Reducing temperatures and dust concentrations of fresh intake air in deep-level mines

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ABSTRACT

Title:	Reducing temperatures and dust concentrations of fresh intake air in deep-level mines.
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Some of the world's deepest mines are located in South Africa. Mines are progressively increasing in depth to obtain mineral deposits, with the deepest mine already reaching 3 891 km deep. As the mine is deepened and virgin rock temperatures (VRT) increase, the mine ventilation network must be expanded and optimised in order to provide safe working conditions, mandated and regulated by the Mine Health and Safety Act of South Africa.

Increased temperatures add to the heat absorbed by the intake air. The return air from the development ends mixes with the intake air of the closest crosscut with through-ventilation, heating the air and introducing additional airborne dust. The air temperature may not exceed a wet-bulb temperature (T_{wb}) of 32.5 °C and a dry-bulb temperature (T_{db}) of 37.0 °C. At the same time, the air velocity of working areas must be between 0.3 m/s and 8 m/s. The lower limit ensures sufficient airflow and the upper limit avoids increased airborne dust. The dust concentration occupational exposure limit (OEL) is 0.1 mg/m^3. Properly executed ventilation control in the mine can alleviate the extra heat and dust added by development end areas.

The study aims to provide a method to mitigate fresh intake air mixing with hot return development air. The study's objectives are to 1) develop a method to decrease localised temperatures and dust concentrations in deep-level mines, 2) apply the method provided to improve the ventilation conditions, and 3) validate the simulation results and method after the optimal solution has been implemented.

The proposed method consists of five steps: identification of air mixing, creation of a ventilation simulation model, identification of possible solutions, development and evaluation of simulation results, and implementation and validation of solution.

The method was applied to two different mines, Mine A and Mine B, with problematic ventilation networks. Two case studies were evaluated where air mixing was identified at the deepest crosscut farthest from the shaft. Solutions to mitigate the air mixing were developed by creating calibrated ventilation simulation models with a mean absolute error (MAE) of < 5%. Thereafter a list of ventilation and cooling methods was created to mitigate localized heat and dust problems.

The provided decision tree diagram suggested the same mitigation strategies for both case studies namely, raisebore hole (RBH) return and unequipped ore pass return. The calibrated ventilation simulation models were used to virtually implement the possible solutions and create different scenarios. The simulation results of the scenarios were compared with an evaluation matrix, and the optimal solutions were chosen. The solution for case study 1 observed a 3 °C drop in T_{wb} at the intake of the working crosscut. At the same time solution for case study 2 observed a 5 °C drop in T_{wb} at the intake of the working crosscut.

The respective simulated solutions yielded satisfactory results and were implemented. The validation of the simulated results was done by empirical data acquired after implementation. The implemented solutions improved the conditions of the working crosscut by decreasing the T_{wb} by 3 °C for case study 1 and 5 °C for case study 2. At the same time, preventing airborne dust created in the development end from entering the intake air stream for both case studies. Thus, case study 1 and case study 2 satisfied all the study objectives.

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Abbreviation	Description
2D	Two-dimensional
3D	Three-dimensional
ACU	Air cooling unit
ACP	Air cooling power
ACC	Air cooling capacity
ASG	Advance strike gully
AVS	Auxiliary ventilation systems
BAC	Bulk air cooler
CC	Cooling cars
DXF	Drawing exchange format
KPI	Key performance indicators
GIS	Geographic information system
MAE	Mean absolute error
MCU	Mobile cooling unit
MHS	Mine health and safety
OEL	Occupational exposure limit
PTB	Process toolbox
RAW	Return Airway
RBH	Raise borehole
VRT	Virgin rock temperature
T_{db}	Dry-bulb temperature
T_{wb}	Wet-bulb temperature

NOMENCLATURE

Symbol	Description	Unit
°	Angle	°
°C	Degree Celsius	°C
A	Cross-sectional area	m^2
Cm	Centimeter	cm
E_p	Potential alpha energy exposure	mJh/m3
kW	Power	kW
$\dot{m}$	Mass flow	kg/s
m^3	Volume	m^3
mbar	Millibar	mbar
mg	Milligram	mg
mSv	Millisievert	mSv
Pa	Pascal	Pa
Q	Volumetric airflow	m^3/s
v	Air velocity	m/s

GLOSSARY

Auxiliary fan:	Between centrifugal and axial fans, axial fans are the most common as the application demands air flow to be a priority rather than air pressure [1]. Auxiliary fan sizes usually range from 4kW to 45kW, depending on the pressure and airflow requirements [2].
Brattice:	A brattice can be a temporary or permanent stopping to control the airflow, provided the pressure difference is insignificant and trackless vehicles need to travel [3].
Crosscut:	Horizontal excavations closest to the ore deposits connect the haulages with the working areas [4], [5].
Dead end:	A dead end is a horizontal excavation with no airflow [6].
Development end:	A development end is a dead end with an auxiliary ventilation system to deliver adequate air quantity to the working face [7].
Haulage:	A haulage is a horizontal excavation that connects the working areas to the shaft [4].
Ore pass:	An ore pass is a vertical excavation that moves ore between levels [4], [8], [9].
Primary fan:	The primary fans are responsible for creating the airflow through the mine. The fans are usually situated on the surface and exhaust the air through the mine. Also called the main fans [3].
Raise borehole:	Raise boreholes are vertical openings used as ventilation airways, either expelling return air from working areas or providing fresh air to working areas [10].
Raise:	A Raise is a vertical or inclined upward-driven opening from one level to another [4], [11].
Regulator:	A regulator is a ventilation door fitted with an opening of a predetermined size to reduce the amount of airflow to an underground area [3].
Secondary fan:	Secondary fans are implemented when the ventilation network's resistance exceeds what the primary fans can overcome. Secondary fans are also called booster fans [12].
Shaft:	Shafts are vertical cavities in the earth which serve as the travel way for personnel, material, mined rock and air between the surface and the

underground tunnel network. Downcast and upcast shaft refers to the main intake and return airways of a deep-level mine, respectively [1].

Stopping: A stopping is implemented when a connection made during development is no longer needed and closed to improve the ventilation network. A stopping is usually a wall built with bricks and concrete [3], [13].

Through-ventilation Through-ventilation is the normal state of ventilation where no auxiliary ventilation systems are required to ventilate an areas the air flows from main intake to a return airway [3]

Travel way: Underground excavation conveys air, personnel, and materials to the working areas [4].

Tunnel: Tunnels are horizontal cavities in the earth which serve as a travel way for personnel, material, mined rock and air between the shaft and the working areas [14].

Ventilation door: A ventilation door is a stopping which allows man and machinery travel [3].

Winze: A winze is a vertical or inclined downward-driven opening from one level to another [4].

Working place: An area where blasting takes place; also known as a stope.

1. INTRODUCTION

1.1. Preamble

This chapter provides a background on deep-level mine ventilation systems and a brief overview of the most popular mining practice used in South African gold mines, specific to this study. Firstly, an overview of deep-level mine ventilation systems is discussed to provide background for the study. Deep-level mines have large, complex tunnel networks created over years of development, guided by the location of underground gold deposits. Various underground elements are encountered searching for gold deposits, such as heat sources, dust and underground water. Ventilation systems are essential throughout the mine to remove heat, dust, and noxious fumes after blasting and provide a habitable environment in underground areas [5], [15]. The problem statement outlines why the study is necessary, and this section also lists what objectives need to be achieved to solve the problem.

1.2. Deep-level mine ventilation systems

Deep-level mines are constantly expanding vertically (increased depth) and horizontally. The deepening increases the heat added to ventilation air due to auto compression and increased virgin rock temperatures (VRT), while the horizontal expansion increases the complexity of the ventilation network. Longer airways with smaller diameters increase the network's resistance, allowing less air to reach the workings far from the shaft. The increased complexity and depth make it more challenging to adhere to ventilation regulations, such as temperature and dust exposure limits of deep-level mines.

Special care is given to airflow throughout the mine when no secondary cooling is available to mitigate increased air temperatures. Moreso to working crosscuts with increased temperatures close to development ends. The fresh air flowing to the working crosscut deteriorates as it mixes with the return air from the development end. The return air of the development end is returned to the nearest working crosscut with through-ventilation. Ultimately preventing the air from mixing will improve the temperature of the air flowing to the working areas and increase the air quality as no dust produced in the development end will travel to the working areas.

Adequate ventilation in deep-level mines is essential as it is the vehicle used to remove heat, dust, and gasses from the underground environment [15]. To be considered adequate, ventilation systems must adhere to ventilation requirements. The air velocity of working areas must be between 0.3 m/s and 8 m/s. At the same time, the air temperature has upper limits with the wet-bulb temperature (T_{wb}) of 32.5 °C and dry-bulb temperature (T_{db}) of 37 °C [5].

Ventilation systems mainly comprise of fans and airways to move the bulk of the air through the mine. Ventilation control systems ensure optimal ventilation in development ends and working places. Figure 1-1 shows a basic schematic of the ventilation network of a typical mine. Table 1-1 lists and describes components typically used in ventilation networks [16].

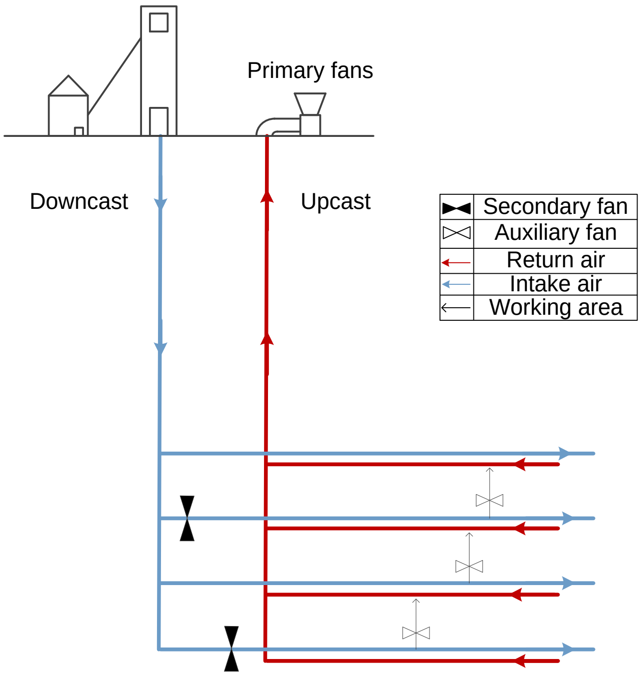


Figure 1-1: Schematic representation of a simple mine ventilation network.

Ventilation systems include a range of different components. The various components, with a short description, are listed in Table 1-1.

Table 1-1: Components of ventilation systems.

Component	**Description**
Primary fan	The primary source of airflow.
Secondary fan	Reduces the system resistance and improves overall airflow.
Auxiliary fan	Direct the airflow to working areas.
Ventilation door	Restricts airflow to an area and allows travel.
Regulator	To throttle the quantity of airflow.
Stopping	A wall or a seal to prevent airflow.
Brattice	A temporary stopping to redirect airflow.

The listed infrastructure can be used in many different configurations to ensure adequate ventilation in the underground environment.

1.2.1. Underground environment/elements

Numerous factors make the underground environment extremely hazardous or perhaps unsuitable for human habitation. Factors like noxious and flammable gasses, dust, and heat that must be removed from the underground working environment if working conditions are to be sustained [5]. In addition, radiation is also present in all underground mines, typically from radioactive uranium oxides [17]. The radiation exposure of personnel is monitored by limiting the time they spend in radiated areas. According to the International Commission on Radiological Protection, no individual is allowed to be exposed to more than 0.014 Jh/m^3 each year, and in regions where there are active operations, the allowable exposure limit is limited to one working level during an 8-hour shift. The effective dose is either 50 mSv in any one year or 20 mSv/year averaged over five years [18]. The sources of dust and heat are discussed in the following sections.

A. Dust

Expelling dust is one of the main reasons ventilation systems are vital for deep-level mines [13]. Dust is created in the act of mining. Mining in deep-level mines includes drilling holes in the rock face, using explosives to loosen the rock (blasting) and using underground trains to transport the rock out of the mine [19]. When inhaled, the dust created from mining can cause various types of Pneumoconiosis depending on the dust type.

Pneumoconiosis is the reaction of lung tissue to the accumulation of inhaled dust particles in the lung. Pneumoconiosis is categorised as fibrotic or non-fibrotic. Examples of fibrotic pneumoconiosis are silicosis, coal workers' pneumoconiosis, berylliosis, asbestosis, and talcosis [20]. Silicosis is a dust disease that causes damage to cardio-respiratory organs, contracted by inhaling dust particles, specifically crystalline silica or quartz [3]. The hazard of contracting the disease is highest when working near freshly produced dust. Dust created underground is not fatal, but long-term exposure can damage the lungs and cause increased susceptibility to colds, influenza, tuberculosis, and chronic bronchitis [21].

B. Heat

Virgin rock

Virgin rock is the term used to describe newly exposed rock. The temperature of the virgin rock is defined by a formula derived from numerical studies done in various parts of South Africa [22]–[24]. The virgin rock temperature (VRT) is a function of the depth below the surface, and the formula is different for the different types of rock layers found in other regions of South

Africa. The different rock types include quartzite, lava, shale, dolerite, and sandstone. Table 1-2 lists thermal properties of rock types from different regions in South Africa.

Table 1-2: Thermal properties of rock from different regions.

Type of rock	Thermal conductivity (W/m°C)	Thermal capacity (J/kg°C)	Density (kg/m³)	Thermal diffusivity (x10⁻⁶m²/s)
Witwatersrand quartzite	5.74	837	2 690	2.55
Ventersdorp lava	3.10	879	2 850	1.24
Karoo shale	2.39	921	2 620	0.99
Karoo dolerite	2.01	879	2 960	0.77
Karoo sandstone	1.97	837	2 470	0.95

The mines in the Free State Province of South Africa fall in the Witwatersrand region [25], [26]. The VRT at any depth in the Free State Province, can be calculated using (Eq. 1-1) [22].

$$VRT = 20 + 14.6(z) \quad \textit{(Eq. 1-1)}$$

Where VRT is the virgin rock temperature (°C), and z is the depth below the surface (km).

After a blast, the broken rock cools down due to the ventilation air flowing over the blasted rock. This type of heat transfer is known as convection [27]. When the ore is transported from the working areas to the shafts, the ore usually travels in fresh air haulages. The heat transfer between ore and air increases as the temperature difference increases [28].

Machinery

Electric-, diesel- and compressed air-powered machinery are used underground to drill holes, load, and transport rock from the working place to the shaft area, where the rock is hoisted out of the mine. Pumps are used to transport water through pipes either horizontally (spindle- and booster pumps) or vertically (dewatering pumps). Machines are not 100% efficient. The portion of input energy not converted into work is converted into heat. The heat produced by machinery need rejected. The heat rejected by the machinery is absorbed by the ventilation air through convection heat transfer [29].

Personnel

All humans generate body heat, called metabolic heat production. However, when a lot of heat is produced, e.g., when physical work is performed, the human body gets too hot and uses its cooling mechanism to keep the body temperature below 37 °C. This mechanism rejects heat from the body into the surrounding area, increasing the temperature in the immediate area [30].

Fissure water

Fissure water is underground water that moves through cracks in the rock from nearby aquifers [31]. The underground water can provide a continuous water supply to areas far away from rivers, and windmills are used to extract the water from deep below the earth's surface [32]. Similarly, when a mine is being developed, it is possible to encounter underground water. This water needs to be accounted for when designing a pump network for underground mines, but it is also crucial to account for the heat load it adds to the mine's ventilation system [33]. Just like with virgin rock, a specific water temperature can be expected, and this temperature is equal to the VRT at the same depth [10].

Auto compression

Auto compression of air is when air travels down the shaft, compressed by the columns of air above it. According to Mishra [34], auto compression generates heat and can increase the dry-bulb temperature by 10 °C/km relative to the surface [35].

1.2.2. Ventilation requirements

A ventilation system's quality is measured by the quantity and temperature of the air passing through the mine. Quantity can be described as volumetric flow rate, measured in m^3/s, or velocity, measured in m/s [3]. The temperature and velocity of the working environment have a noticeable effect on a worker's performance [36]. An increase in velocity can help increase a miner's performance at elevated wet-bulb temperatures [37].

A. Air temperature and velocity

According to the Mine Health and Safety Act 1996 [38], the maximum temperatures allowed for personnel to work underground are 32.5 °C wet-bulb and 37.0 °C dry-bulb.

The air velocity or wind speed ranges between a permitted minimum of 0.3 m/s and a recommended maximum of 20 m/s. There are limitations to the velocities allowable in the underground environment due to the possibility of dust pickup at velocities higher than 8 m/s

[3]. In contrast, at velocities lower than 0.3 m/s, the air cooling power is insufficient for effective evaporation [39].

Figure 1-2 shows how the environment's windspeed can significantly impact the miner's work performance at a given wet-bulb temperature. For example, at a 31 °C wet-bulb temperature and a wind speed of 0.5 m/s, a miner will have a work performance of approximately 90%. By only increasing the wind speed, the miner's work performance will return to nearly 100% [37].

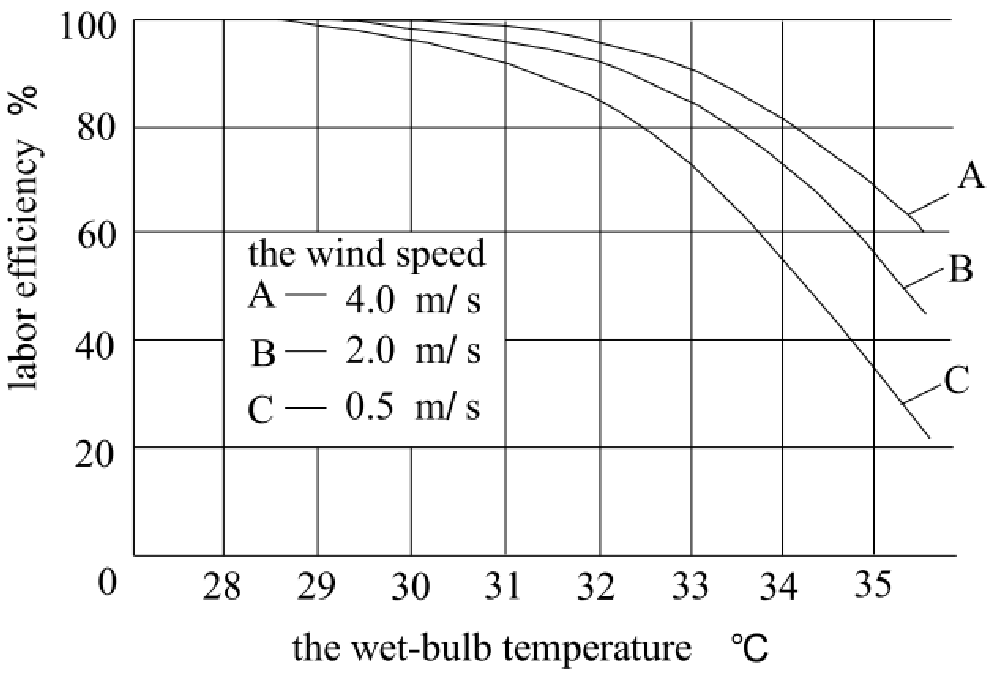


Figure 1-2: Labour efficiency of miners vs the wet-bulb temperature and wind speed [32].

Table 1-3 lists the maximum recommended air velocities for specific airways. The minimum air velocity of 0.3 m/s is proposed only for travelling ways as air movement is barely noticeable. For working faces, the minimum air velocity is usually 1 m/s [3].

Table 1-3: Maximum recommended air velocities in prescribed airways [3]

Area	**Maximum recommend velocity (m/s)**
Working faces	4
Conveyor drifts	5
Main haulage routes	6
Smooth/lined main airways	8
Hoisting shafts	10
Ventilation shafts	20

From Figure 1-2, the air velocity in a working place plays a significant role in maintaining a miner's work performance at nearly 100% at elevated temperatures. However, the amount of air travelling to the working area, known as the volumetric flow rate of air, is the main parameter in analysing the dilution and removal of harmful gasses and dust from the working area [5]. The volumetric flow rate of air can be calculated using (Eq. 1-2) [3]:

$$Q = v \times A \qquad \textit{(Eq. 1-2)}$$

Here, Q is the volumetric flow rate of air (m^3/s), v is the mean velocity of the air (m/s) and A the cross-sectional area of the airway or duct (m^2).

B. Dust concentration

Quartz with pollutant code 522, per the Mine Health and Safety Act, of 1996, has an occupational exposure limit (OEL) of 0.1 mg/m^3 [38]. The OEL is the time-weighted average concentration for an 8-hour workday and a 40-hour workweek to which workers may be exposed repeatedly without experiencing adverse health consequences. A gravimetric pump, as discussed in Appendix A, measures the personnel's exposure to dust. An employee wears this device for a whole working shift, after which the device's filter is weighed to determine the dust concentration of the working place [40].

1.3. Narrow reef mining methods

There are multiple underground mining methods around the world such as Room-and Pillar mining, Vein mining, Shrinkage stoping, Bighole stoping, Vertical Crater Retreat, Cut-and-Fill stoping, Longwall mining, Sublevel caving, and Block caving [4].

The choice of mining method depends on how the mineralised rock was formed at the specific site. Each rock formation has unique features and attributes described by the orebody characteristics. Orebody characteristics include orebody shape, size, geometry, rock mass characteristics, grade characteristics, mining considerations, and cost considerations. Balt and Goosen proposed an approach to mining method selection [41]. However, the mining method selection process is out of the scope of this study and is not described in detail.

In the case of South African deep-level gold mines, the mineralised rock formed thin reef-type, deposits which necessitate the use of narrow reef mining methods [4], [11]. The reef width in the Witwatersrand basin ranges from about 10 cm to 120 cm with an average of 60 cm. At the same time, the average dip angle is typically about 24° and decreases progressively towards the south [42], [43].

Typical narrow reef mining methods in the South African gold mining industry is highly conventional and labour intensive requiring the use of handheld pneumatic rock drills to mine the hard gold reef conglomerates [44]. However, some mines use mechanised mining methods where reef widths allow[1].

Scattered mining was used in deep South African gold mines before 1998. However, the method was abandoned due to the increased mining depth, leading to unacceptably high energy release rates due to high stress levels in the rock. The scattered mining method is still used at some shallower mines in the Free State province of South Africa. The longwall mining method was not used as the variable grade and geological structures called for a more flexible mining method. The sequential mining method was introduced to accommodate for the variable grade and presence of geological structures [45].

Figure 1-3 shows a simplified representation of a conventional underground mine.

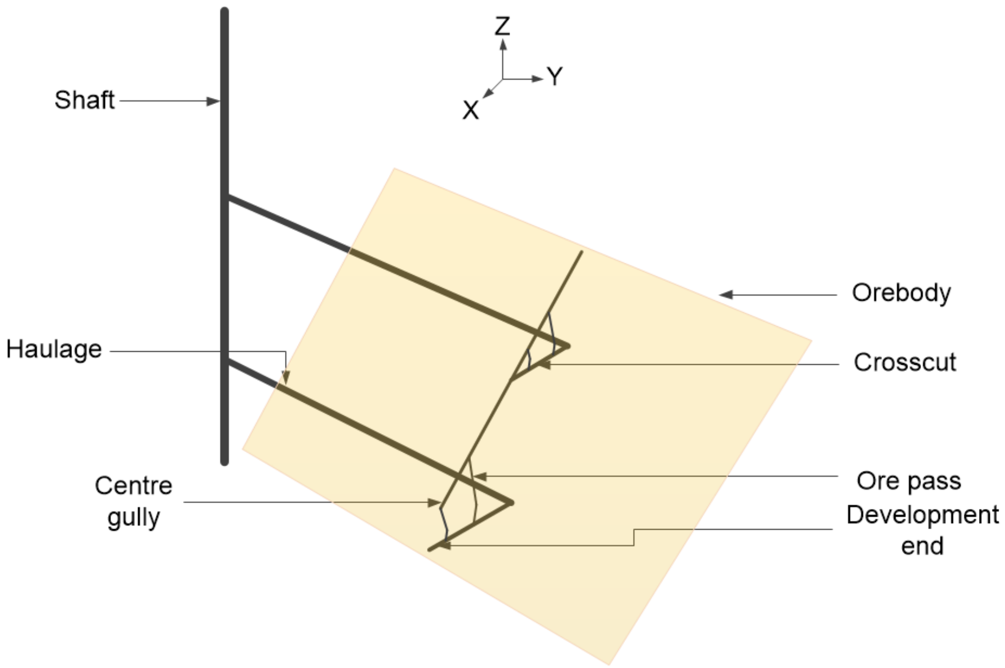


Figure 1-3: Simplified underground mine layout.

