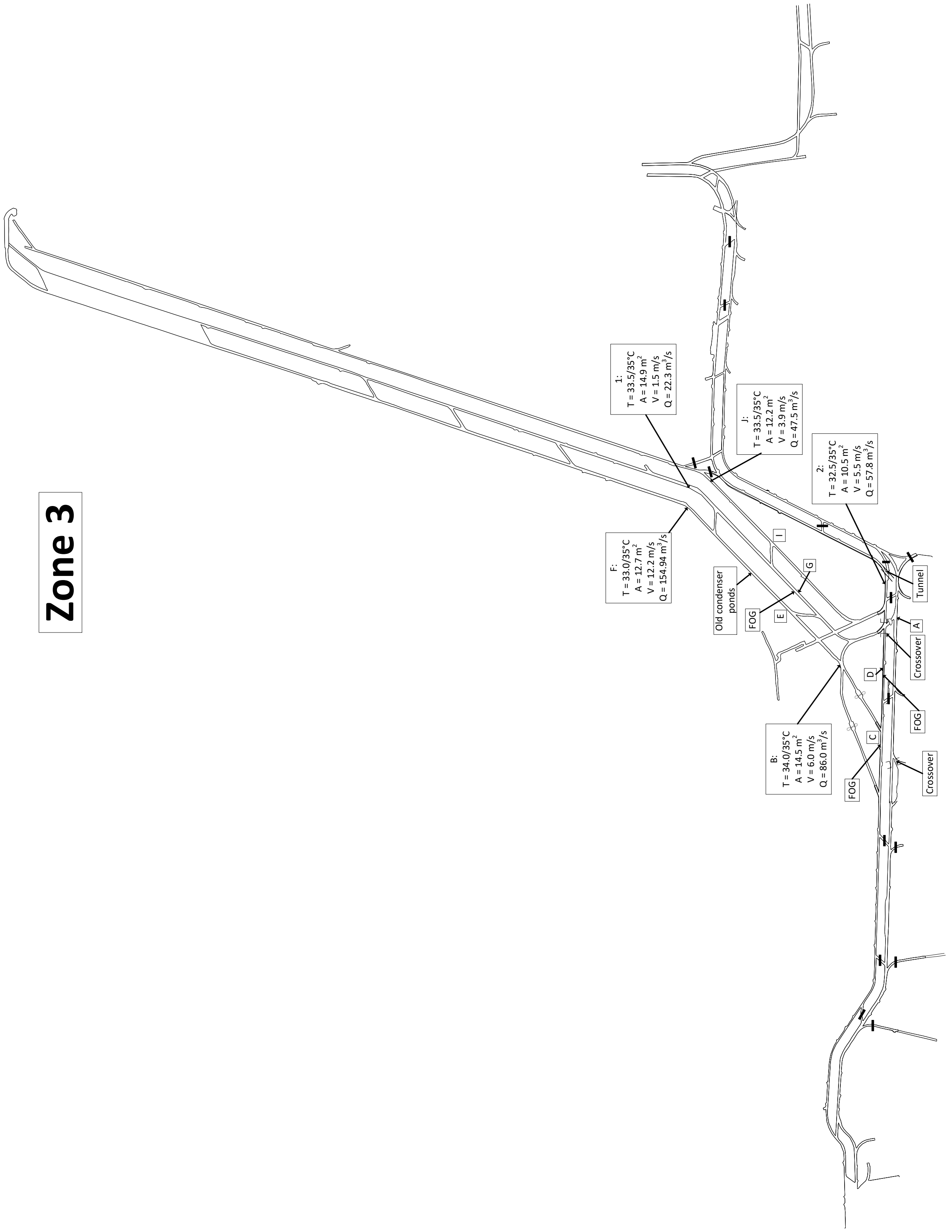


Figure I-11: Zone 3 detailed findings