Haulages are excavated from the shaft to the mineral-rich inclined plane or orebody. Crosscuts break away from the haulage in such a way that the ore body is directly above and continue until the ore body is intersected. While crosscuts are developed, the excavated area from the

[1] *https://www.mining-technology.com/projects/target/?cf-view&cf-closed [Accessed on: 2024-03-03]*

haulage to the developing face is called a development end, until through-ventilation is established. Through-ventilation is the normal state of ventilation where no auxiliary ventilation systems are required to ventilate an area. The centre gully is developed parallel to the crosscut in the XY-plane, and parallel to the incline of the orebody in the XZ-plane. Ore passes convey the broken rock from the centre gully down to the crosscut or development end. A box front is installed where the ore pass and crosscut connect. The box front is used to control the flow of broken ore from the ore passes into the hoppers. Hoppers are carts mounted on train tracks propelled by an electric or diesel locomotive to transport ore from the working areas to the shaft.

Figure 1-4 shows a top view of a stope where the sequential grid mining method is used. It shows the relative location of the face, blasting barricade, advance strike gulley (ASG), mined out area, and the centre gully.

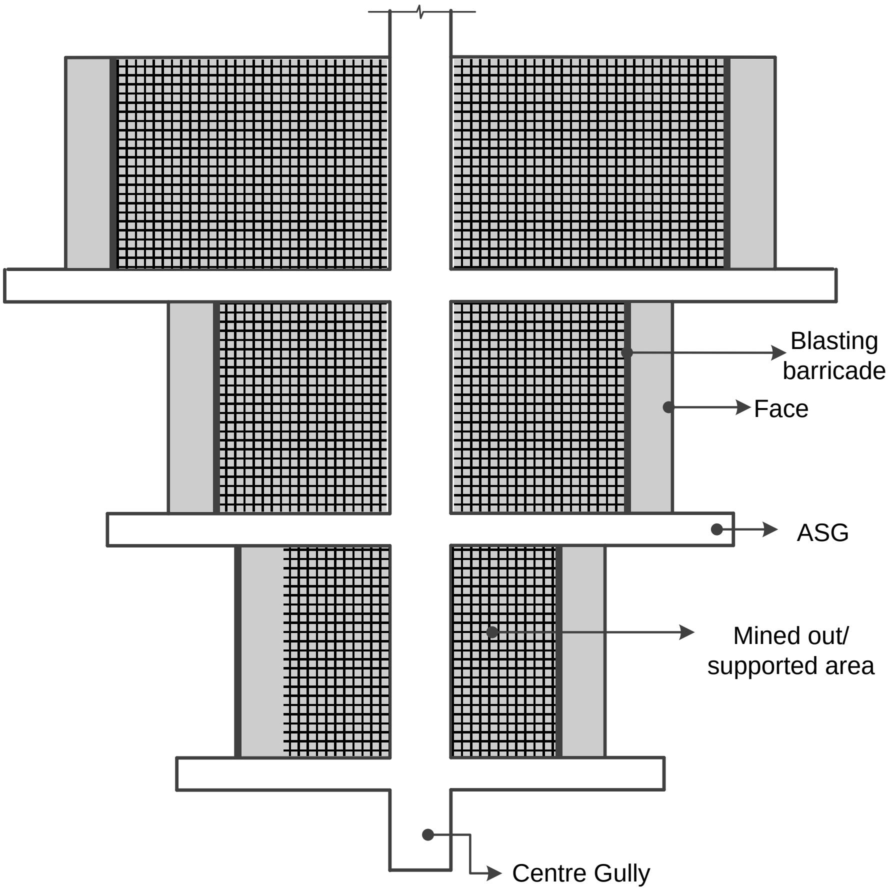


Figure 1-4: Top view of sequential grid mining layout.

The hanging wall in mined out areas is supported with backfill or roof bolts, timber packs, and props [46], [47]. The blast barricade prohibits the blasted rock from flying into the back areas[2].

[2] https://www.uniqueeng.co.za/images/downloads/Blast-Barricade-Brochure-V2.pdf [Accessed: 2024-09-05]

Scraper winches move the blasted rock from the face to the advance strike gully (ASG). The ore is moved from the transport drift along the centre gully to the ore passes, where the ore will be loaded into hoppers.

The mining practice and equipment used in a mine introduces heat sources added to the mine as described in Section 1.2.1 B. Simulation models can incorporate the characteristics of the mine's ventilation systems, and heat sources to yield a thermo-hydraulic simulation model. The simulation model predicts the underground ventilation conditions, which can be compared to the requirements to ensure the future working areas meet the ventilation requirements discussed in Section 1.2.2 A.

1.4. Simulation environment

Simulation software is a means to create a simulation environment or simulation model which represents the real world. Different simulation types exist such as discrete event simulation, process simulation, and dynamic simulation. Simulation models can be used to virtually implement and compare various critical changes to a system to identify the optimal solution [2], [48]. Some critical changes may include:

- Establishing a new ventilation district to improve the ventilation conditions in established areas or developing areas,
- Adding a secondary cooling system to mitigate increased air temperatures.
- Changes in the water or compressed air reticulation system due to mine expansion or downscaling.

Simulation is advantageous for mine planning specifically to complete what-if analysis, for energy management and optimising ventilation, compressed air, and water networks for service delivery improvements [49], [50], [51].

Simulations have also been used to develop a life cycle ventilation simulation and optimise ventilation networks [52], [53]. Furthermore, simulation can characterise ventilation networks with fluctuating surface conditions [54]. Further details regarding the simulation software used in this study (Process Toolbox) are discussed in Section 2.3.1.

1.5. State of the art

Several studies on simulation, optimisation, contamination, and improvement techniques in deep-level mines and whether a method was used to solve ventilation problems are reviewed and discussed. The common objective of the studies was to characterise ventilation networks and improve the underground environment by optimising ventilation systems.

Table 1-4 lists the questions formulated to determine the relevance of a study to each category and brief explanations are provided for each question.

Table 1-4: Questions and comments per category to determine study relevance.

Category	Question	Explanation
Simulation	Did the study use a ventilation simulation model to develop and test various scenarios to find the optimal solutions?	This is important because simulation is a powerful tool to improve inefficient underground ventilation networks.
Optimisation	Did the study yield a more efficient ventilation network?	This focuses on whether the outcome had either operational or service-delivery improvements.
Contamination	Did the study highlight or mitigate the risks of heat or dust in deep-level mines?	This is important because workers' health in deep-level mines should always be considered when changes are proposed to any ventilation network.
Improvement techniques	Did the study elaborate on the ventilation or air cooling techniques to improve underground air conditions by preventing air-mixing or recirculation?	This is needed as this study lists several techniques for improving the air conditions of deep-level mines.
Method	Did the study provide a method to improve underground air conditions, specifically to reduce air temperatures and dust concentrations at crosscut intakes?	This is important because this study provides a method to solve underground ventilation problems using simulation from problem identification to a proposed solution. Then, after implementation, the simulated solution is validated with measured results.

The following keywords were derived from the questions above.

Keywords: Deep-level mine, ventilation, simulation software, heat management, dust management, recirculation, environmental conditions, air-mixing.

The keywords and various combinations thereof were used to search *Science Direct*, *Google Scholar* and *EBSCOhost* to identify the relevant studies discussed in this section.

A. Current Developments and Challenges of Underground Mine Ventilation and Cooling Methods [55]

Author(s) : A. Kamyar, S. M. Aminossadati, C. Leonardi, and A. P. Sasmito.

Overview : The study focussed on mine refrigeration techniques to address the rise in energy costs and the requirements to provide a healthy work environment. Additionally, the study applied a monitoring and control technique to provide sufficient air temperatures and velocities while reducing the energy consumption of mine cooling equipment.

Outcomes : The study explained different mine refrigeration plants, including surface bulk air cooling, underground cooling techniques, mobile localised (spot) cooling, and ice cooling systems. Furthermore, a figure indicates which cooling techniques should be implemented based on the depth of a deep-level mine. Finally, the study proved that management's concerns regarding the performance and cost-effectiveness of these methods would be addressed by implementing energy efficiency and optimisation strategies.

Relevance : The study provided several techniques on how to reduce underground air temperatures and provided a guide for when each of the techniques should be implemented.

B. Improving the climatic conditions in development and production workings of hot underground mines by re-designing the auxiliary ventilation system: A case study [56]

Author(s) : P. Roghanchi and K. C. Kocsis

Overview : The study examined the auxiliary ventilation systems (AVS) used to ventilate a development end in a deep-level mine. Simulation models determined the climatic conditions at a development end with different AVS. The study evaluated the heat load and distribution in a development end. It aimed to identify the optimum AVS to provide adequate air temperatures and deliver the required air volumes to the workings. Furthermore, the skin temperatures of the workers at the primary return airway were compared with the maximum allowable skin temperatures at different work intensities.

Outcomes : A 0.5 m/s air velocity at development ends is insufficient to deliver fresh air during the mining cycle. Furthermore, spot cooling systems should be considered when mine workers perform heavy work. It was observed that an exhaust AVS reduced the face temperature as opposed to a forcing AVS.

Relevance : The study proved that simulation models can simulate the underground environment. It showed that the T_{wb} and T_{db} of development end return air reaches 32.5 °C and 39.0 °C during the mining cycle. This air must be expelled to a RAW as it is no longer safe for humans to work in air with T_{wb} and T_{db} exceeding 32.5 °C and 37.0 °C.

C. Controlled Recirculation in Deep South African Gold Mines [57]

Author(s) : M. Butterworth

Overview : The study focussed on the benefits and advantages of using controlled recirculation and solutions to address the shortcomings of the ventilation technique. Energy savings resulting from the use of controlled recirculation were examined using simulations.

Outcomes : Two simulation models were constructed: the start of full mining cycle and the end of full mining cycle, each with two scenarios with and without recirculation. It was noted that the primary fan flow decreased by 48%, resulting in a power reduction of 66%. The bulk air cooling capacity increased by 33% to account for the heat added by the recirculating fans. Applying the recirculation to the two models realised annual energy savings of USD 1M and USD 0.8M for the start and end of full mining cycle, respectively.

Relevance : The study examined controlled recirculation (air mixing) in deep-level mines with simulation. The study showed that additional cooling is required to execute controlled recirculation and compensate for the heat produced by recirculating fans.

D. Evaluating complex mine ventilation operational changes through simulations [58]

Author(s) : A. J. H. Nel, J. C. Vosloo, and M. J. Mathews

Overview : This study presents a scalable method for optimising mine ventilation networks through computer-aided simulations, improving service delivery and reducing operational energy costs. The method allows for improved decision-making, and the case study mining personnel adopted it as a new standard.

Outcomes : The study provided a scalable method to evaluate operational changes in a deep-level mine. The method was applied on a deep-level mine. Implementing the method improved service delivery at the mine and saved 13.32 GWh of energy.

Relevance : The study provided a method to evaluate mine ventilation systems using simulation.

E. Evaluating the impact of auxiliary fan practices on localised subsurface ventilation [16]

Author(s) : D. J. de Villiers, M. J. Mathews, P. Maré, M. Kleingeld, and D. Arndt

Overview : The study focussed on evaluating the efficiency of auxiliary fan systems of subsurface ventilation systems. The auxiliary fan system is a go-to ventilation management system as it is easy to install and is a quick solution. However, these systems' efficiency is rarely investigated and quantified. This study highlights that fan selection, ducting design, and continuous maintenance are vital to the efficacy of the ventilation network.

Outcomes : The investigation considered six different auxiliary fan systems from four South African deep-level gold mines, which yielded an overall efficiency of 5% with a 38% fan efficiency from the 33 fans. The reason for the poor fan efficiency is that the fans were not operating to their design conditions. The overall efficiency is due to ducting inefficiencies and nearby auxiliary systems affecting the systems in the vicinity.

Relevance : The study concluded that using auxiliary systems is not always the answer to ventilation network difficulties, as these systems can pose various problems when installed.

F. A GIS-based approach: Influence of the ventilation layout to the environmental conditions in an underground mine [59]

Author(s) : M. Bascompta, A. M. Castañón, L. Sanmiquel, and J. Oliva

Overview : The study recorded the environmental conditions of a mine for a year. The geographical information system (GIS) software *ArcGIS* was used to integrate graphics or drawing exchange format (DXF) files and recorded data. The model analysed air recirculation effects on environmental conditions over time.

Outcomes : The results show that the layout of a ventilation network remains a crucial parameter in the effectiveness of ventilation networks. Poorly designed networks will yield networks with increased recirculation and decreased environmental conditions.

Relevance : Software was used to analyse a ventilation network over time. The study showed that the ventilation network's effectiveness is very sensitive to its configuration. The study showed that mixing hot air with fresh air to use as intake air for downstream working areas is undesirable as this increases the air temperature.

G. Heat stress management in underground mines [60]

Author(s) : A. Ryan and D. S. Euler

Overview : The study proposed a heat management strategy to minimise personnel exposure to excessive heat in underground mines. The methodology included heat source identification, data collection and heat load calculations using ventilation modelling software.

Outcomes : The method proposed two options to mitigate heat stress in working areas. The first was calculating the cooling required to cool the available air to acceptable limits. The second was to limit the personnel's exposure time to excessive heat. The cost to add the cooling to the system was estimated, and the proposed cooling location was identified.

Relevance : The study aimed to improve the underground working conditions of the workers in deep-level mines. The study presented a heat management methodology to minimise the workers' exposure to heat stress and improve safety.

H. The use of 3D simulation system in mine ventilation management. [61]

Author(s) : W. Feng, F. Zhu, and H. Lv

Overview : The study focuses on reducing the system resistance in a deep-level mine using a simulation model of the ventilation network created with *Ventsim*, a 3D simulation software.

Outcomes : Using a simulation model, the increased restriction in the ventilation network was identified as a deformed airway resulting in a decreased cross-sectional area. A simulated solution reduced the system resistance and increased the available airflow. After satisfying results from the study, the ventilation management team used the simulation to manage other ventilation problems, such as contaminant spread and escape route planning.

Relevance : Ventilation optimisation was successfully done by identifying a problem in the ventilation network and creating a solution using simulation software. However, the solution was not physically implemented in the mine; thus, no actual results were recorded to verify the simulated results.

I. Evolution of the Henderson mine ventilation system [62]

Author(s) : K. Kolobe, C. Rutter, and N. Shea

Overview : The mine implemented ventilation on demand (VOD). Control systems are installed at raises, and ore passes are used to increase ventilation efficiency and reduce overall ventilation power.

Outcomes : Automated ventilation control systems aid the VOD practice adopted by the mine. However, the increased control infrastructure posed challenges from a maintenance aspect. Reduced control infrastructure reduces the maintenance effort for the ventilation system. The optimal control was realised to be one automated booster fan, whereas auxiliary fans control the airflow underground at key areas. Ventilation power costs were reduced by 50% since VOD was implemented.

Relevance : The ventilation network was improved by repurposing old ore passes and using them as alternative airways.

J. Research and application of controlled circulating ventilation in deep mining [63]

Author(s) : P. Wang, K. Zhu, Y. Zhou, J. Liu, and C. Shi

Overview : The study focussed on technology that will improve working conditions in deep-level mines by addressing typical ventilation problems experienced in deep-level mines, such as high temperatures and low air velocities.

Outcomes : This study elaborated on how recirculation of ventilation air can be a feasible solution for mines with insufficient air to ventilate the mine. The method discussed controlled circulation ventilation technology's social and economic benefits.

Relevance : The study aimed to use controlled circulation ventilation to improve ventilation conditions. Controlled circulation entails diluting the return air from working places to mix with fresh air, and sending it to the working place again while keeping the contamination and temperatures to acceptable standards.

Most studies used simulation software to optimise underground ventilation networks and discussed the ventilation techniques available to improve the underground environment of deep-level mines.

Summary of state of the art

Table 1-5 summarises the themes for each of the studies. The purpose of this summary is to point out the main points of each individual study.

Table 1-5: State of the art summary

No.	Source	Simulation	Optimisation	Contamination	Improvement techniques	Method
A	[55]	✗	✓	✓	✓	✓
B, J	[56], [63]	✗	✓	✓	✓	✗
C	[57]	✓	✓	✗	✓	✗
D, G, H	[58], [60], [61]	✓	✓	✗	✗	✓
E	[16]	✗	✗	✗	✓	✗
F	[59]	✓	✗	✓	✓	✗
I	[62]	✗	✓	✗	✓	✗

The studies stressed the importance of using simulation software to solve deep-level mine ventilation problems. Furthermore, most of the studies did not provide a method to solve ventilation problems in deep-level mines. The studies which did provide a method failed to either consider simulation, air contamination or were not implemented as ventilation improvement techniques.

1.6. Problem statement and objectives

Special care is given to airflow throughout the mine when no secondary cooling is available to mitigate increased air temperatures, particularly at working crosscuts with increased temperatures close to development ends. The return air of the development end is returned to the nearest working crosscut with through-ventilation.

Problem statement: The quality of fresh air flowing to the working crosscut deteriorates as it mixes with the return air from the development end. This contaminates the fresh air flowing to the working crosscut by increasing the temperatures and dust concentrations.

Need for the study: A method to reduce the air temperatures and dust concentrations of fresh intake air flowing to working crosscuts is required.

The study aims to develop a method to reduce the air temperatures and dust concentrations of fresh intake air flowing to working crosscuts.

The following objectives will serve as a measure to evaluate the method provided:

1. Develop a method to decrease localised temperatures and dust concentrations in deep-level mines by:
   1.1 Building a calibrated ventilation simulation model.
   1.2 Identifying techniques that were previously used to improve ventilation conditions.
   1.3 Providing a decision tree that will aid in choosing the optimal solution.
2. Apply the method provided to improve the ventilation conditions by:
   2.1 Decreasing the wet-bulb temperature of working crosscuts.
   2.2 Decreasing dust concentrations of working crosscuts.
   2.3 Maintaining the airflow requirements of working crosscuts as prescribed by the MHS Act.
3. Validate the simulation results and method after the optimal solution has been implemented by ensuring the MAE of the actual vs simulated results < 5%.

All the objectives mentioned must be achieved to validate the method provided in the study.

1.7. Summary

Underground ventilation networks are large networks spanning hundreds of kilometres. Ventilation systems are essential to remove the underground environment's heat, dust, and harmful gasses.

The T_{wb} and T_{db} limits are 32.5 °C and 37.0 °C, respectively, and quartz dust concentrations should be kept below the OEL of 0.1 mg/m^3 to prevent personnel from contracting silicosis. Some elements contributing to high temperatures are VRT, auto compression, and fissure water. At the same time, the factors contributing to dust creation underground are drilling, blasting, cleaning and the dry rock backfill process. High temperatures and dust creation are considered attributes of development ends in the mine. Thus, the air returning from development ends is hot and contains airborne dust particles that may harm humans when inhaled. Herein lies the problem statement that air returning from development ends mixes with the fresh air travelling to working crosscuts and deteriorates the quality of the fresh air stream.

The need exists to develop a method to mitigate the mixing of the return air from development ends with the fresh air stream travelling to working areas. A methodology is provided in the next chapter that will aim to satisfy the objectives stated in Section 1.6.

1.8. Research Methodology

The case study design methodology was followed while conducting this study. This methodology was deemed applicable as the following criteria is met within the mining environment:

- The research aim is to answer the "why" and "how" questions.
- When behavioural events cannot be controlled.
- When contemporary or current events are studied.

Figure 1-5 shows a generic case study method adapted from Teegavarapu [64].

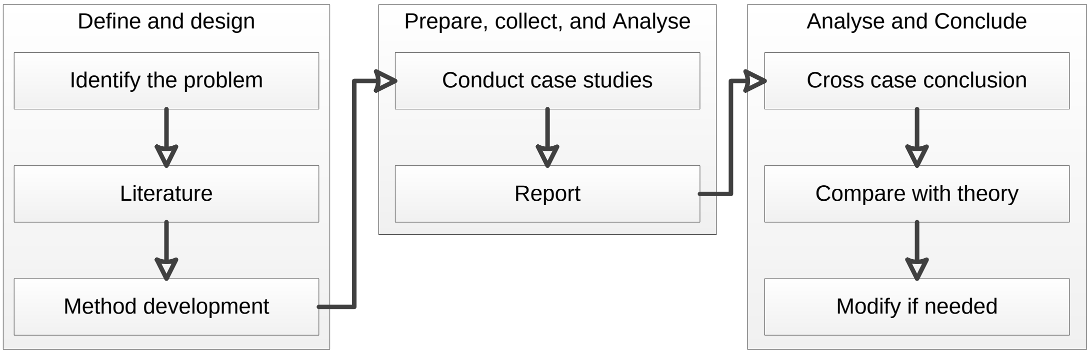


Figure 1-5: Case study method

The case study method shown in Figure 1-5 will serve as an outline for the dissertation. Each block, "Identify the problem" to "Modify if needed", are allocated to chapters discussed in the dissertation. Figure 1-6 shows how the cases study method was used to determine the dissertation structure.

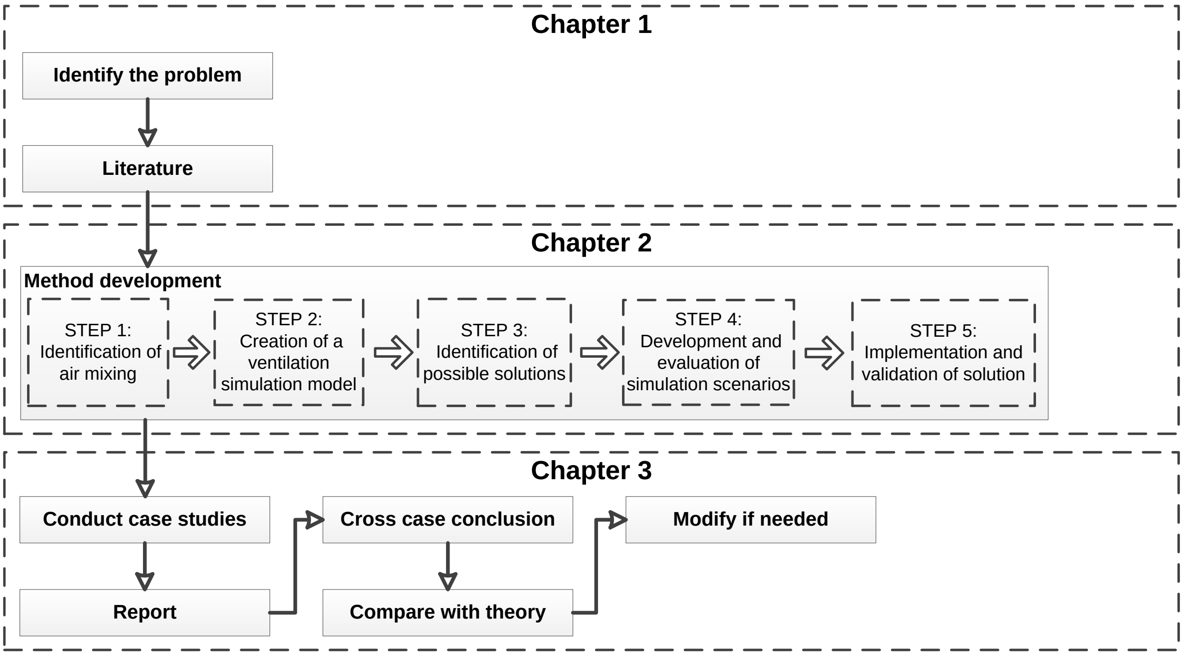


Figure 1-6: Case study method converted to the dissertation layout

The dissertation layout provided in Figure 1-6 is further discussed in the next section.

1.9. Dissertation layout

Chapter 1

This chapter provided background on deep-level mine ventilation systems and briefly discussed narrow reef mining practices and the need for simulation. Furthermore, the critical literature study conducted was summarised, from which the problem statement was derived and outlined, and the objectives for the study were listed.

Chapter 2

This chapter will describe a method that consists of five steps: identification of air mixing, creation of a ventilation simulation model, identification of possible solutions, development and evaluation of simulation scenarios, and implementation and validation of solution. The method will aim to achieve the objectives outlined in Section 1.6.

Chapter 3

This chapter will describe two case studies in which the method provided in Chapter 2 are applied to deep-level gold mines in South Africa, Mine A and Mine B. The air mixing was identified, a ventilation model was constructed, and possible solutions were identified using a decision diagram. The possible solutions were used as input to the simulation model, and scenarios were created to solve the problem stated in Chapter 1. The results will be discussed, as well as the validation of the method for both case studies.

Chapter 4

This chapter will conclude the study by discussing whether the study's objectives were satisfied and provide recommendations for future studies.

2. METHOD DEVELOPMENT

2.1. Preamble

Chapter 1 provided information about the underground environment of deep-level mines, including heat and dust, ventilation requirements, and a brief overview of the mining method. This section will describe a proposed method that consists of five steps: identification of air mixing, creation of a ventilation simulation model, identification of ventilation methods at development ends, development and evaluation of simulation scenarios, and implementation and validation of solution. The method will aim to achieve the objectives outlined in Section 1.6. Figure 2-1 outlines the proposed method discussed in this section. Each step within the method is discussed in the following sections.

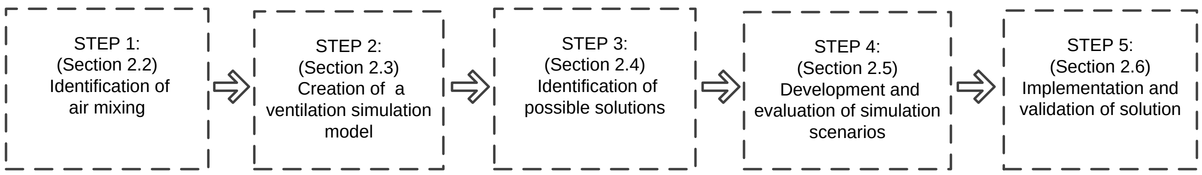


Figure 2-1: Overview of a new method to reduce the air temperatures and dust concentrations of fresh intake air.

Step 1 – Identification of air mixing (Section 2.2) will focus on gathering information about the ventilation network, such as infrastructure, layout, and measurement of the underground environment. Furthermore, the environmental conditions at development ends are investigated, specifically how the return air is discarded. Studies show that identifying the problem is the first step to solving it [60].

Step 2 – Creation of a ventilation simulation model (Section 2.3) will describe various software packages that simulate the ventilation network of underground mines and the construction of a ventilation simulation model. Studies by Ryan [60] and Euler, Feng *et al.* [61] stressed the importance of using a ventilation simulation model to solve ventilation problems in deep-level mines.

Step 3 – Identification of possible solutions (Section 2.4) will describe the ventilation methods for development ends and cooling methods for air in working crosscuts, and narrow down the number of possible solutions. This step is added here to provide the reader with possible solutions to prevent or mitigate the effects of air mixing at the intake of working areas.

Step 4 – Development and evaluation of simulation scenarios (Section 2.5) will describe the process when using the calibrated simulation model from Section 2.3 to develop and evaluate the simulation scenarios identified in Section 2.4.

Step 5 – Implementation and validation of solution (Section 2.6) describe the implementation and validation of the solution developed and chosen in Section 2.5.

2.2. Step 1: Identification of air mixing

Identifying air mixing in an underground ventilation network can only occur when the ventilation system is fully understood. Section 2.2.1 outlines the information required to understand a ventilation network. Section 2.2.2 focuses on the ventilation of development ends specifically and how the return air is discarded. Air mixing usually occurs when the return air from a development end meets the fresh intake air of the last working crosscut [19]. The return air flows to the last working crosscut because it is the only way the return air can escape to the RAW [3]. Figure 2-2 outlines the methodology and more detail regarding Step 1.

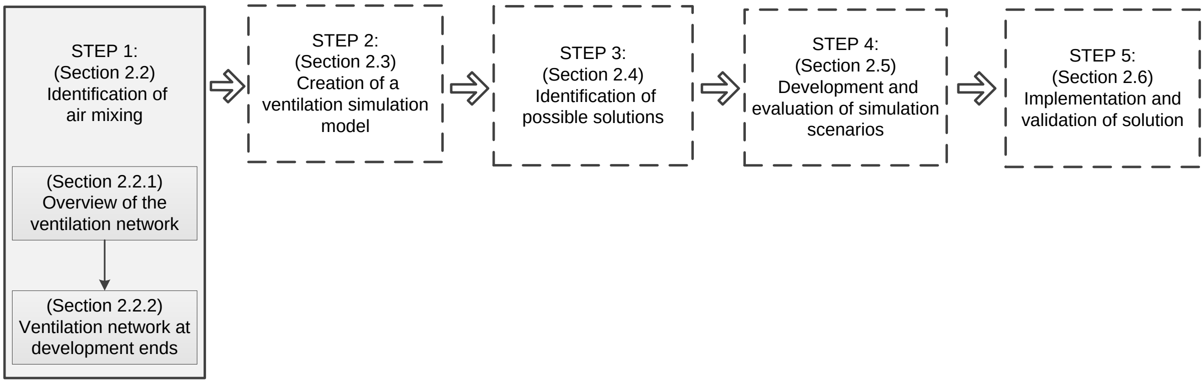


Figure 2-2: Step 1 of a new method to reduce the air temperatures and dust concentrations of fresh intake air.

2.2.1. Overview of the ventilation network

Underground mines' ventilation networks are complex systems with new, old, and current mining areas. Fully understanding the ventilation network can be complicated and time-consuming. However, gathering the mine's primary ventilation fans, secondary cooling infrastructure specification, drawing exchange format (DXF) files, volume surveys, engaging with site personnel, and conducting ventilation audits of the underground environment makes the process easier. The information mentioned above, will be discussed in this section.

A. Primary ventilation fans

A characteristic fan curve is a specification sheet produced for a fan, and it shows the performance and efficiency of the fan. The fan curve is digitised and imported into the simulation software to accurately simulate how the fan will perform in the mine ventilation network. Figure 2-3, shows an example of a characteristic fan curve.

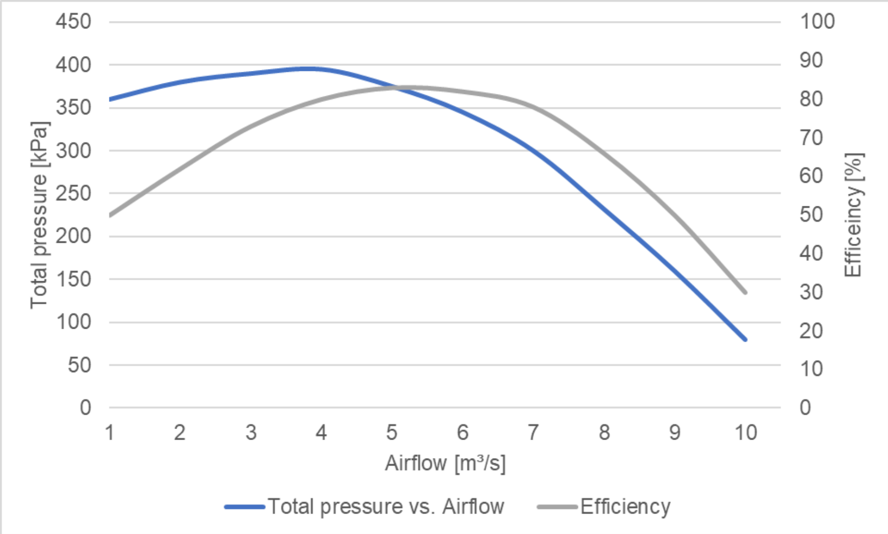


Figure 2-3: Example of a characteristic fan curve (Adapted from [65]*).*

A characteristic fan curve is the result when the total pressure of a fan is plotted against the airflow. The fan efficiency is also shown on the graph with regards to the airflow. The operating point of a fan is always along the curve and is influenced by the resistance of which the fan is connected to [65]. In this case, the resistance of a ventilation system is linked to the layout of the underground network.

B. Secondary cooling infrastructure

The typical secondary cooling infrastructure of mines are refrigeration plants which supplies chilled water to bulk air coolers (BAC) which in turn cools the air before being downcast to the working areas [66]. The chilled water is also sent underground to underground BAC's and to the working area to provide additional cooling [67].

The main parameters required are the in and output values of the water flow, -temperature, and air flow, -temperature, -relative humidity, -barometric pressure of the BAC. With these values the cooling duty of the BAC can be determined and incorporated into the ventilation simulation model. The BAC water temperature and flow are typically determined by the refrigeration plant on site. The airflow is determined by the fans installed, which fans cures need to be obtained, as part of the BAC. For surface BAC's the inlet air conditions are equal ambient air conditions. If the site is well instrumented the acquisition of this data should be easy.

C. Drawing exchange format (DXF) files

A DXF layout maps the underground environment with coordinates embedded in the file. A DXF file is created using AutoCAD software. The DXF file was created for use between different CAD software packages[3]. The AutoCAD software is provided with coordinates gathered by the mines survey department and a "map" of the underground environment is built. A DXF file is imported into the simulation software, this shows pathways to which the ventilation network is built in the virtual environment. The user can import multiple DFXs into a simulation software program, and the program will position the layouts correctly according to the embedded coordinates. A three-dimensional model of the mine is created with two or more layouts [68].

D. Volume surveys

The mine conducts quarterly volume surveys of the entire mine. The T_{wb} and T_{db} and volumetric airflow rates are recorded at level intakes and returns, crosscut intakes and development end intakes and returns. The size and location of fans, ducting, regulators, stoppings, doors, and brattices are also recorded.

E. Engage site personnel

The site personnel have extensive knowledge of the underground environment, so engaging with them is crucial. Personnel in the ventilation department know what the airflow direction and speed should be, as some personnel might have been part of the design of the ventilation network while, personnel in the mining department have knowledge of the rock movement in the stoping areas. This is important as rock movements can change the air flow quantities and in extreme cases reverse the air flow direction completely.

F. Visit underground areas and ventilation audits

Only studying the volume surveys and information from discussions with the site personnel is insufficient to understand the underground environment fully. It is therefore necessary to schedule underground site visits to all identified areas. After studying the DXF layouts together with the volume surveys, a ventilation audit plan can be created to ensure an effective underground visit. The visit can be executed effectively with a plan after studying the volume surveys and DXF layouts. During an underground visit, a ventilation audit can be conducted to maximise the information gathered during the time spent underground.

The barometric pressure is not recorded in a volume survey and is needed to calculate mass balances throughout the mine. A ventilation audit includes ventilation measurements, Twb and Tdb, volumetric air flow rate and barometric pressure that are recorded at specific locations

[3] https://www.adobe.com/africa/creativecloud/file-types/image/vector/dxf-file [Accessed on: 26 March 2024]

throughout the ventilation network [69]. Additional information is collected such as auxiliary fan locations and size; the duct leaks, sizes, and lengths; the presence and condition of ventilation doors, walls, seals and regulators, or airway restrictions. Ventilation measurements characterise the mine ventilation network and monitor the effects of installations and excavations on the ventilation network [54]. Regular ventilation audits are required to quantify underground heat sources' impact on the air stream's condition [70].

Figure 2-4 shows the plan view of a simplified schematic of underground mine levels. The schematic indicates the typical airflow with arrows, and the positions where manual measurements are taken during a ventilation audit are numbered from 1 to 8. The blue arrows indicate fresh intake air, whereas the orange arrows indicate air used to ventilate development ends and is considered hot return air.

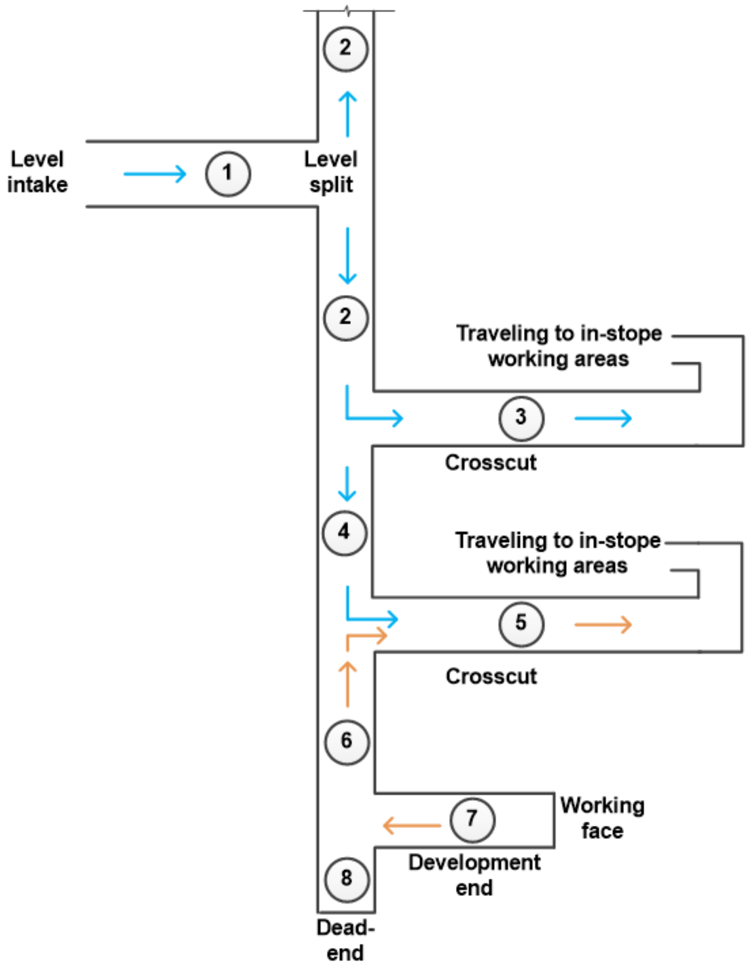


Figure 2-4: A simplified schematic of an underground mine level.

The T_{wb} and T_{db}, volumetric airflow rate, barometric pressure, and tunnel area will be measured at the locations indicated in Figure 2-4. Table 2-1 lists the numbered locations and the purpose of measuring at each location.

Table 2-1: Descriptions of the measurement positions

No.	Purpose for measurement
1	Determine the conditions of the fresh intake air available for use on the level.
2	Determine the conditions of the fresh intake air available for use for the half level.
3, 5	Determine the conditions of the fresh intake air available for use at the in-stope working areas.
4	Determine the conditions of the fresh intake air available for use for the rest of the half level after a crosscut.
6, 7	Determine the conditions of the hot return air coming from the development ends.
8	Determine the conditions of the air at the dead end.

The locations and their purpose listed in Table 2-1 can be applied to various locations throughout the mine.

Specialised equipment is used to conduct ventilation audits. The devices used to measure the required air properties are:

- Whirling hygrometer
- Davis vane anemometer
- Stopwatch
- Kestrel
- Laser distance meter
- Barometric pressure sensor

The whirling hygrometer measures the T_{wb} and T_{db} in degree Celsius (°C) [71]. The Davis vane anemometer consist of an impeller and a set of gears connected to a dial. The impeller rotates proportional to the air speed of the air stream the anemometer is exposed to. The gears translate the rotational motion of the impeller to a linear distance measurement. A stopwatch is used to record the amount of time the anemometer was exposed to the air stream. The minimum exposure time is 60 seconds [72]. The linear distance is divided by the exposure time to determine the air stream velocity in meters per second (m/s) [73]. Alternatively, the Kestrel, a digital device can be used to measure air velocity directly in meters per second (m/s) [74].

To measure the mass flow rate, a laser distance meter is used to measure the height and width of the tunnel in meters (m) [75]. The tunnel’s height and width determine the tunnel's cross-sectional area in square meters (m^2). The volumetric flow rate (m^3/s) can be determined using (Eq. 1-2. The barometric pressure sensor measures the barometric pressure of the air in (kPa) [76]. The mass flow rate is calculated using (Eq. 2-1, Euler's law for the conservation of mass [22].

$$\dot{m} = \rho \times Q \qquad \text{(Eq. 2-1)}$$

Here, $\dot{m}$ is the mass flow rate (kg/s), ρ is the fluid density (kg/m^3), and Q is the volumetric airflow (m^3/s).

Appendix A provides a detailed description of the equipment and how each device is operated.

The ventilation measurements for in-stope conditions are beyond the scope of this study and as a result, are not discussed. The ventilation measurements for in-stope conditions are not discussed. This study focuses on improving the conditions of the air stream flowing to the in-stope working areas. Therefore, the sources of the air stream must be evaluated to improve the air conditions without secondary cooling. The source refers to where the air comes from and what might influence it before arriving at its intended destination. The influences on the air in underground mines are discussed in Section 1.2.1. Air is used to ventilate the mine where any work is done; however, the ultimate destination is the working areas.

2.2.2. Ventilation network at development end areas

Section 2.2.1 gave an overview of the ventilation network in a typical deep-level mine. It concluded that the sources of the air streams flowing to the last working crosscut need to be investigated to reduce the air temperature of the last working crosscut. Figure 2-5 shows a simplified schematic of the ventilation network at a development end.

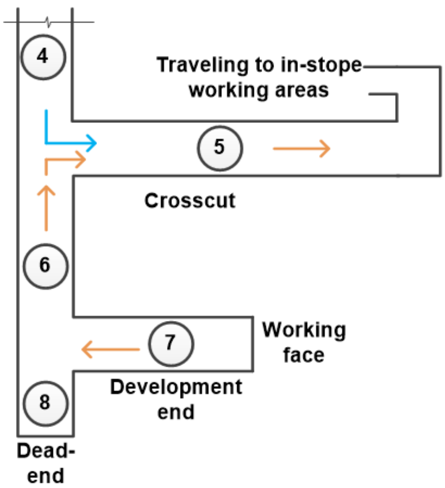


Figure 2-5: A simplified schematic of the ventilation network at a development end.

From Figure 2-5, the last working crosscut has two sources: points 4 and 6. Point 4 represents fresh intake air from surface and point 6 represents the air returning from development and dead ends.

After a review of the ventilation audit, the following information can be highlighted and will be used to construct a ventilation simulation model:

- The ventilation infrastructure
- The airflow directions
- Airflow quantities
- The T_{wb} and T_{db} at points 1-8 shown in Figure 2-4.

The ventilation infrastructure is essential to build the skeleton of the simulation model. The airflow directions are used to verify the simulation airflow direction. Thereafter, the temperature and airflow quantities are used to calibrate the simulation's temperature and airflow quantities.

2.3. Step 2: Creation of a ventilation simulation model

Step 1 explained how to identify unwanted air mixing within a mine. It focussed on gathering pertinent data to fully understand the mine, particularly the development ends. The next stage will be to build a ventilation model to solve the issue mentioned in Chapter 1, now that the necessary data and knowledge have been collected.

This section will provide information on various ventilation simulation software packages capable of simulating the ventilation network of underground mines. Step 2 provides the guidelines for constructing a ventilation simulation model.

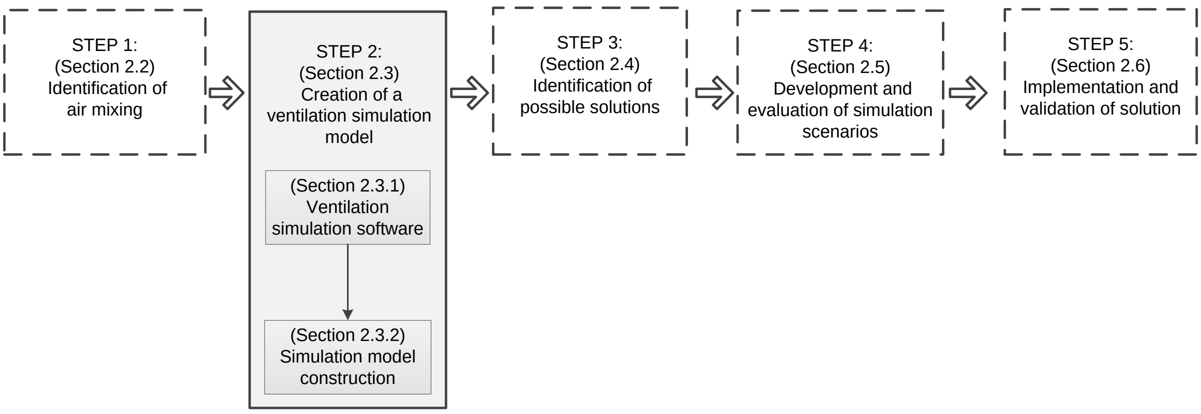


Figure 2-6: Step 2 of a method to reduce the air temperatures and dust concentrations of fresh intake air.

2.3.1. Ventilation simulation software

Ventilation simulation software packages, also called mine-ventilation software, enhance the ventilation management of deep-level mines [77]. *Ventsim*, *Vuma3D*, and *Process Toolbox* (PTB) are software packages that allow the user to create three-dimensional (3D) models of the mine's ventilation system [12], [78], [79]. The model developed in the software consists of a series of components that give the software the ability to simulate the thermodynamic parameters of the underground environment. Each software package has its distinguishing features, which will be discussed in this section.

The construction of a simulation model is similar across the different software packages and involves importing a DXF file into the simulation software to provide a map to follow when building the virtual underground network [50]. The components used to create the simulation model are preloaded with default values for various parameters, including, but not limited to, the rock density (kg/m^3), rock thermal conductivity (kW/m/°C), tunnel area (m^2), and VRT (°C). It is important to note that the default values, although sensible, must be challenged when building a simulation model to ensure that the simulation reflects the underground environment accurately [65]. The information required for the parameters can be requested from the mine's occupational hygiene or ventilation department. The overall accuracy of the simulation model can be improved significantly by conducting frequent underground visits.

A. Ventsim

Ventsim is a 3D simulation software package that models and simulates underground ventilation networks, considering the pressure, temperature, heat, etc. This simulation software is capable of advanced compressible flow modelling and automatically simulates natural ventilation and adjusts for density and fan curves. The temperatures and humidity due to rock and auto compression can be predicted. The thermodynamic environmental simulation incorporates heating and cooling systems, rock thermal input, diesel equipment and natural ventilation, and the complex ventilation network[4].

[4] https://ventsim.com/ventsim-design/ [Accessed on: 26 August 2021]

B. VUMA-3D

VUMA is a simulation software package that allows the user to design and simulate the ventilation systems of underground mines. The software can simulate the airflow through the mines, taking into account the thermodynamic properties of air[5].

C. Process Toolbox (PTB)

PTB is a transient one-dimensional Computational Fluid Dynamics (CFD) code solving thermo-hydraulic networks. For compressible flow PTB uses a compressible quasi-steady-state semi-implicit algorithm with a linearised pressure matrix. PTB models and simulates an underground mine ventilation network, considering the thermodynamic properties of air and rock. Additional capabilities include transient modelling, static modelling, and joint simulation between water, ventilation, and compressed air networks [54].

D. Selection of simulation software

The requirements for adequate ventilation optimisation are for the simulation software to have a thermo-hydraulic solver, calculate mass flow balances, and be capable of analysing compressible flow. Thermo-hydraulics comprise three main parts: thermodynamics, fluid mechanics, and heat transfer. Thus, a thermo-hydraulic solver can determine heat gains and losses, temperature distribution, and pressure differences [50]. Mass flow rate balances are critical to ensure all mass is conserved within the simulation. The fluid simulated in a ventilation simulation is air, a compressible fluid [80], and therefore the simulation software should be capable of analysing compressible flow. The software selection will depend on access to the software and the data required to construct the model and the available data.

2.3.2. Simulation model construction

The model can be created after selecting the most relevant simulation package. The construction of a simulation model can be categorised into two parts, namely a) construction of the skeleton and b) calibration and verification of the simulation model. These two parts are the focus of this section. PTB was selected as it satisfies the requirements discussed in the previous section (2.3.1D) and access to the software was provided by Mine Clever (Pty) Ltd. Selected software package was used to provide a more detailed method for the construction of the skeleton and calibration and verification of the simulation model.

[5] https://www.vuma3d.com/vuma-network/ [Accessed on: 26 August 2021]

A. Construction of the skeleton

The skeleton of the simulation model is a version where little regard is given to the temperature and airflow quantities throughout the model. Here the focus is to replicate the mine's underground infrastructure as accurately as possible. The information gathered in Section 2.2 on the size and location of fans, ducting, regulators, stoppings, doors, and brattices will be used to construct a simulation model of the actual mine.

Once the skeleton is built and the ventilation infrastructure is accounted for, the airflow direction and barometric pressure will be calculated. Barometric pressure throughout the simulation model is essential as pressure differences in a system induce airflow [81]. Engaging with the site personnel again is beneficial to ensure that the information and preliminary results on the model reflect the actual mine. A skeleton of a deep-level mine's ventilation simulation model is shown in Figure 2-7.

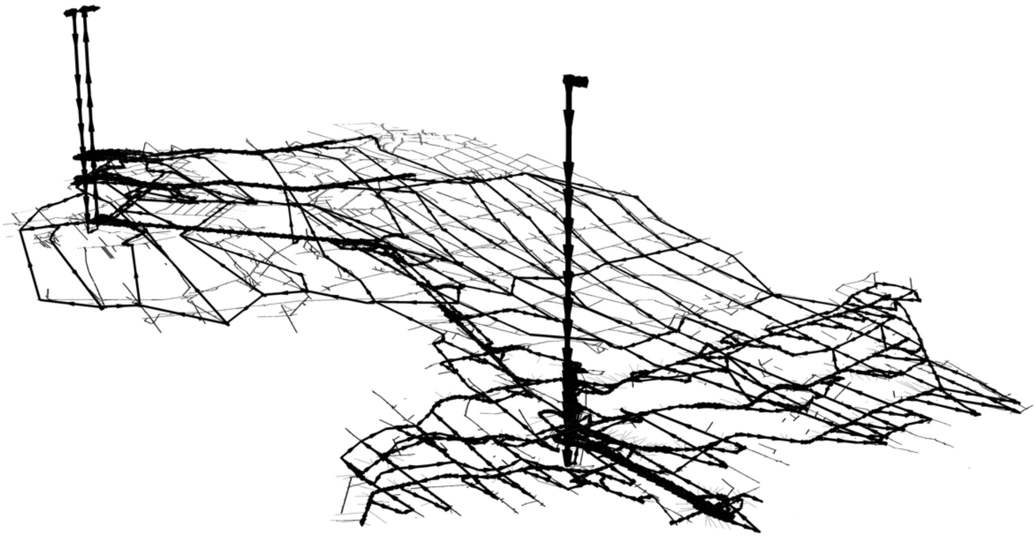


Figure 2-7: 3D view of a deep-level mine's skeleton ventilation simulation model.

After the skeleton is complete, the calibration of the simulation model can commence, where the airflow and temperatures will be calibrated.

B. Calibration and verification

The calibration process of a simulation model includes calculating the temperature, humidity and volumetric airflow throughout the mine. The T_{db} and T_{wb} will increase as the heat in the system increases. However, the T_{wb} is a function of the relative humidity and absolute air pressure. Relative humidity is the ratio of water vapour content compared to the maximum amount at a given T_{db}. The calibration is complete when the simulation values are within an error of 5% of the actual measurements [79]. The error between the actual and simulation results are determined using the mean absolute error. The mean absolute error (MAE) equation is shown in (Eq. 2-2) [82].

$$E_{\%} = \frac{1}{N}\sum_{n=1}^{N} \left| \frac{A_n - S_n}{A_n} \right| * 100 \qquad \textit{(Eq. 2-2)}$$

Where $E_{\%}$ is the MAE, N is the number of data entries, n is the specific data entry, A_n is the actual data entry and S_n is the simulated data entry.

Table 2-2 shows how the simulation and actual values will be compared. The MAE will be calculated for each of the parameters.

Table 2-2: Example for simulation vs actual comparison with MAE

Location	**Simulation**			**Actual**			**MAE**		
	T_{wb}	**T_{db}**	**ṁ**	**T_{wb}**	**T_{db}**	**ṁ**	**T_{wb}**	**T_{db}**	**ṁ**
	(°C)	**(°C)**	**(kg/s)**	**(°C)**	**(°C)**	**(kg/s)**	**%**	**%**	**%**
1									

Figure 2-8 shows a calibrated ventilation simulation model of a deep-level mine. Here a colour gradient is applied to the tunnels, where dark blue represents the coldest T_{wb} temperature @ 7.66 °C and red represents the hottest T_{wb} temperature @ 36.57 °C.

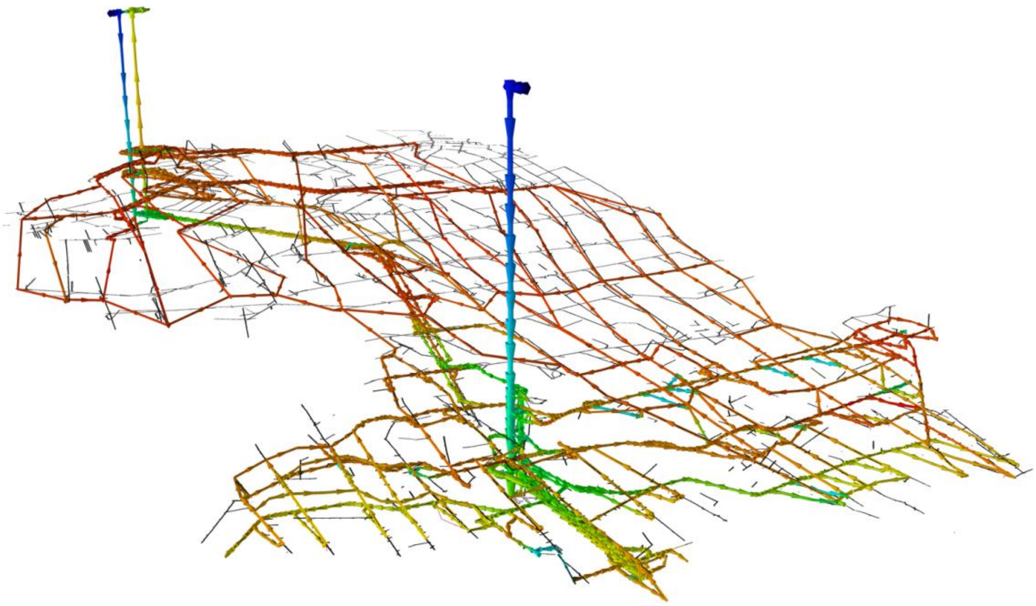


Figure 2-8: 3D view of a deep-level mine's calibrated ventilation simulation model.

The verification of a simulation is done after the calibration process is complete. A test can be conducted where parameters will be changed in the actual mine, and a ventilation audit records the changes. The changes are then implemented in the simulation model, and the results are compared with the ventilation audit measurements to verify the model's accuracy.

2.4. Step 3: Identification of possible solutions

This section will discuss step 3 of the method to reduce the air temperatures and dust concentrations of fresh intake air as shown in Figure 2-9.

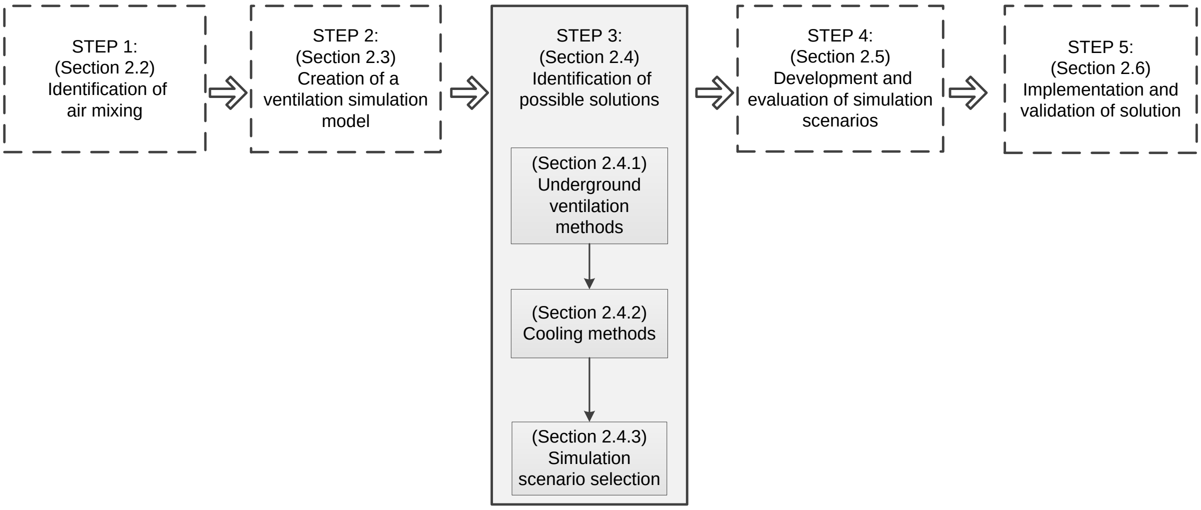


Figure 2-9: Step 3 of a method to reduce the air temperatures and dust concentrations of fresh intake air.

The various ventilation and cooling methods used to improve the environmental conditions at development ends in deep-level mines are also discussed. Thereafter, a tree diagram is discussed to help narrow down the methods and select the most applicable solutions.

Ventilation methods can typically be categorised into two types: dilution and displacement. At the same time, cooling methods can be classified as bulk cooling and spot cooling. Bulk cooling is when large amounts of air is cooled, usually on surface at the downcast shaft or underground at the intake of a level. Whereas spot cooling is typically used for localised cooling for example at development ends or working places.

2.4.1. Underground ventilation methods

Underground ventilation methods can be categorised as dilution and displacement, and these methods mitigate excess dust and increased air temperatures in deep-level mines. In addition to dilution and displacement, water sprays can decrease the dust concentration in deep-level mines [83].

Dilution ventilation reduces the concentration of a contaminant per unit of air, or increases airflow quantity [12], [57]. Introducing more fresh air into the working area reduces the concentration of dust per cubic meter of air in that working area [7]. Implementing ventilation dilution comes at high capital and operational expense as additional auxiliary ventilation systems must be acquired and installed with less than desired results [19].

Displacement ventilation is when the dust source and extraction to the return airway are downstream of the working area, completely removing the workers from the dust source [84]. The displacement ventilation method is favourable for dust control as it isolates the worker from the dust source and is more efficient, cost-effective and sustainable [3], [85].

Water sprays are systems where high-pressure nozzles with atomising abilities are fitted to the hanging wall of the tunnel [19]. The atomised water droplets are introduced into the airstream to capture the dust by increasing the particles' weight and dragging it down to settle on the footwall [86]. Water spray systems are adequate to control airborne dust. However, water suppression systems are more effective when the rock face is hit before the dust is generated [87].

The ventilation methods, auxiliary ventilation systems and brattice configurations can be categorised as either dilution or displacement ventilation methods, depending on the applications. Whereas displacement ventilation methods include raise boreholes and unequipped ore passes. Auxiliary ventilation systems, brattice configurations, Raise boreholes and unequipped ore passes, will be discussed in this section.

A. Auxiliary ventilation systems (AVS)

Primary fans supply the mine with fresh intake air but cannot provide adequate ventilation to all mine areas. Areas far away from the fans need additional infrastructure to ensure adequate quality and quantity of air. AVS provide the proper ventilation to dead-end working areas where development is in progress [1]. However, the hot air or any pollutants removed from the working face are carried along the return airway, which deteriorates the air quality or the downstream working places. This section describes the components and configurations of AVS and system requirements to achieve adequate ventilation in development ends.

a) Force system

The force system comprises a fan inducing a positive pressure in the ducting, forcing the air from the main airway, and discharging directly onto the development end's working face. The advantages of this system are that flexible ducting can be used, and any leakages along the column help to reduce the contamination in the air returning from the development end. The disadvantages are that any pollutants removed from the working face are carried along the return airway, which deteriorates the air quality. Also, increased velocities from the column discharge may result in dust problems at the working face [7]. Figure 2-10 depicts a schematic representation of a force system.

Exhaust system

The exhaust system includes a fan inducing a negative pressure in the ducting, removing the air from the development end's working face and discharging the air into the main airway. The advantages of this system are that any contaminants are immediately removed from the airway through the ducting, allowing fresh air to travel along the airway leading to the working face. Also, airborne pollutants can easily be removed by installing dust filters in the ducting.

The disadvantages are that the air travelling to the working face can pick up heat from the surrounding rock and other sources. Most importantly, the intake of the column needs to maintain a close distance to the face to avoid unwanted recirculation at the working face. Also, more expensive rigid, or non-collapsible ducting is required, as flexible ducting will collapse due to the negative pressure in the ducting [7]. Figure 2-11 depicts a schematic representation of an exhaust system [3].

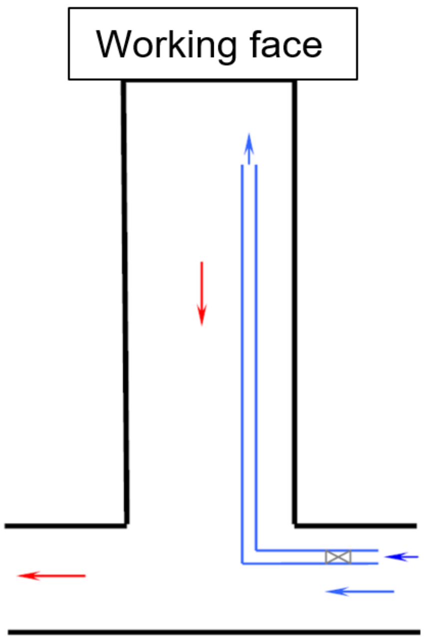


Figure 2-10: Force system.

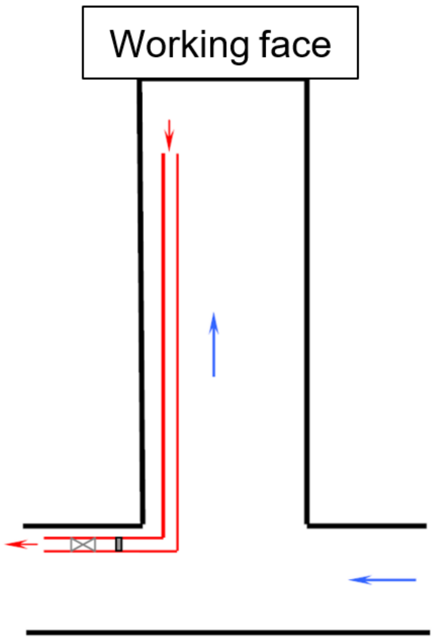


Figure 2-11: Exhaust system.

Overlap system

The overlap system, called the push-pull system, combines the force and exhaust systems. Figure 2-12 illustrates the force overlap system where the force system acts as the primary system, with the exhaust system as the secondary. Figure 2-13 shows the exhaust overlap system where the exhaust system is the primary system, and the force system is secondary [6].

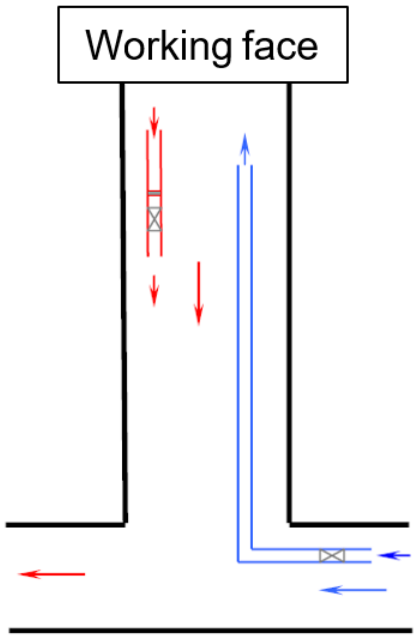


Figure 2-12: The force system with an exhaust system overlap.

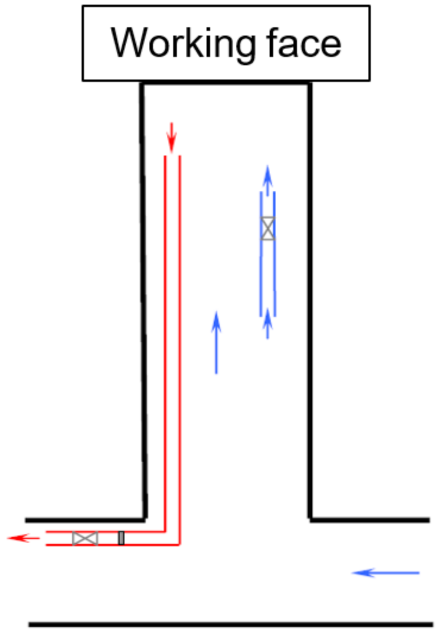


Figure 2-13: The exhaust system with a force system overlap.

B. Brattice configurations

Brattices are used when ventilation controls are required, with a slight pressure difference over the brattice and when large machinery is used in the area [13]. Placing a brattice along the tunnel creates two air paths and prevents the hot return air from mixing with the fresh intake air. A disadvantage of this configuration in mines is that locomotives and machinery like LHD's and haul trucks travel along the tunnel, leaving little room to install a brattice. Installing a brattice perpendicular to the airflow is very useful in applications where a slight pressure difference is observed, and trucks need to access the area.

Figure 2-14 and Figure 2-15 illustrate the positive effect of brattices on an underground ventilation network. Figure 2-14 shows the airflow path when no brattices are installed. The air will take the path of least resistance, which in this case, is the shortest route from the intake area to point five. There might be unwanted air also finding it easier to flow from other working areas, point four, to the return airway, point five. If the objective was to provide air to point two, no brattices would have to be installed. However, ventilation control systems are needed if the goal is to provide airflow to point 1.

Figure 2-15 shows the path of the airflow when brattices are installed to achieve the goal of providing point one with air. Brattices installed at points two and three prevent the air from taking a shortcut to point five. Now the path of least resistance is the long way around, as the brattices create a high resistance area.

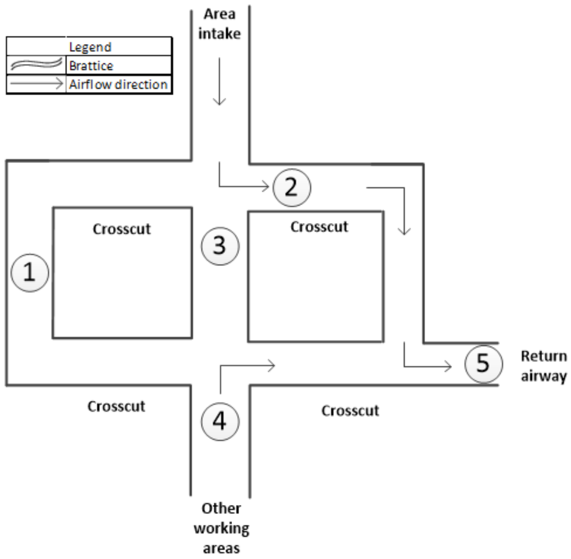


Figure 2-14: Underground schematic without brattices installed.

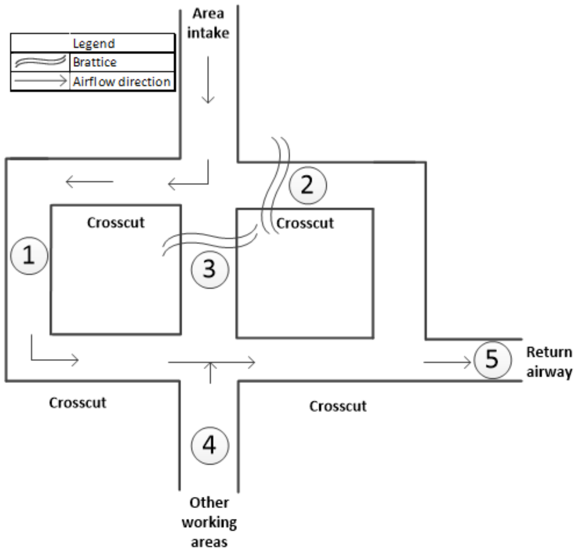


Figure 2-15: Underground schematic with brattices installed.

The brattices in Figure 2-15 can be permanent or non-permanent installations that allow vehicle travel. The parallel brattice configuration is mainly used in shafts to create two separate airways for air to downcast and upcast in the same excavation.

C. Raise borehole (RBH)

An RBH is created to serve as additional airways, which increases airflow and reduces the resistance in the mine. Implementing an RBH underground can improve the ventilation conditions of that area [87]. The ventilation conditions are improved through increased airflow, which could dilute hot return air through controlled recirculation or discard hot return air filled with airborne dust particles. An RBH large enough to fit a human should not be used for travelling up or down, and entering such an excavation can be fatal.

Figure 2-16 shows the airflow through a typical ventilation network. The blue line represents fresh air flow, down the downcast shaft to level C. This continues into the working area, leading to level B, represented by the green line. At the same time, the red line represents the hot return air discarded from level B to level A. In contrast, the black lines represent closed-off areas. Seismic events can cause the opening between levels A and B to collapse, requiring alternative airways [88].

Figure 2-17 depicts a proposed location for an RBH if the airway from level B to level A collapsed.

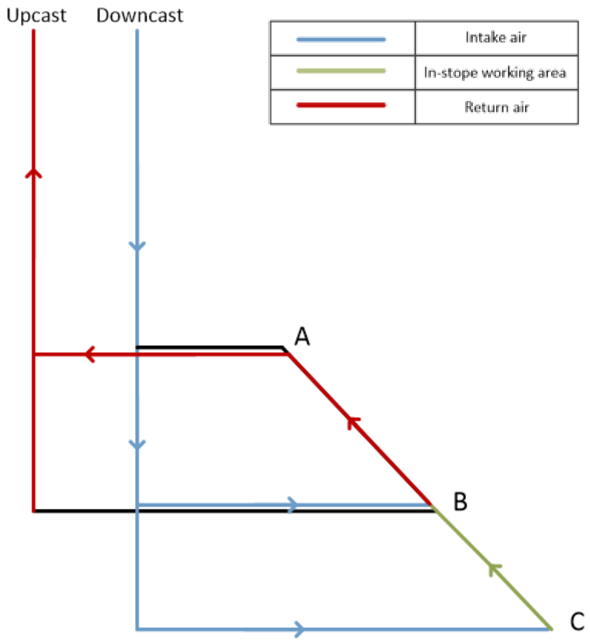


Figure 2-16: Schematic without an RBH.

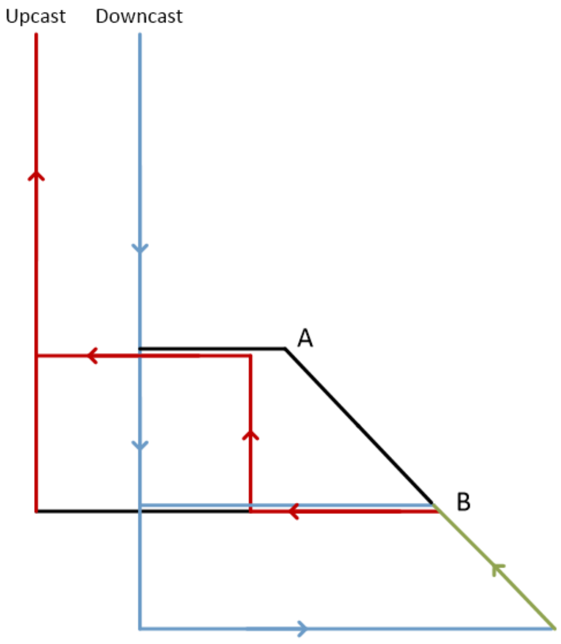


Figure 2-17: Schematic with an RBH.

The size of the RBH can be specified to accommodate the air required and reduce the system resistance in that area. The air is successfully rerouted by installing the RBH from levels A to B.

D. Unequipped ore pass

Ore passes are used to transport and temporarily store ore between levels. A box front is installed at the bottom of the ore pass to control the ore flow. An unequipped ore pass is no different from an RBH. Therefore, rather than creating an RBH, the unequipped ore passes can be used as temporary return airways [62].

Consider a scenario with a similar layout to, Figure 2-16 where an alternative route for return air is required. However, a crosscut still in development cannot yet use the raise to return air to the RAW. An ore pass is used as an alternative route instead of an RBH. Figure 2-18 represents an underground environment where an ore pass returns hot air from the development end. Without the ore pass to route the hot return air to the RAW, an AVS must be used to ventilate the development end, as discussed in Section 2.4.1.

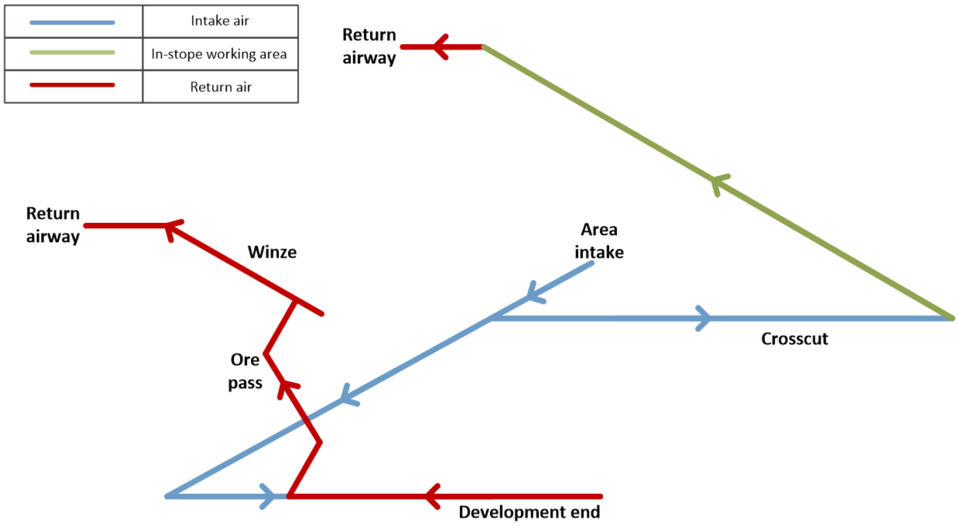


Figure 2-18: Illustration of the use of ore passes as ventilation airways.

It is important to note that an ore pass can only route hot return air to the RAW when the centre gully is developed downward (winze) to the level with the development end. Table 2-3 provides a comment on how this section has satisfied objective 1.2.

Table 2-3: Section 2.4.1 satisfies objective 1.2

OBJ.	Description	Comment
1.2	Identify techniques that were previously used to improve ventilation conditions.	Section 2.4.1 identified ventilation methods used in industry to improve ventilation conditions.

2.4.2. Cooling methods

A. Bulk air cooler (BAC)

A bulk air cooler (BAC) is typically a large installation situated on the surface, close to the shaft underground, or strategically, where permanent installation is feasible. This type of installation is, in essence, a large heat exchanger used to cool the air going to the working area, with air-to-water being the most common configuration. The water is cooled through refrigeration plants, and introducing the water into the airstream removes heat from the air. The water can be introduced with tubes (indirect contact heat exchanger) or sprayed into the airstream (direct contact heat exchanger) [36].

Figure 2-19 shows a simplified cross-sectional sketch of a direct contact water-to-air BAC. The airflow direction through the BAC is indicated with arrows, and the air temperature change from warm to cold is indicated with a red arrow that turns orange and then blue. The intake fan forces air into the spray chamber. The dashed blue lines indicate cold water sprayed into the spray chamber to allow heat exchange between the water and air.

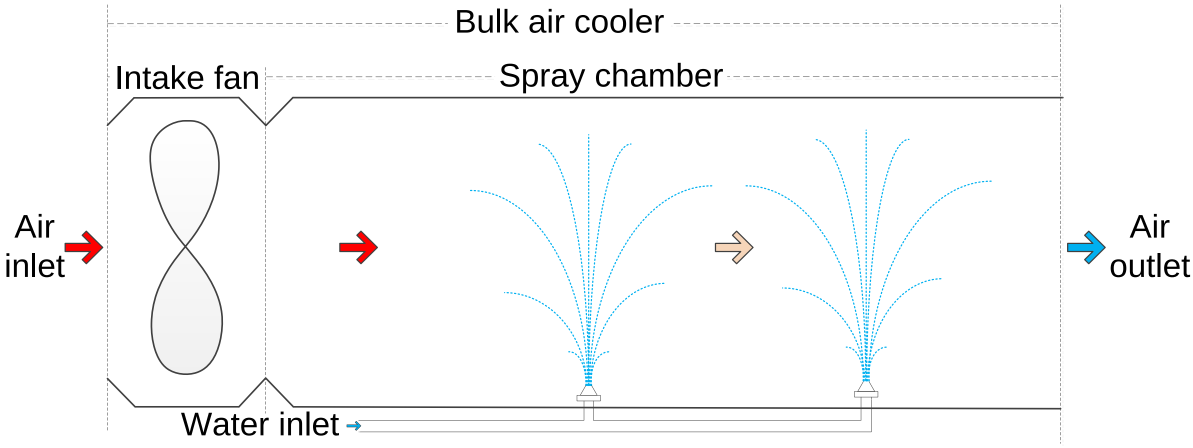


Figure 2-19: Simplified schematic of a direct contact water-to-air BAC.

B. Spot cooling

Mobile cooling unit (MCU)

An MCU is an indirect contact water-to-air heat exchanger. Air is forced over finned tubes to transfer the heat from the air to the water, and the cold water is supplied from the chilled water supply line. The hot water is dumped on the footwall and taken out of the mine by the dewatering system [35]. MCU's are installed in areas to decrease the ventilation air temperature. MCU's can only be installed where chilled water is available.

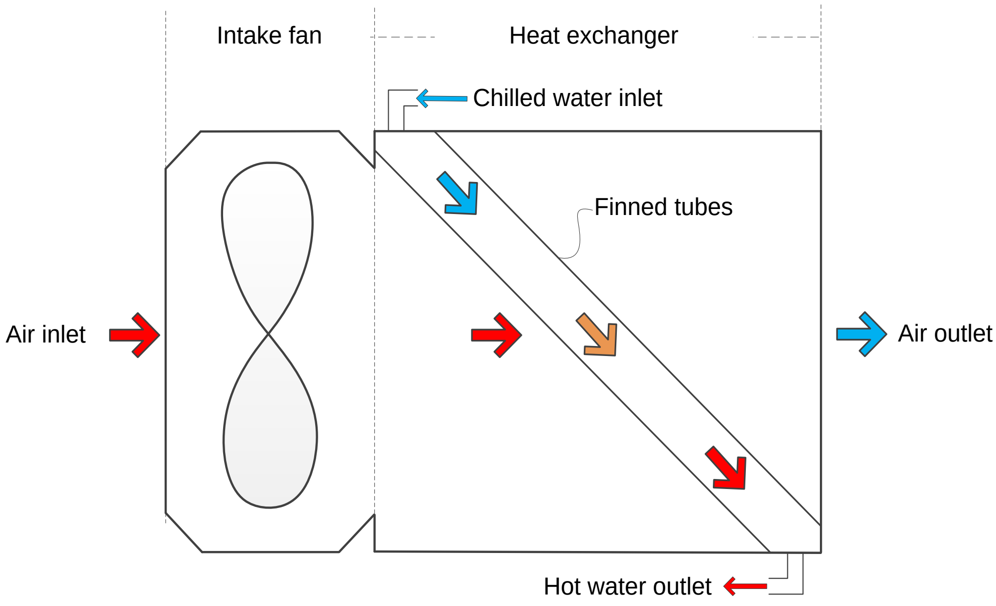


Figure 2-20: Simplified schematic of an MCU.

Air cooling unit (ACU)

Air cooling units (ACU) are mobile units with an onboard refrigeration plant. The ACU cools hot water using the onboard refrigeration plant and pumps the water through finned tubes placed in the airstream. An airstream is created by encapsulating the finned tube unit in a box with an inlet and outlet. A fan is installed on the box outlet to pull air through the box and over the finned tubes [35]. ACU's are installed in areas to decrease the ventilation air temperature. The ACU does not require chilled water, it can operate with inlet water temperature up to 32 °C[6].

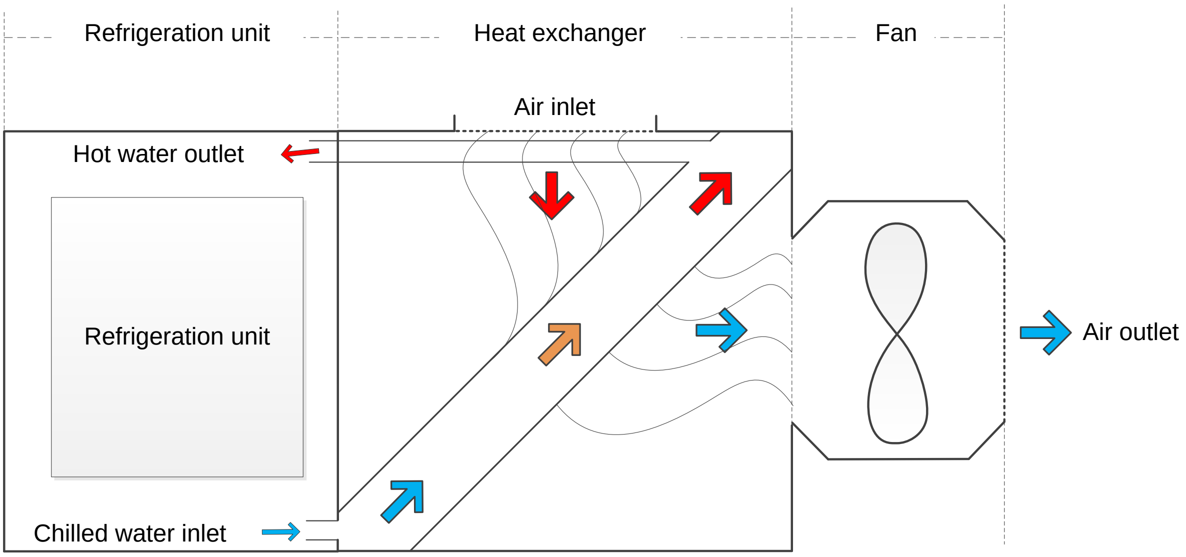


Figure 2-21: Simple schematic of an ACU.

The MCU or ACU can be used to cool air in a working place. However, neither tool is used to reduce airbourne dust. Furthermore, it is important to note that the MCU requires chilled water, whereas the ACU does not[7]. Table 2-4 comments on how this section has satisfied objective 1.2.

Table 2-4: Section 2.4.2 satisfies objective 1.2

OBJ.	Description	Comment
1.2	Identify techniques that were previously used to improve ventilation conditions.	Section 2.4.2 identified cooling methods used in industry to improve ventilation conditions.

[6] https://www.mtechindustrial.com/products/ [Accessed: 2024-09-20]
[7] https://www.crown.co.za/reader/modernmining/2014/February/files/assets/basic-html/page55.html [Accessed: 2024-09-05]

2.4.3. Selection shortlist (simulation scenario selection)

In Sections 2.4.1 and 2.4.2, many solutions have been identified to mitigate high temperatures or reduce dust concentrations in deep-level mines. Developing a scenario for all the solutions would be time-consuming and waste time and money. This section aims to reduce the time spent developing scenarios using simulation by narrowing down the possible solutions with a decision diagram.

The decision diagram is shown in Figure 2-22 can be used to narrow down possible solutions. The decision diagram acts as a guide, and answering the questions asked in the diagram will highlight possible solutions to the problem.

The decision diagram starts with all the ventilation and cooling methods identified in Sections 2.4.1 and 2.4.2 as possible solutions for the ventilation problem. The decision diagram has several questions which guide the reader to find the optimal solution for their ventilation problem.

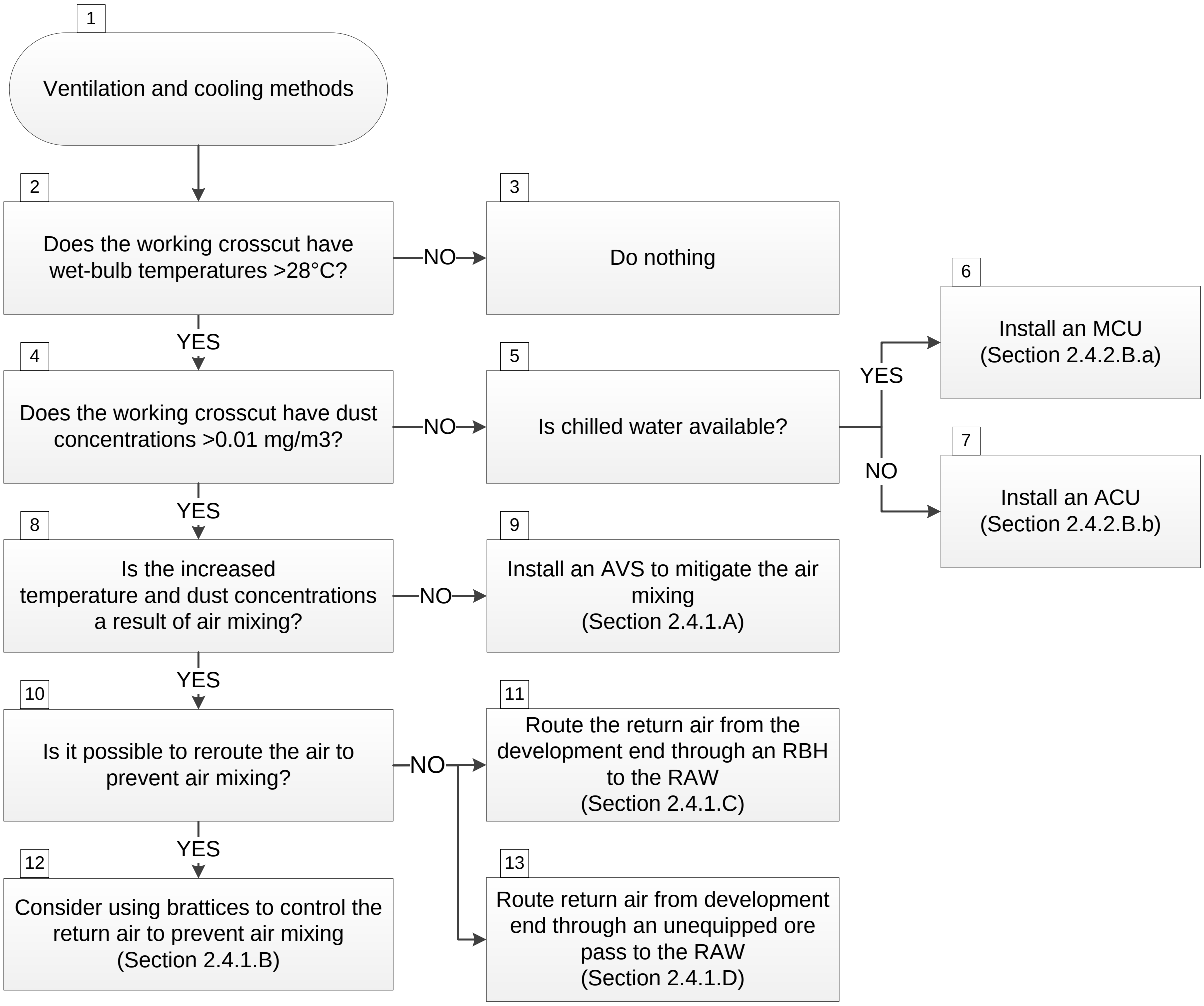


Figure 2-22: Decision diagram to choose possible solutions for any given case study.

The T_{wb} upper-limit mentioned in the second bubble is derived from Lambrechts [89]. The legal limit of T_{wb} is 32.5 °C as mentioned in Section 1.2.2, however some mines have a “stop and fix” T_{wb} limit of 31.5 °C. This means that when the $T_{wb} \geq 31.5$ °C in a work area the workers should stop work and fix the ventilation controls to ensure a $T_{wb} < 31.5$ °C. Lambrechts noted that the average heat pick-up in air from intake to exit of a stope is 220 kW. Using Lambrechts' calculations and assumptions, it was calculated that for an exit T_{wb} <31.5 °C, an inlet T_{wb} of 28 °C is required.

It is important to have clear objectives when using the decision diagram. Keep the mine standards and the abilities of the simulation software package in mind when deciding which solution to develop with simulation. The decision tree can yield more than one possible solution, and it is therefore important to develop a simulation scenario for all the possible solutions selected by the decision tree. Table 2-5 comments on how this section has satisfied objective 1.3.

Table 2-5: Section 2.4.3 satisfies objective 1.3

OBJ.	Description	Comment
1.3	Provide a decision diagram that will aid in choosing the optimal solution.	Section 2.4.3 provided a decision diagram, and in Section 3.2.4, the decision diagram was used to identify two solutions.

2.5. Step 4: Development and evaluation of simulation scenarios

The previous section discussed the steps required to select the preferred ventilation or cooling method (to address the specific problem statement in Section 1.5). This section will provide a process to follow in the “Development and evaluation of simulation scenarios” step of the solution. Figure 2-23 shows the categories of scenario development, scenario result evaluation, and scenario selection, which will be discussed in further detail.

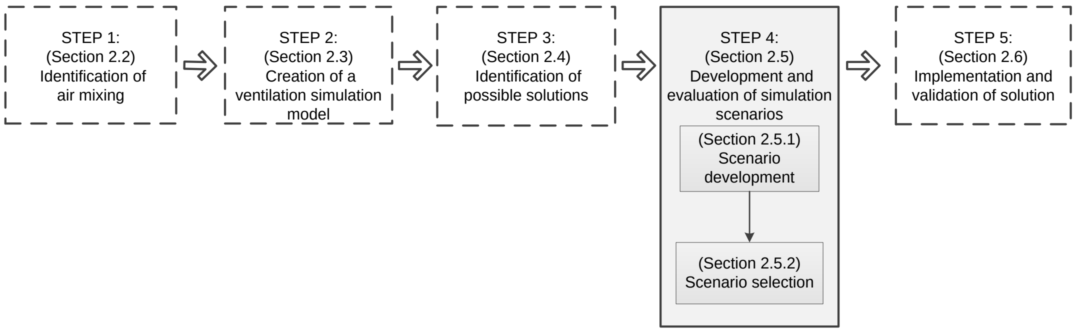


Figure 2-23: Step 4 of a method to reduce the air temperatures and dust concentrations of fresh intake air.

2.5.1. Scenario development

In Section 2.3.2, a ventilation simulation model was built, calibrated and verified. Section 2.4.3 delivered a short list of possible solutions. The calibrated ventilation simulation model can now be used to virtually implement the possible solutions selected in Section 2.4.3. The mine usually has standards to which they comply. There are standards for the development (e.g., horizontal excavations, AVS, and raise boreholes.) and stoping (e.g., ore pass dimensions, panel dimensions, and in-stope ventilation methods).

A similar approach to the simulation model construction described in Section 2.3.2 can be followed when developing the scenarios for the simulation model. First, the skeleton will be built, and the desired airflow direction in the area will be calculated. Change the layout of the scenario if the desired airflow direction is not achieved in the first iteration. Repeat the process until the desired results are obtained. Secondly, attention can be given to the airflow quantity and temperature after the airflow direction is established.

It is vital to keep in mind the mine standards when developing the scenarios with the simulation model. Adhering to the standards will ensure that the implementation of the scenario is possible, and it will help to convince the mine management of the soundness of the scenario.

2.5.2. Solution selection

A decision diagram was provided in Section 2.4.3, as a guide to narrow down the possible solutions for ventilation problems. The possible solutions can be developed using the simulation model calibrated and verified in Section 2.3.2. In this section, the evaluation of the simulation results obtained for the simulation will be discussed to choose one final solution to be implemented to address the problem stated in Section 1.6. All the options shortlisted in the previous step (Section 2.4.3) will be evaluated against certain key performance indicators (KPIs) to find the most viable and appropriate solution.

The primary KPIs are used as these parameters are legal requirements, as discussed in Section 1.2.2, and the secondary KPIs are chosen as they represent the financial aspect of the solution. There are legal requirements regarding other parameters, such as gasses and nuclear radiation. These parameters were not included in this study as the study focuses on the reduction of air temperatures and dust concentrations. Table 2-6 lists the primary and secondary KPIs. The primary KPIs determine if the proposed solutions satisfy the case study’s problem, whereas the secondary KPIs compare the different scenarios.

Table 2-6: Description and weight of the KPIs

KPI		Weight	Description
Primary	Temperature	2	Decrease temperatures in the last working crosscut.
	Dust	2	Decrease dust concentration in the last working crosscut.
	Airflow	2	Maintain airflow requirements of working crosscuts.
Secondary	Additional development time	1	Construction time.
	Cost	1	Cost of implementation.
	Sustainability & Repeatability	1	How long will the solution be feasible? & Can the solution be implemented again?

Table 2-7 shows the evaluation matrix for the results of two scenarios. A scenario will score a one or zero depending on whether the criteria are met or not, as described in Table 2-6. The temperature, dust and airflow have more weight than the other KPIs as the health and safety of workers carry higher importance than the financial feasibility of a project. The total column for each scenario is the product of the weight and score of each KPI. Additional scenarios can be added to the right of the matrix.

Table 2-7: Scenario evaluation matrix

KPI		Weight	Scenario 1		Scenario 2	
			Score	Total	Score	Total
Primary	Temperature	2				
	Dust	2				
	Airflow	2				
Secondary	Additional development time	1				
	Cost	1				
	Sustainability & Repeatability	1				
Total						

For example, if Scenario 1 satisfies all the KPIs except "Temperature" and Scenario 2 only satisfies the Primary KPI, then Scenario 2 will be chosen over Scenario 1. Also, if both Scenarios 1 and 2 meet the Primary KPI, the Secondary KPIs will be the deciding factor.

2.6. Step 5: Implementation and validation of solution

In Section 2.5.1, one or more solutions were developed using simulation. In Section 2.5.2, the simulation scenarios were evaluated using an evaluation matrix where temperature, dust and airflow were the primary KPIs in deciding which scenario would become the solution to be implemented. Figure 2-24 shows that "Implementation and validation of solution" is the last step of the 5 steps in the solution process.

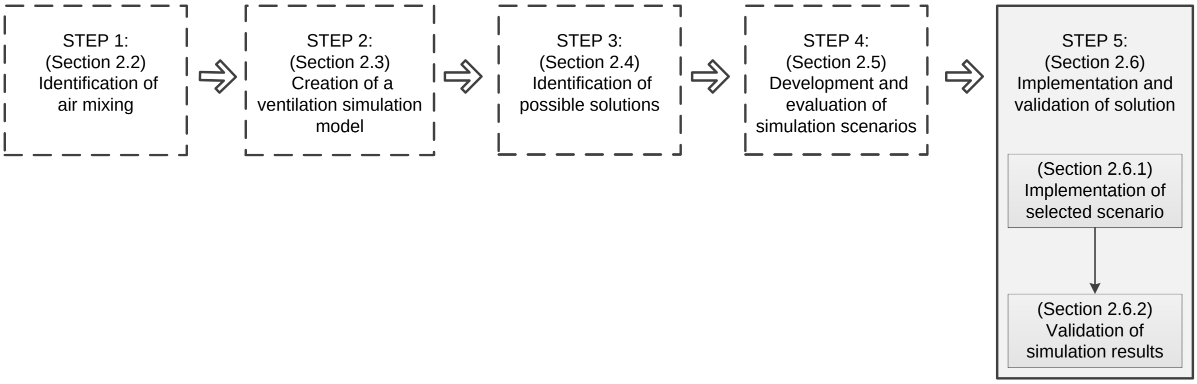


Figure 2-24: Step 5 of a method to reduce the air temperatures and dust concentrations of fresh intake air.

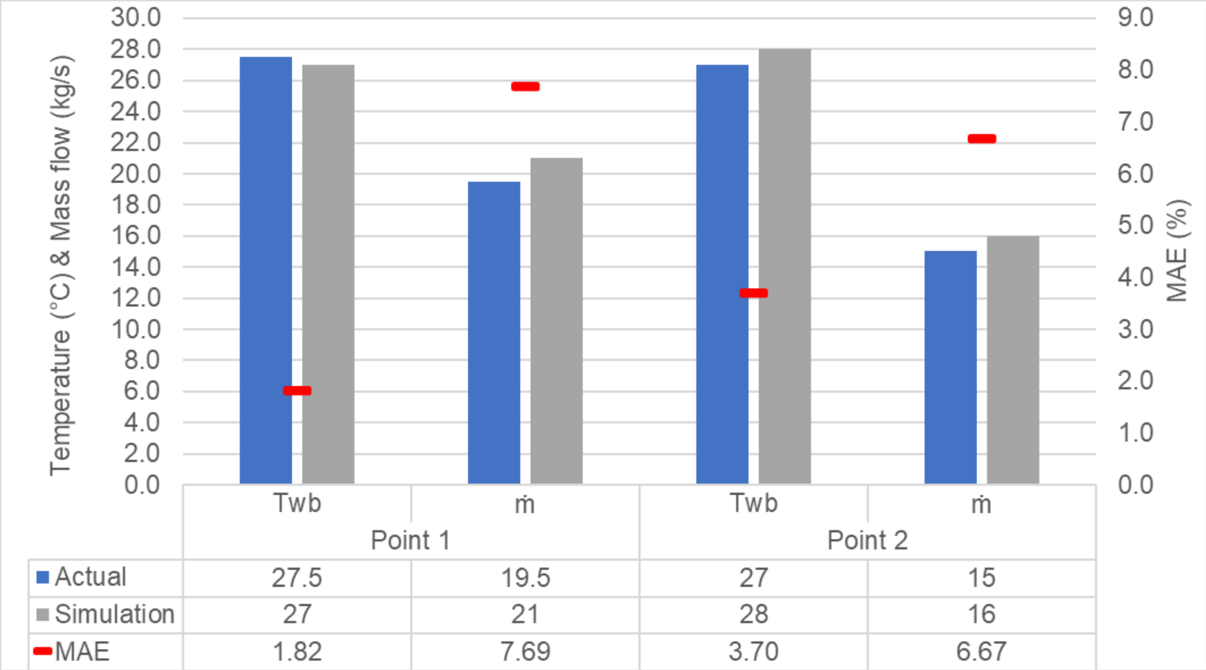
2.6.1. Implementation

The scenario chosen with the evaluation matrix in Section 2.5.2 can be implemented in the actual mine. The mine planners will schedule the implementation timeline, and regular meetings with mine personnel will help keep to the schedule and ensure the implementation is done correctly. After implementation, the results must be verified.

2.6.2. Validation

The simulation results are compared with actual measurements recorded after the final solution's implementation (actual). The difference, if any, is recorded and will either validate or refute the method developed in this study. Furthermore, the measurement results before and after implementation are compared to determine if the method satisfied Objectives 2.1, 2.2, and 2.3.

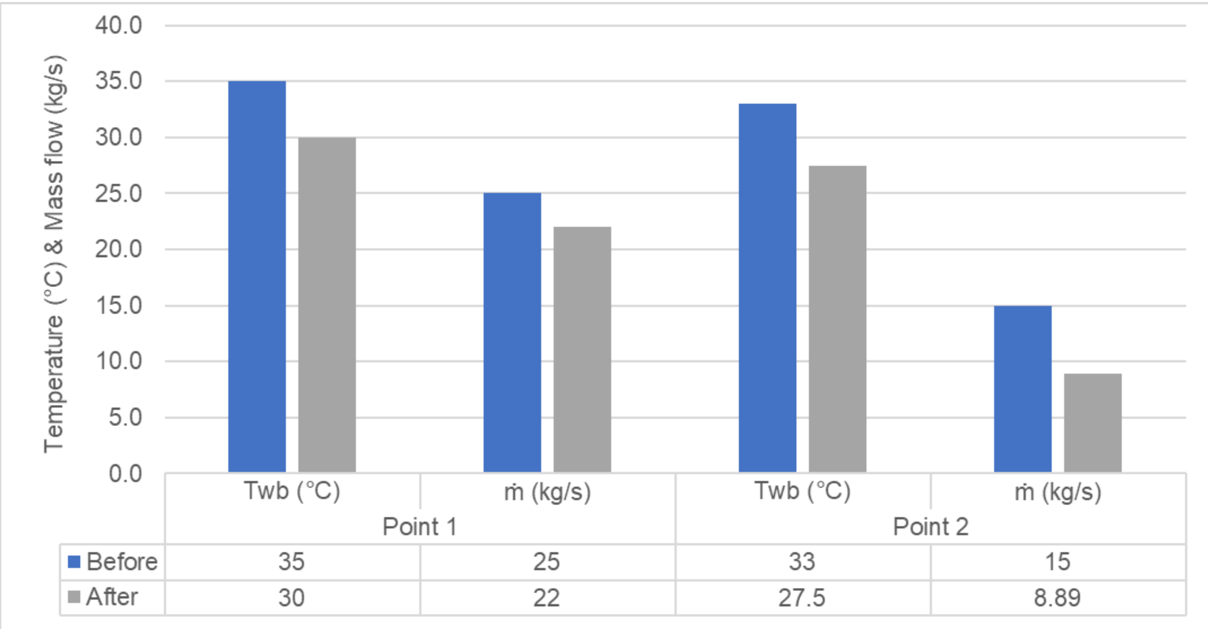
Figure 2-25 shows an example of a graph comparing the simulated and actual results, and the MAE of the parameters between the simulated and actual results.



	Point 1 Twb	Point 1 ṁ	Point 2 Twb	Point 2 ṁ
Actual	27.5	19.5	27	15
Simulation	27	21	28	16
MAE	1.82	7.69	3.70	6.67

Figure 2-25: Example graph of the simulated vs actual results comparison.

Figure 2-26 shows an example of a graph comparing the actual results before and after implementation.



	Point 1 Twb (°C)	Point 1 ṁ (kg/s)	Point 2 Twb (°C)	Point 2 ṁ (kg/s)
Before	35	25	33	15
After	30	22	27.5	8.89

Figure 2-26: Example of actual results before and after implementation.

From the graph, the difference in temperature and mass flow will be clear, and the solution's success can be determined.

2.7. Summary

This section described a method that consists of five steps to prevent mixing fresh intake air with hot return air from development ends. The method addressed the following objectives outlined in Section 1.6:

1. Develop a method to improve ventilation conditions in deep-level mines.
   1.1. Build a calibrated ventilation simulation model (Section 2.3).
   1.2. Identify techniques that were previously used to improve ventilation conditions (Sections 2.4.1 and 2.4.2).
   1.3. Provide a decision tree that will aid in choosing the optimal solution (Section 2.4.3).

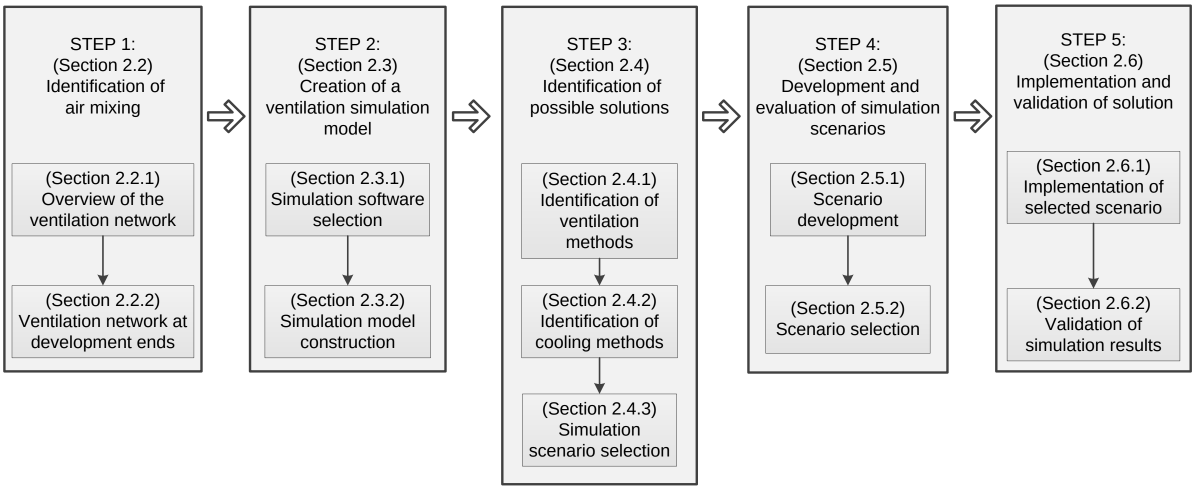


Figure 2-27: Final proposed method with subheadings.

Step 1 – Identification of air mixing focussed on gathering information about the ventilation network, such as infrastructure, layouts, and measurement of the underground environment. Furthermore, the environmental conditions at development ends were investigated, specifically how the return air from development ends is discarded.

Step 2 – Creation of a ventilation simulation model described various software packages able to simulate the ventilation network of underground mines and the construction of a ventilation simulation model.

Step 3 – Identification of possible solutions described the ventilation methods for development ends and cooling methods for air in working crosscuts. A decision matrix was introduced to narrow down the number of possible solutions.

Step 4 – Development and evaluation of simulation scenarios describe the process of using a calibrated simulation model from Section 2.3 to develop and evaluate the scenarios identified in Section 2.4.

Step 5 – Implementation and validation of solution described the implementation and validation processes of the solution developed and chosen in Section 2.5.

3. RESULTS

3.1. Preamble

This chapter will apply the proposed method provided in Chapter 2 on two deep-level gold mines located in Welkom, South Africa. Hereafter Mine A and Mine B respectively. The methodology comprises five steps, and Figure 3-1 repeats the different steps of the proposed method.

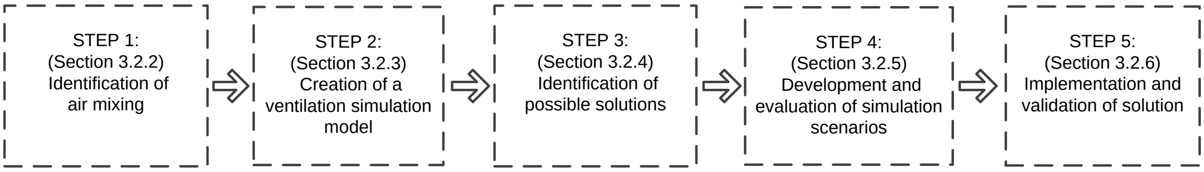


Figure 3-1: Method overview.

3.2. Case study 1

3.2.1. Background

The ventilation networks of underground mines are complex and ever-expanding, with production prospects driving the expansion. The case study mine is a deep-level gold mine in South Africa, extracting 330 kt of rock annually through the narrow reef mining method, as described in Section 1.3. The mine has four active levels and a life-of-mine of eight years. Table 3-1 is the legend for Figure 3-2, which shows a 3D view of the ventilation network of Mine A.

Table 3-1: Legend for Figure 3-2

Symbol	Description
	No airflow
	Production areas
	Intake air
	Return air
	Old mined-out levels
	Active mining Levels

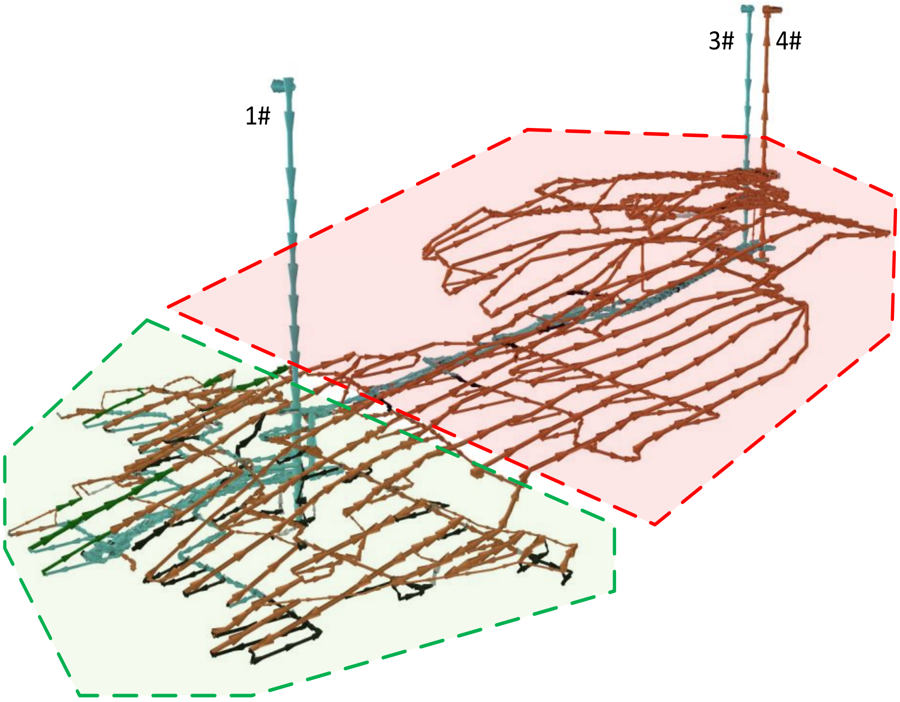


Figure 3-2: Mine A ventilation network generated using PTB.

Mine A consists of three shafts, two downcast shafts (1# and 3#) and one upcast shaft (4#). Three centrifugal fans are installed at 4#, where two fans are active simultaneously, with one fan on standby. The fans extract approximately 450 kg/s of air from the mine via 4#. At the same time, 1# and 3# downcast 270 kg/s and 180 kg/s, respectively. The four active levels are 1 170 m, 1 210 m, 1 290 m, and 1 370 m below the surface, indicated in green, with an average mining depth of 1 290 m.

Due to the relatively shallow operating depth, ventilation-only cooling is sufficient, and no chilled water is required. Ventilation controls and network optimisation have become critical with increasing underground air temperatures due to the horizontal expansion of the mine.

3.2.2. Step 1: Identification of air mixing

This section identifies air mixing underground by analysing the underground ventilation network. Figure 3-3 shows Step 1 as the starting point in the proposed method discussed in Section 2.2.

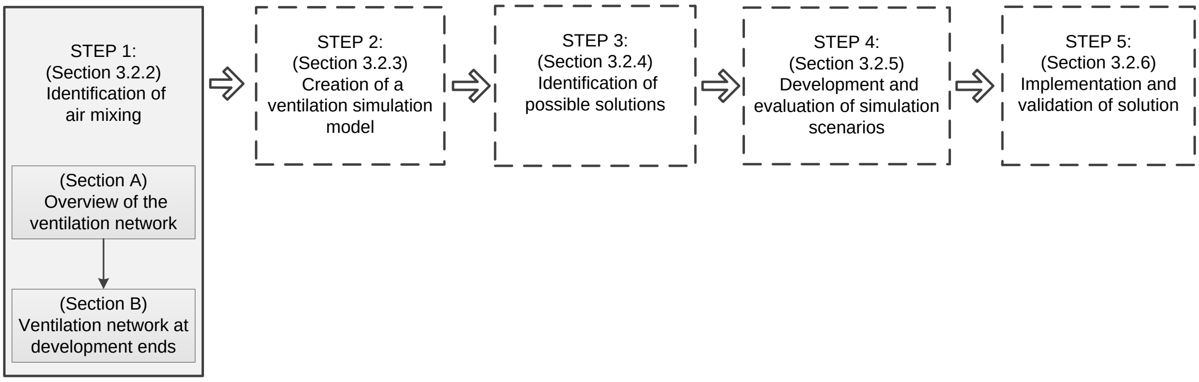


Figure 3-3: Application of Step 1 of the proposed method.

Step 1 will provide information about Mine A's underground ventilation network and aim to identify an area where air mixing is present.

A. Overview of the ventilation network

Primary ventilation infrastructure

Mine A has three primary fans connected in parallel. All three fans have power output ratings of 1 000 kW with similar pressure vs volumetric flow rate graphs. The fan curves for each fan are the same, and the fan curve is shown in Figure 3-4.

Two primary fans are in operation in the typical operation for Mine A. The operating condition for the fans was measured. A pitot tube was used to measure the velocity of the air through the fans and the static pressure. The use and operation of the pitot tube is explained in Appendix A.

Figure 3-4 shows the characteristic curve for the three primary fans installed at Mine A. Where the fan static pressure (kPa), fan efficiency (%), and fan power (kW) are plotted against the volumetric flowrate (m^3/s) at different guide vane angles. Furthermore, the operating points for fan 1 and fan 3 are represented by the light and darker grey dots, respectively.

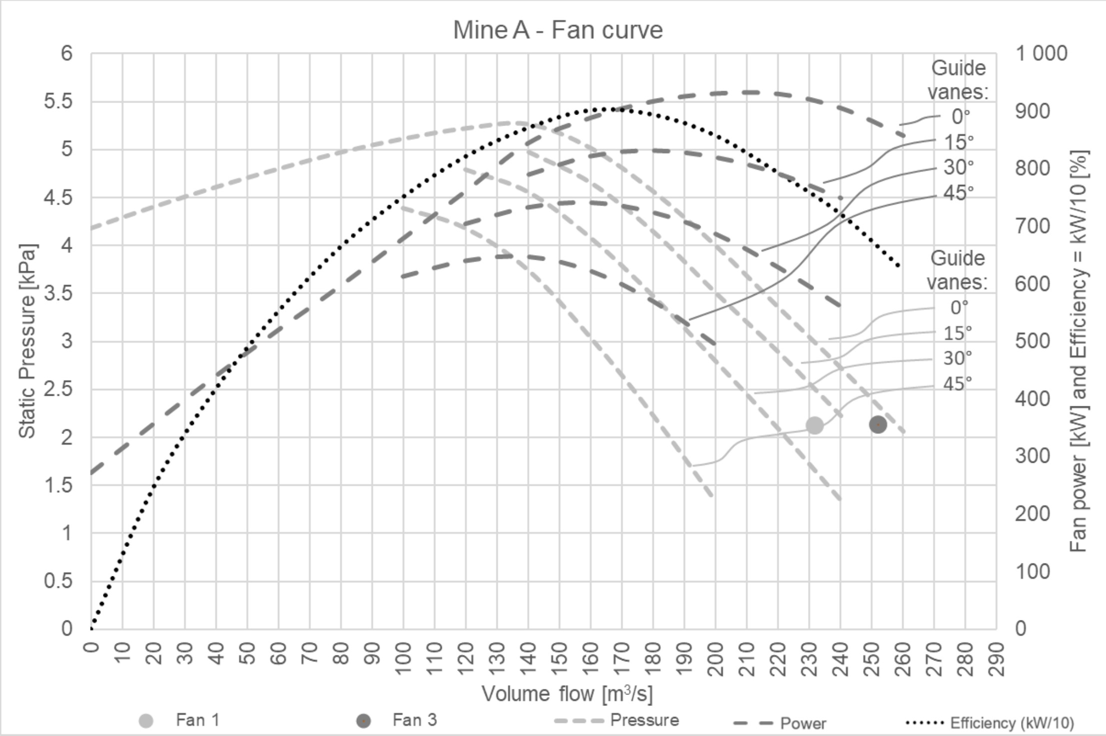


Figure 3-4: Primary fan curves for Mine A.

DXF layout

A DXF layout shows the underground workings of a mine, and a layout usually depicts one level. The DFX layout in Figure 3-5 shows multiple levels overlayed in one image, with the deepest lower level in the figure at 1 370 m and the shallowest upper level at 1 100 m.

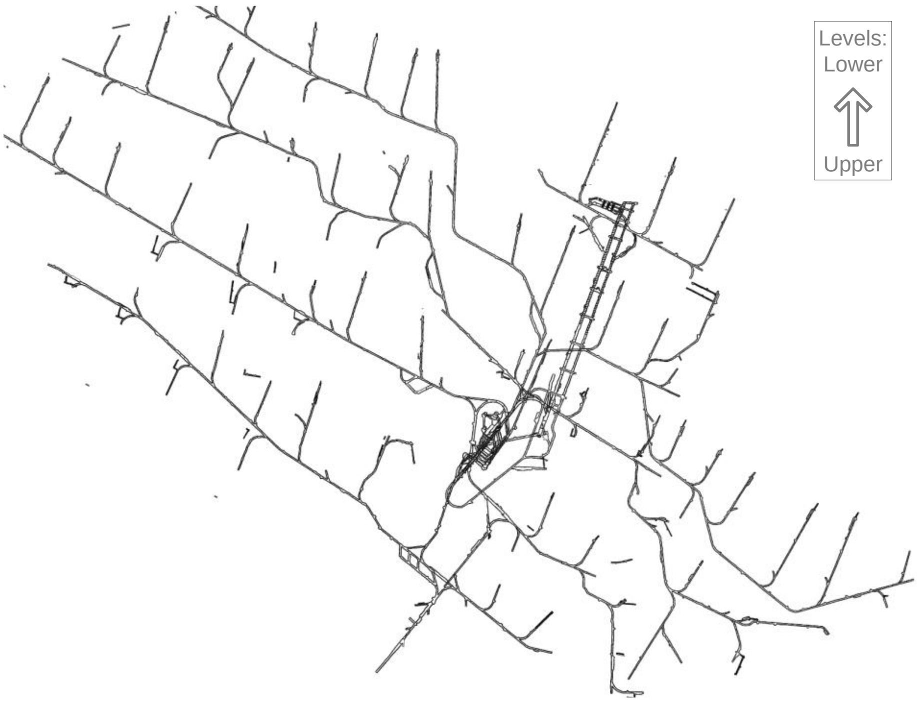


Figure 3-5: Top view of the DXF layouts of Mine A.

The layouts are obtained digitally as DXF files. The files will be imported into the simulation software, with the components placed to create the simulation model.

Volume surveys & engage site personnel

Volume surveys are obtained from site personnel to understand the ventilation system layout. The ventilation system layout includes locations of the AVS, the ventilation control systems and ventilation measurements throughout the system. Looking at the volume surveys and communications with the site personnel is not enough to fully understand the ventilation system; thus, underground visits are essential.

Visit underground areas and conduct ventilation audits

The volume surveys of the mine and conversations with the site personnel about the underground environment provide a good understanding of the mine's underground ventilation system. However, it is essential to personally visit the underground areas and conduct ventilation measurements to fully understand the ventilation system and build an accurate ventilation simulation model.

Figure 3-6 is the result of a ventilation audit. The figure shows a DXF layout of the deepest level in the mine, where a working crosscut, and a development end is located. The numbers indicate the locations where measurements were taken to record the conditions of the ventilation system at that point, while the airflow directions are indicated by the arrows.

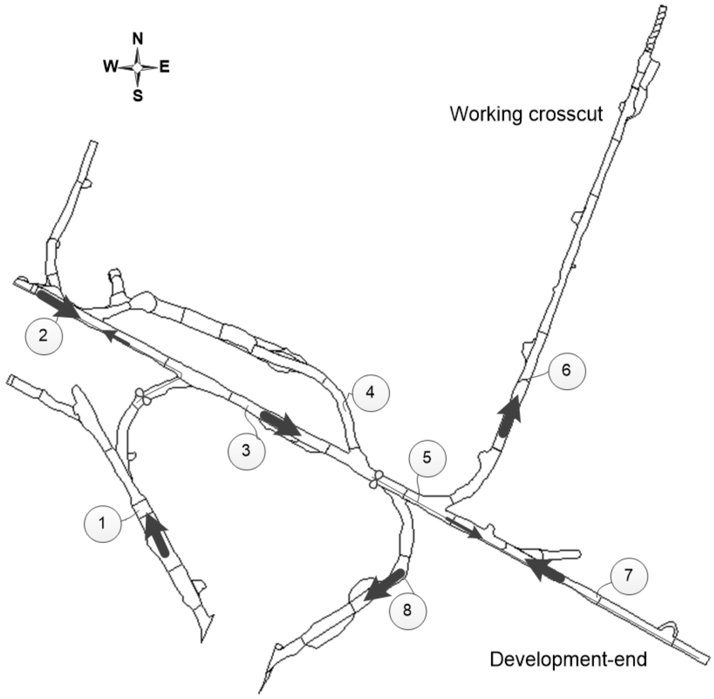


Figure 3-6: Ventilation audit of Level X.

The measurement points, described in Section 2.2.1, are marked in Figure 3-5, and the different parameters recorded are listed in Table 3-1 with the corresponding number.

Table 3-2: Level X ventilation audit

Point	T_{wb} (°C)	T_{db} (°C)	Barometric Pressure (kPa)	Area (m^2)	Quantity (m^3/s)	Mass flow (kg/s)	Dust concentration (mg/m^3)
1	28.0	31.5	102.95	22.05	21.84	25.34	-
2	31.5	34.0	102.97	11.56	10.85	11.97	-
3	28.5	32.5	102.99	13.02	11.04	12.79	-
4	32.0	35.5	102.99	9.60	3.66	4.25	-
5	29.0	32.2	103.05	12.96	8.32	9.78	-
6	31.5	33.0	103.09	10.35	16.30	18.90	-
7	30.5	34.5	103.06	11.98	11.04	12.16	0.031
8	30.0	33.0	103.00	13.35	4.60	5.12	-

The instruments are described in Section 2.2.1 were used to obtain the most of the measurements in Table 3-2. The dust concentration measurements were obtained using a gravimetric dust sampler described in Appendix A. Point 4 has the highest T_{wb} and T_{db}, and at the same time, the lowest airflow quantity. The high temperatures are a result of the low airflow quantities as the air cannot remove the heat from the area. Elevated temperatures at Points 5-7 require further investigation. This area will be the focus, where the objective is to decrease the temperature at Point 6. At the same time, the airflow should be maintained or increased.

B. Ventilation network at development end areas

From Table 3-2, Points 5-7 have the highest temperatures with high airflow. Here the airflow sources will be investigated to determine the cause of the increased temperatures at the identified points. In Figure 3-7, Point 7 is a development end and forms part of the localised ventilation system, Points 5, 6 and 7, where Point 5 is the intake and Point 6 is the system's return.

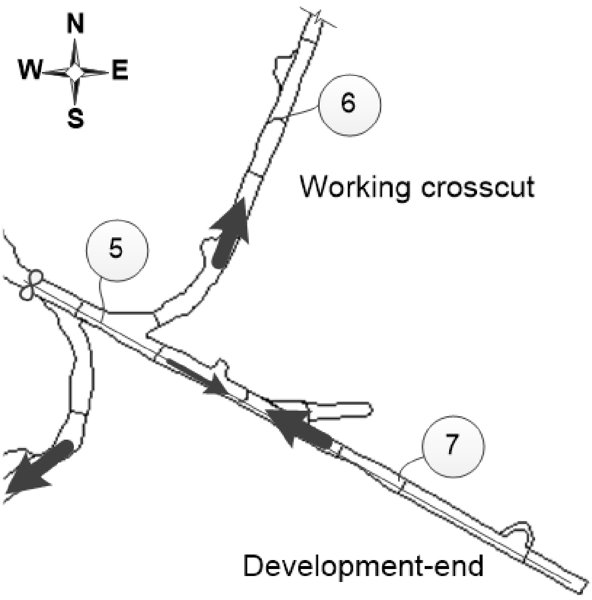


Figure 3-7: Schematic of Level X development end.

Fresh intake air enters the localised ventilation system, where the bulk flows directly to Point 6 to ventilate the in-stope working areas. The fan at Point 5 picks up some of the air and delivers the air to the development end face at Point 7 via the ducting system. The used air from the working face at the development end returns to Point 7 and mixes with the air flowing from Point 5 to Point 6. The mixing of air streams from Points 5 and 7 causes an increase in temperatures and dust concentration at Point 6.

3.2.3. Step 2: Creation of a ventilation simulation model

Section 3.2.2 provided information on the underground environment and identified the air mixing. This section is Step 2 of the methodology discussed in Section 2.3.

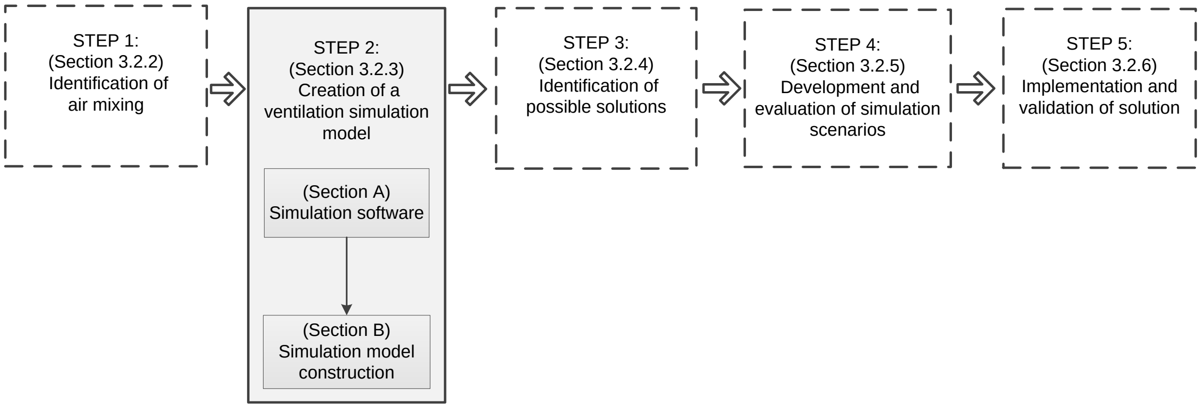


Figure 3-8: Application of Step 2 of the proposed method.

Step 2 aims to create a verified simulation model to simulate the underground environment's ventilation network. A verified simulation model can predict the outcome of any changes made to the ventilation network [53], [90].

A. Simulation software

The software used to create the simulation model is Process Toolbox (PTB), a mass flow solver with a built-in thermal-hydraulic solver. The data gathered in Section A is sufficient to construct a PTB ventilation simulation model.

B. Simulation model construction

The construction of a simulation model can be categorised into skeleton, and calibration and verification. These two parts are the focus of this section.

Skeleton

The skeleton of a ventilation simulation model of a deep-level mine comprises a series of components called nodes and tunnels, arranged along the DXF layouts. The layouts are imported into the simulation software as a DXF file, and nodes and tunnels are placed along the pathways indicated by the DXF file. The nodes and tunnels are connected in an alternating pattern, where the node component allows multiple connections, and the minimum connections are one in and one out. The tunnel component only allows one in-and-out connection. The ventilation infrastructure, including the doors, seals, walls, fans and ducting, is added to the simulation according to the volume surveys described in Section A. At this point, the airflow direction can be calculated.

Once the airflow directions in the tunnels match the directions indicated on the volume surveys, mark the tunnels with the pre-defined colours for intake and return air, production areas and development ends. Figure 3-9 shows a DXF layout imported into PTB. The layout is oriented so north points to the top of the page.

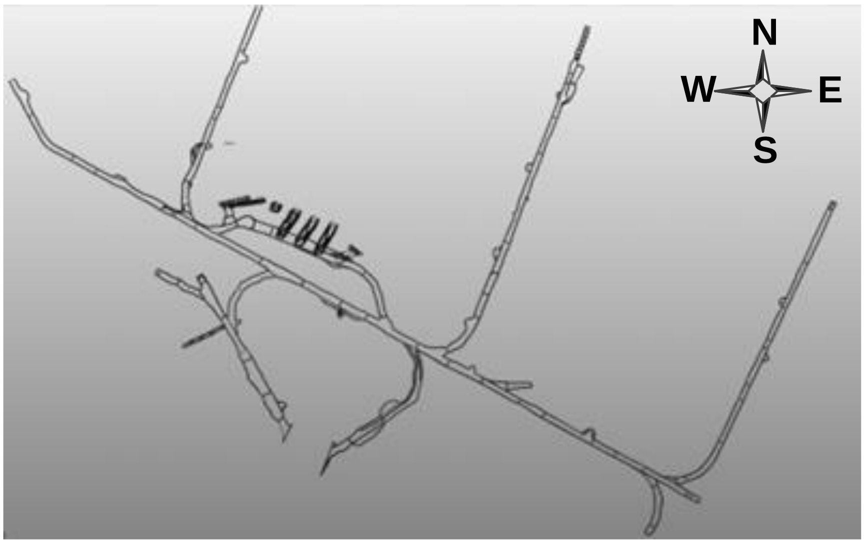


Figure 3-9: DXF layout imported in PTB.

Figure 3-10 shows how the nodes and tunnels are arranged along the pathways indicated by the DXF layout.

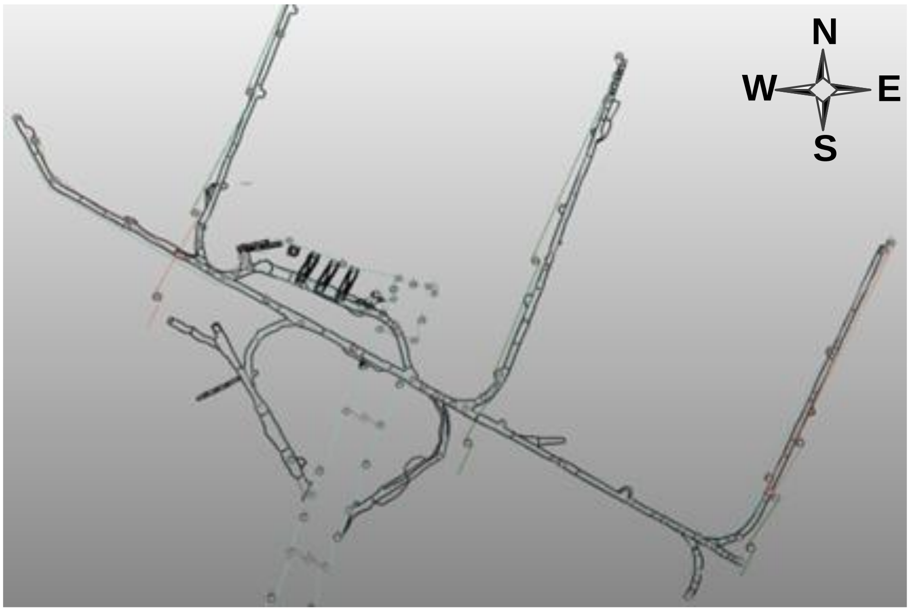


Figure 3-10: DXF layout with node and tunnel components placed.

Figure 3-11 shows the detailed view of the network where the airflow directions are indicated, and the air streams and areas are marked with colour. The light blue tunnels indicate fresh intake air, orange tunnels indicate return air and green tunnels indicate production areas. The grey tunnels show tunnels with no airflow.

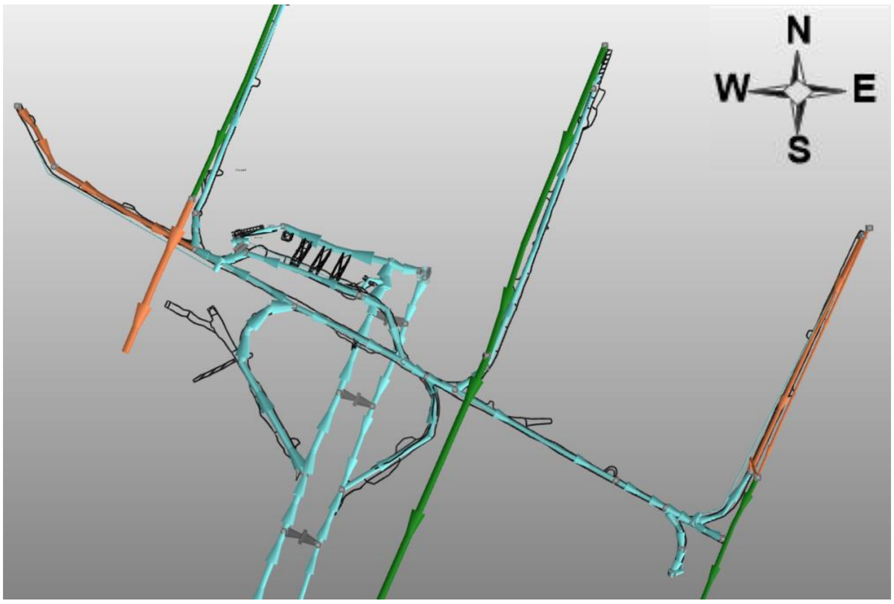


Figure 3-11: Detail view of the network.

PTB can build the layouts of different levels on separate layers, and the layouts can be connected in the all-layer view. The result is a 3D image of the mine, and Figure 3-12 shows the complete simulation skeleton.

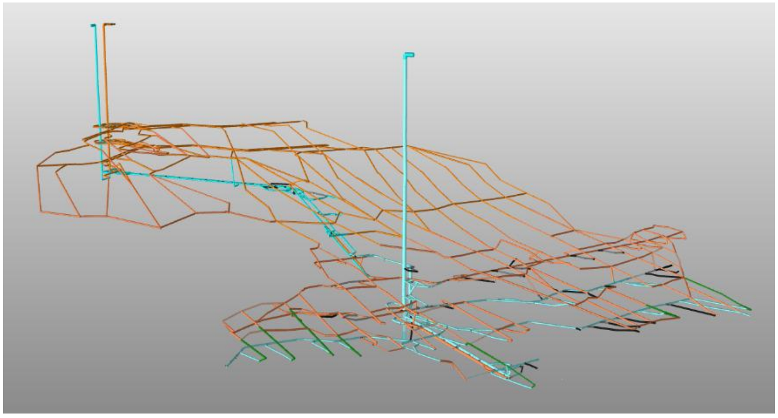


Figure 3-12: A 3D image of the ventilation skeleton model.

Once the airflow in the skeleton model resembles the airflow indicated on the volume surveys and the colour assignment is complete, the model can be calibrated and verified with actual measurements. After the temperatures are calibrated in the next section, the MAE between the simulated results and actual measurements should be calculated using (Eq. 2-2).

Calibration and verification

The skeleton step delivered a simulation model which includes the ventilation network's dimensions and infrastructure. The calibration and verification aim to accurately represent the underground ventilation network using airflow and temperature as metrics. The heat sources VRT, machinery, personnel, fissure water, and auto compression described in Section 1.2.1

are quantified and incorporated into the simulation model to accurately represent the underground ventilation network.

The VRT at any depth in the area can be determined using (Eq. 1-1. The depths for each level are listed in Table 3-3, and the VRT for each level is calculated.

Table 3-3: VRT calculation for each level in Mine A

Depth (km)	Equation	Unit	Value
0.60	=20+14.6(0.60) =20+8.76	$°C$	28.76
0.70	=20+14.6(0.70) =20+10.22	$°C$	30.22
0.90	=20+14.6(0.90) =20+13.14	$°C$	33.14
0.98	=20+14.6(0.98) =20+14.31	$°C$	34.31
1.04	=20+14.6(1.04) =20+15.18	$°C$	35.18
1.10	=20+14.6(1.10) =20+16.06	$°C$	36.06
1.17	=20+14.6(1.17) =20+17.08	$°C$	37.08
1.21	=20+14.6(1.21) =20+17.67	$°C$	37.67
1.29	=20+14.6(1.29) =20+18.83	$°C$	38.83
1.37	=20+14.6(1.37) =20+20.00	$°C$	40.00

The VRT values for the levels calculated in Table 3-3 are imported into the tunnel components of the simulation.

An adjusted heat value accounts for the heat produced by the electrical system, personnel, machinery, and fissure water in the underground environment. The adjusted heat is distributed throughout the mine in the intake tunnels. The adjusted heat value is obtained by comparing the simulated results with the actual measurements. Iterate the adjusted heat values until the MAE is <10%. Further calibration can be done to achieve an MAE of 5% by changing the wetness of the haulages. The wetness factor or moisture factor of haulages changes the heat transfer coefficient of the air stream. A higher wetness factor will increase the T_{wb}, T_{db} and the humidity of the air stream, whereas a lower wetness factor will mainly increase the T_{db} and have lower humidity [91].

Figure 3-13 and Figure 3-14 show 30 measurement points close to the identified air mixing area. Figure 3-13 compares the simulated results with the actual measurements of the T_{wb} and plots the MAE of the measurements at each location.

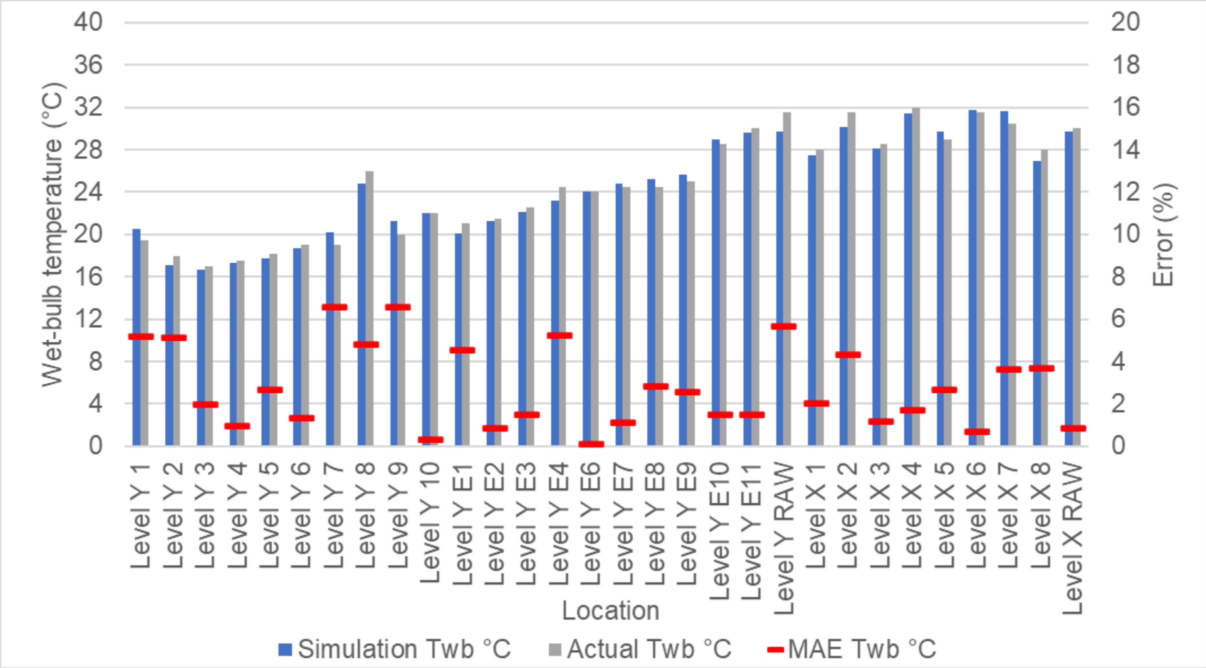


Figure 3-13: Simulation vs Actual comparison of T_{wb} and MAE of Mine A.

Figure 3-14 compares the simulated results with the actual T_{db} measurements and plots the MAE of the measurements at each location.

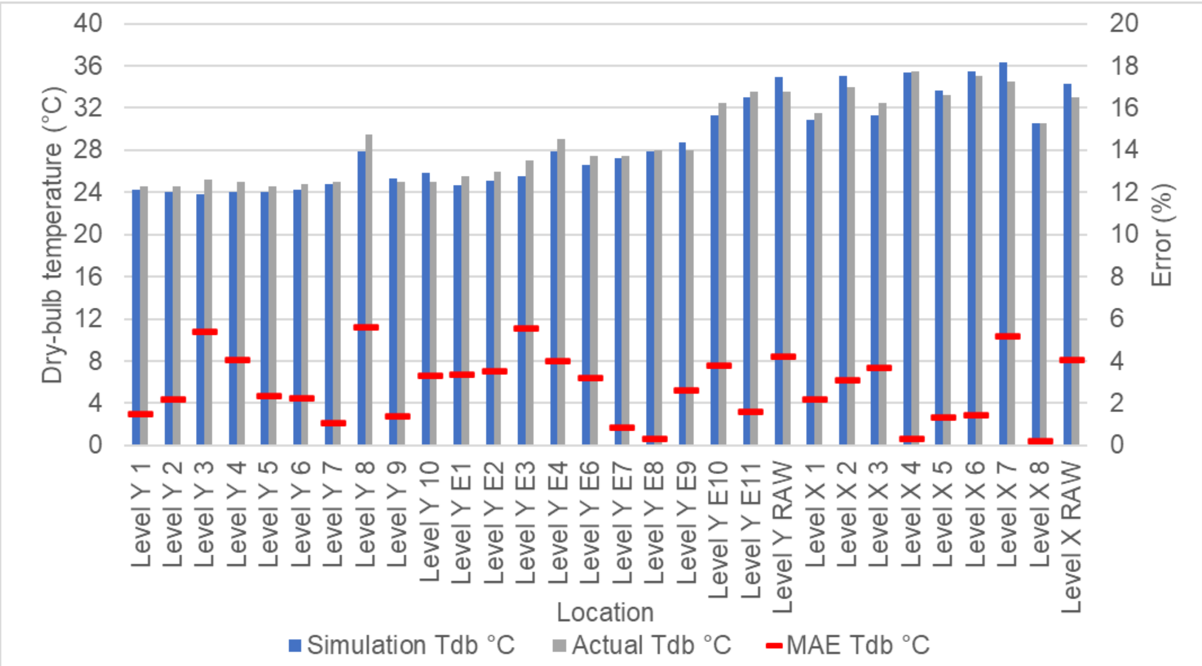


Figure 3-14: Simulation vs Actual comparison of Tdb and MAE of Mine A.

Figure 3-15 compares the simulated results with the actual T_{db} measurements and plots the MAE of the measurements at each location.

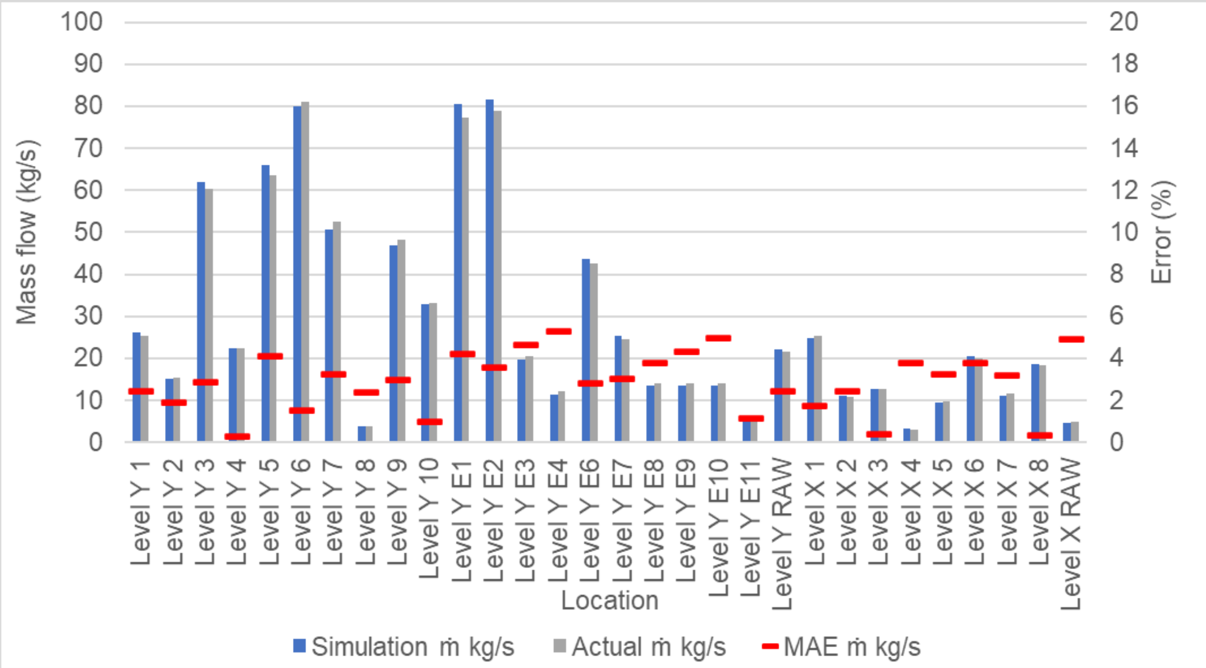


Figure 3-15: Simulation vs Actual comparison of air mass flow and MAE of Mine A.

Figure 3-16 shows the MAE for the three parameters of the simulated results and the actual measurements.

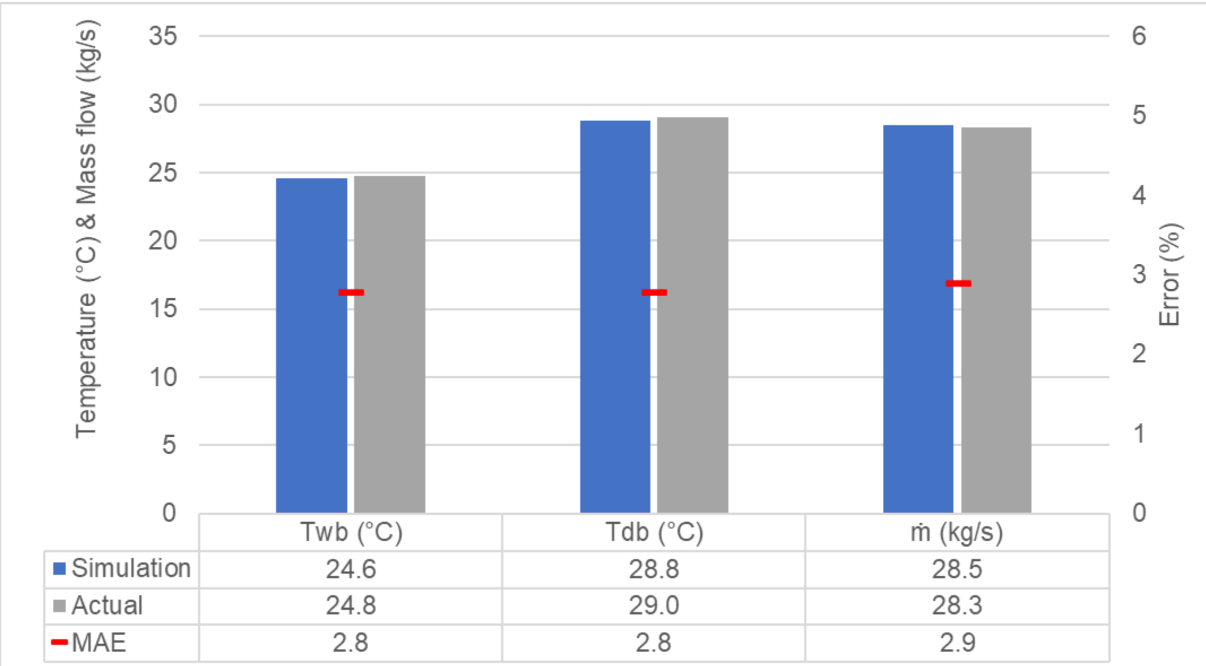


Figure 3-16: Average values of simulation vs actual comparison and error of Mine A.

Once the MAE for the parameters is calculated as < 5%, the simulation model is considered accurate and calibrated [92].

After calibration, the simulation results need to be verified. The verification process of a simulation model is when a calibrated simulation model is subjected to the same input changes as the actual underground environment. The simulated results and actual measurements are compared after the input changes are implemented.

A baseline is established to verify the simulation model, to which any change can be compared. The baseline used for the verification is the results, as presented in Figure 3-13 - Figure 3-15. The input change to the actual mine and the simulations was the surface ambient conditions. The surface ambient conditions for the two scenarios, baseline and input change, are winter and summer, respectively. Winter months are May to August, while summer months are September to April. Figure 3-17 shows the average surface ambient conditions for winter and summer.

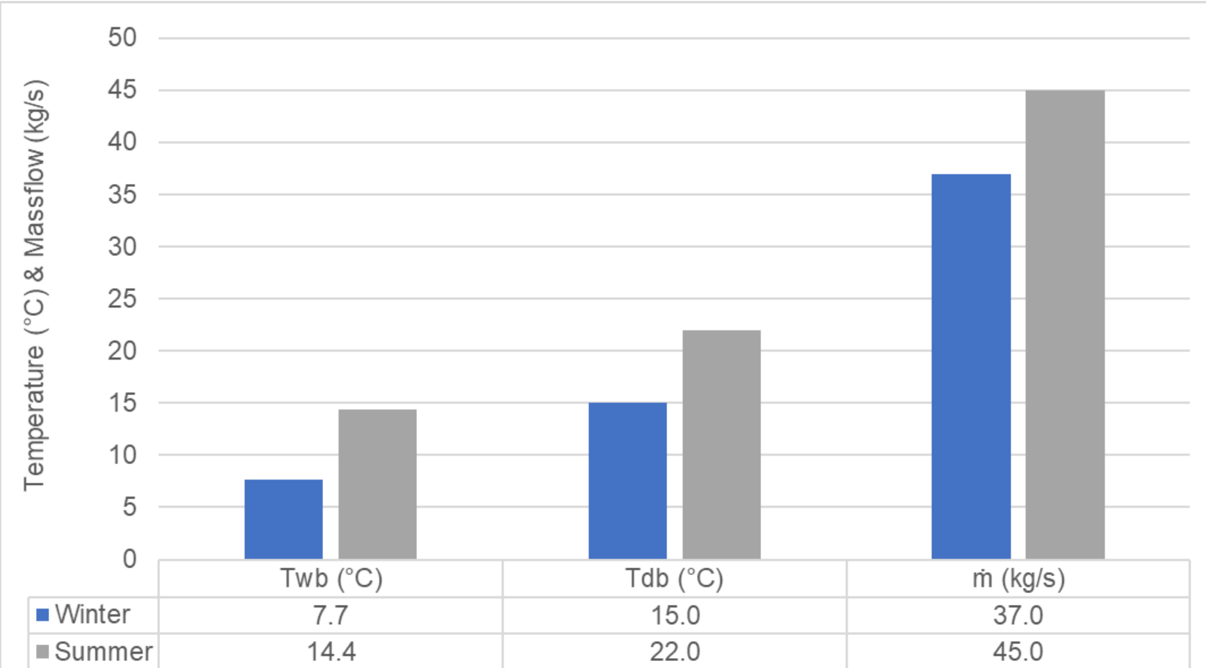


Figure 3-17: Surface ambient conditions for Mine A.

Two locations were identified and used as KPIs to verify the simulation model: The working crosscut (137L XC E5) where the air mixing was identified, and the development end (137L dev end) from which the hot return air flows.

Figure 3-18 compares the simulated results with the measurements for T_{wb}, T_{db} and $\dot{m}$ for the identified KPI locations.

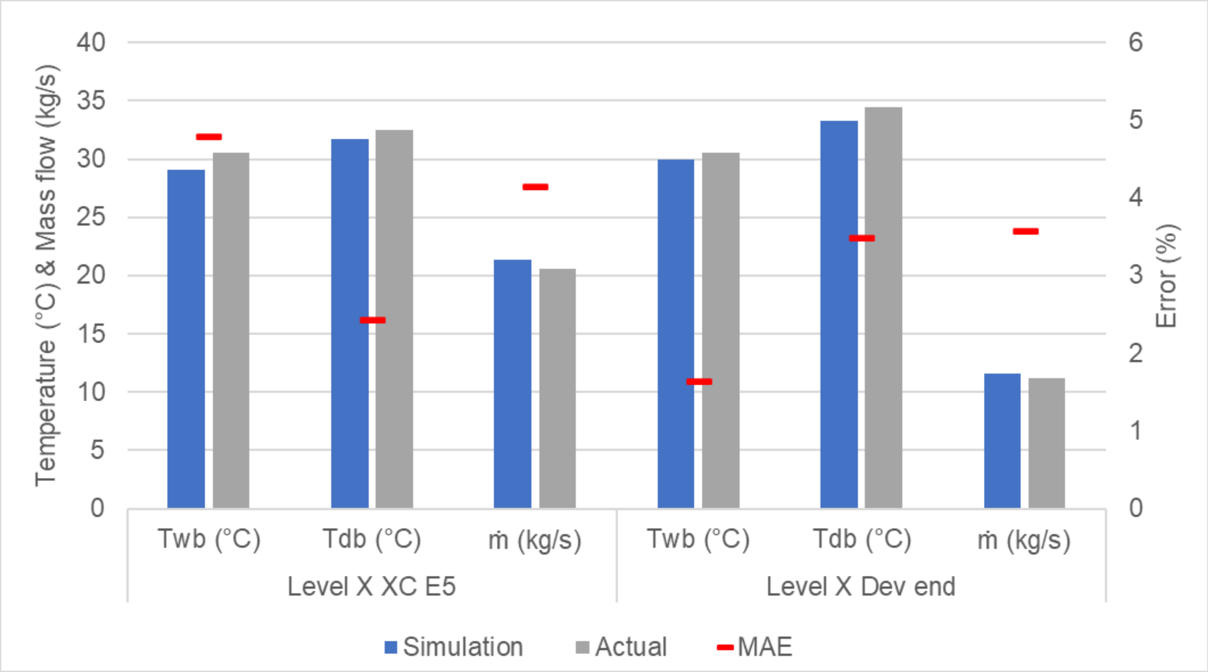


Figure 3-18: Baseline simulation results of Mine A.

The summer surface ambient conditions yielded the results shown in Figure 3-19 for the pre-defined locations.

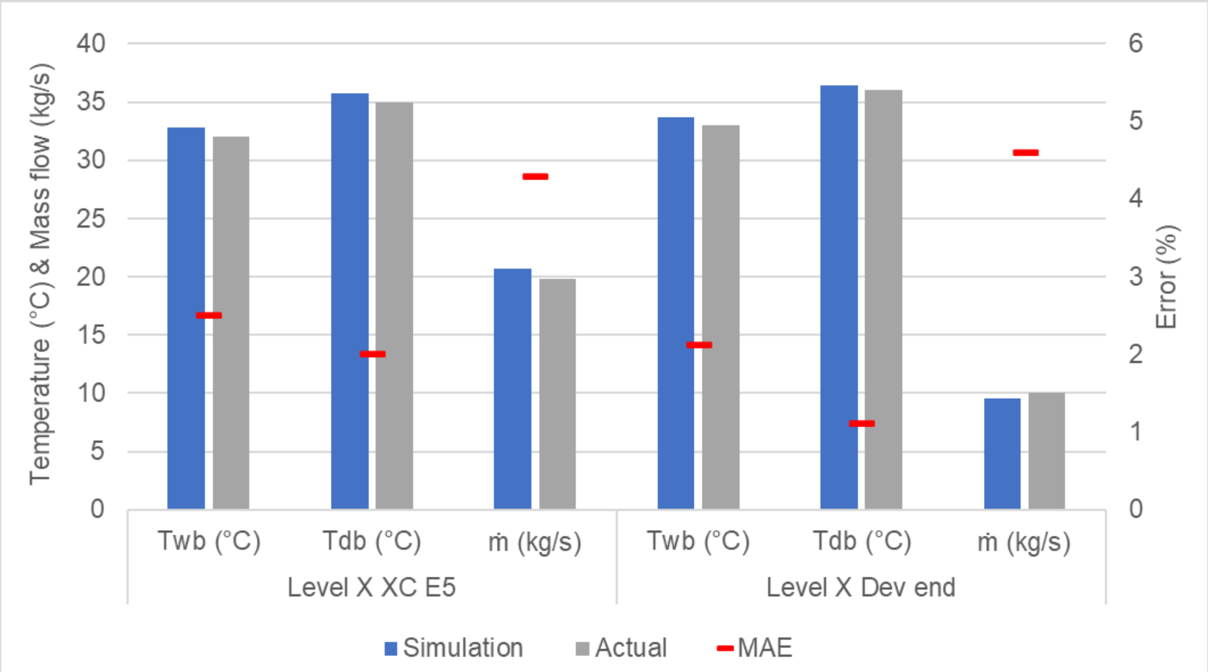


Figure 3-19: Input change simulation verification of Mine A.

The MAE between the simulated and actual results for all three parameters is <5%. Therefore the simulation model can be considered accurate and, thus, verified [92]. Table 3-4 provides a comment on how this section has satisfied part of Objective 1.

Table 3-4: Section 3.4 satisfies Objective 1.1 of case study 1

OBJ.	Description	Comment
1.1	Build a calibrated ventilation simulation model.	The outcome of Section 3.2.3 is a calibrated ventilation simulation model.

After the verification, Step 2 is complete. The various ventilation and cooling methods identified in Section 2.4 will be subject to a decision matrix in the next section.

3.2.4. Step 3: Identification of possible solutions

Section 3.2.3 produced an accurate ventilation simulation model that can be used to test different scenarios to optimise the mine ventilation network. The methods identified in Sections 2.4.1 and 2.4.2 will be evaluated using the tree diagram, Figure 2-22, discussed in Section 2.4.3. The section aims to create a short list of applicable scenarios of which simulations will be constructed to mitigate the air mixing at the working crosscut.

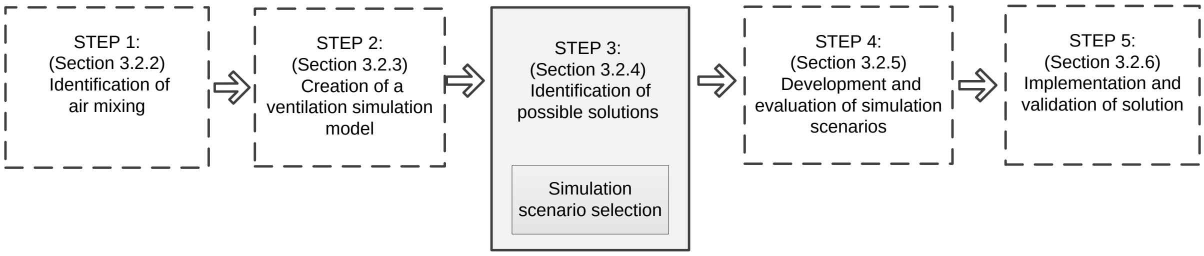


Figure 3-20: Application of Step 3 of the proposed method.

Figure 3-21 was created by following the line of questioning set out in Figure 2-22. The path formed by the coloured blocks results from applying the decision diagram to the case study. The objectives of the study are to decrease the T_{wb} and dust concentrations in working crosscuts while maintaining the airflow at the working crosscut within the legal limits set out by the MHS Act [38].

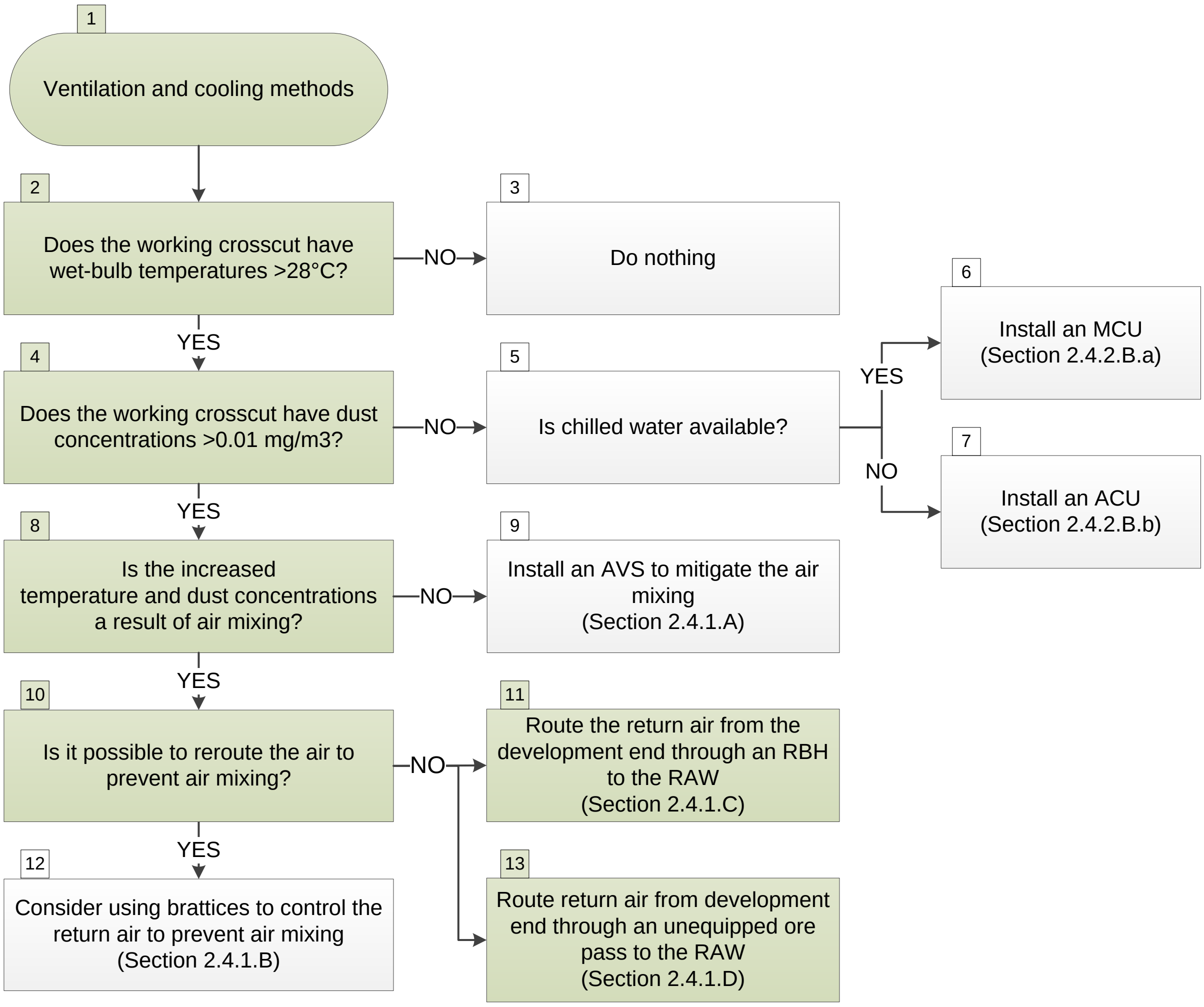


Figure 3-21: Decision diagram applied to case study 1.

After the study's objectives were applied to the decision diagram, Figure 3-21 was produced. The figure indicates the possible solutions that satisfy the study's objectives are RBH and unequipped ore pass, as described in Sections 2.4.1.C and 2.4.1.D, respectively.

Table 3-5: Section 3.5 satisfies Objective 1.3

OBJ.	Description	Comment
1.3	Provide a decision diagram that will aid in choosing the optimal solution.	Section 3.2.4 used the decision diagram provided in Section 2.4.3 to identify 2 solutions.

The possible solutions identified in this step will be implemented into the ventilation simulation model, built in Section 3.2.3, to develop and evaluate scenarios in Section 3.2.5.

3.2.5. Step 4: Development and evaluation of simulation scenarios

This section will focus on developing simulation scenarios for the possible solution identified in Section 3.2.4. Figure 3-22 shows the subsections required to complete Step 4 of the methodology discussed in Section 2.5.

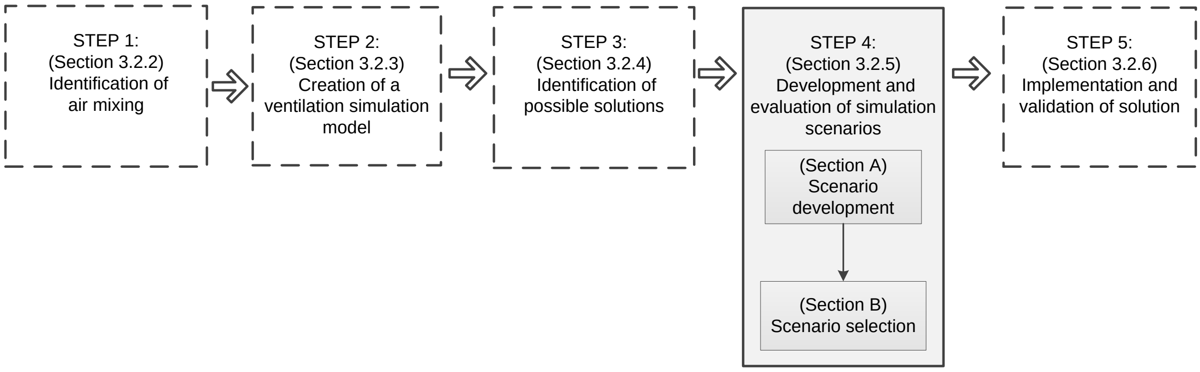


Figure 3-22: Application of Step 4 of the proposed method.

The locations chosen for the comparison were selected to determine which scenario satisfies the objective. The objectives are to decrease the T_{wb}, decrease the dust concentration, and ensure the airflow meets MHS standards. Air mixing was identified as the cause of the increased T_{wb} and dust concentrations at the working crosscut. The ventilation methods proposed in Section 3.2.4 aim to mitigate the increased T_{wb} and high dust concentrations at the working crosscut. Both scenarios will include a solution to discard the hot return air from the development ends to the RAW before it mixes with the fresh intake air of the working crosscut.

A. Scenario development

Scenario 1 - RBH

Scenario 1 features an RBH connecting the working level to the RAW on the level above. The RBH is connected from the haulage on the working level to an old crosscut on the level above. The old crosscut is converted to a RAW.

This case study has two development ends and requires AVS to supply the development faces with sufficient airflow. Firstly a 45 kW fan was placed in the haulage leading to the development end to pick up the fresh air and introduce the fresh air directly onto the face. Then the air needed to reach the second development end, and another AVS delivered air to the development face.

An RBH requires additional development and can only be used for ventilation due to its small size. The location of the RBH is critical to ensure ventilation standards are met, as described in Section 1.2.2 A. It will serve as a RAW for multiple development ends on the level discarding the hot return air to the level above (Upper level). Figure 3-23 depicts the area's layout where hot return air from the development ends and the fresh intake air of the working crosscut mixed.

The figure indicates the area intake, working crosscut, stoping area, measurement points, the proposed fan and ducting placement, the location of the RBH, and where it connects to the RAW on the upper level. The blue coloured lines indicate fresh intake air, with the orange line representing hot return air. At the same time, the green lines show the stoping area where the drilling and blasting of the gold mining process occur, as described in Section 1.3.

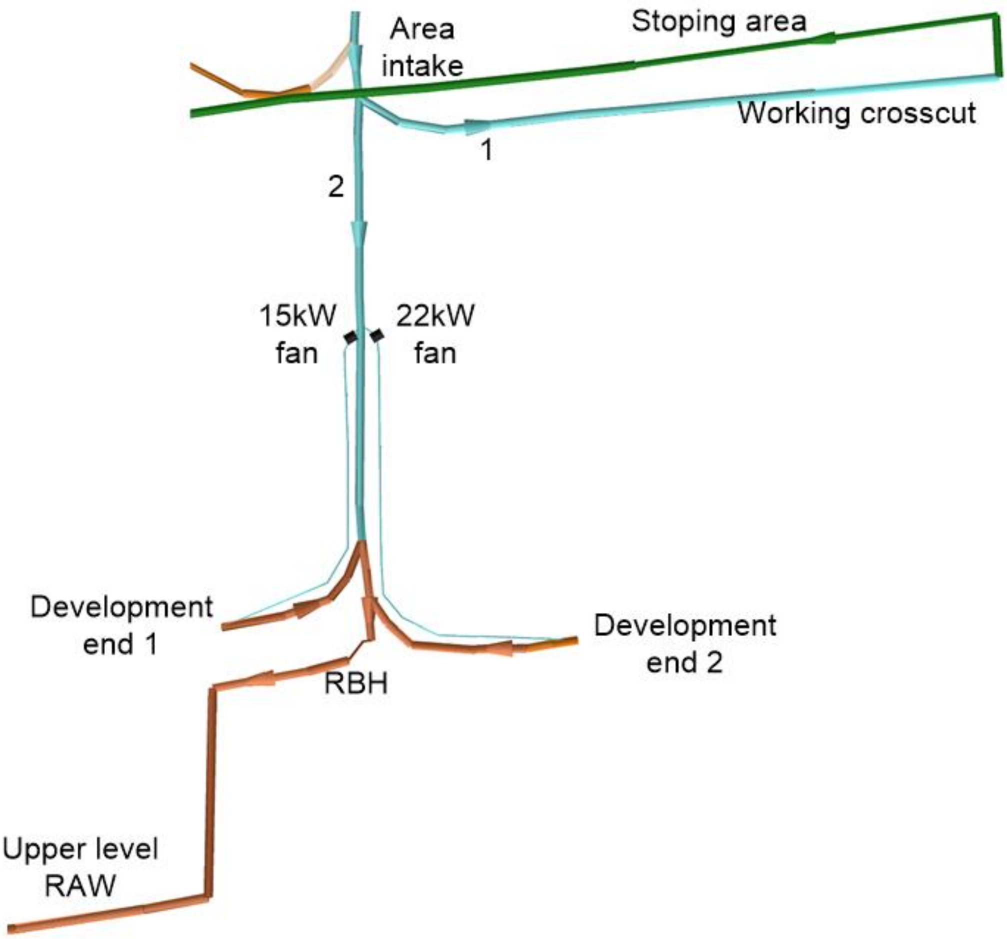


Figure 3-23: Scenario 1 – RBH.

The results from the simulation model with Scenario 1 implemented are shown in Figure 3-24 compared to the baseline. The figure shows the T_{wb} and $\dot{m}$ of the air for both scenarios and measurement points. Points 1 and 2 represent the measuring point for the working crosscut and haulage leading towards the development ends, respectively.

Figure 3-24 compares the simulated results of the baseline simulation and Scenario 1 simulation.

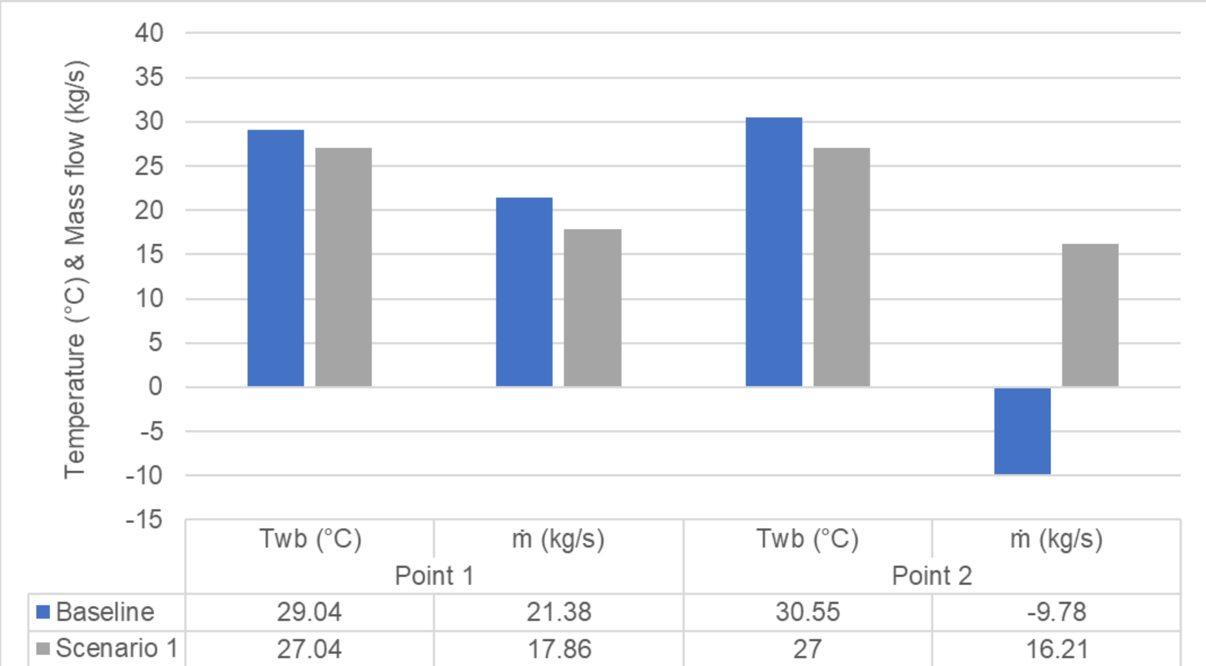


Figure 3-24: Baseline in comparison to Scenario 1 of case study 1.

Figure 3-24 shows that introducing an RBH at the specified location has a desirable effect on the system. Scenario 1 resulted in a 2 °C decrease in T_{wb} at Point 1 and a 3.5 °C decrease in T_{wb} at Point 2. Furthermore, a slight reduction in airflow at Point 1 was observed, with the airflow still above the limit set by the MHS [38]. Most notably, a flow reversal was achieved at Point 2. The flow reversal observed at Point 2 indicates that no air mixing will occur at the intake of the working crosscut.

The RBH is an additional piece of ventilation infrastructure. Additional costs will be required to develop the RBH. The projected development cost for the proposed RBH is R 6 Mil (RBH =R 4.5 Mil and Break away from haulage to base of RBH = R 1.5 Mil[8]). The effect on production time will depend on whether a third party will develop the RBH or will the mine use its personnel. The use of a third party will have no impact on the production, whereas pulling personnel from another project could affect the other project's timeline.

[8] Costs derived from other projects, costs may vary if a third party is used for the development.

Table 3-6 shows a break down of the development time for an RBH (conventional blasting with a drill rig, not reaming).

Table 3-6: Development time for scenario 1 of case study 1.

Description	Advance per blast (m)	Blasts per month	Length (m)	Development time (months)
RBH development	2	16	180	5.7
Flat development	2	16	50	1.6
Total development time (months)				7.3

One RBH per development end is required to produce the results from an RBH as depicted in Figure 3-24.

Scenario 2 – Unequipped ore pass

Similar to Scenario 1, discussed in Section A, Scenario 2 aims to mitigate the increased T_{wb} and dust concentrations at the intake of the working crosscut caused by air mixing. Here an unequipped ore pass is temporarily used as a RAW during crosscut development.

After the ore pass connects the stoping area to the crosscut and before a box front is installed to regulate the ore flow, the opening can be used for ventilation. The planning department determines the location of an ore pass and cannot be moved. Nevertheless, the time the ore pass is open and used for ventilation can be extended to optimise the ventilation network in the immediate area. The mine plan indicated that the crosscut and centre gulley will be established with through-ventilation before production starts. Thus there is scope for the extension.

Figure 3-25 depicts the area's layout where hot return air from the development ends and the fresh intake air of the working crosscut mixed. The figure indicates the area intake, working crosscut, stoping area, measurement points, the proposed fan and ducting placement, the location of the RBH, and where it connects to the RAW on the upper level. The blue coloured lines indicate fresh intake air, with the orange line representing hot return air. The green lines show the stoping area where the drilling and blasting of the gold mining process occur, as described in Section 1.3.

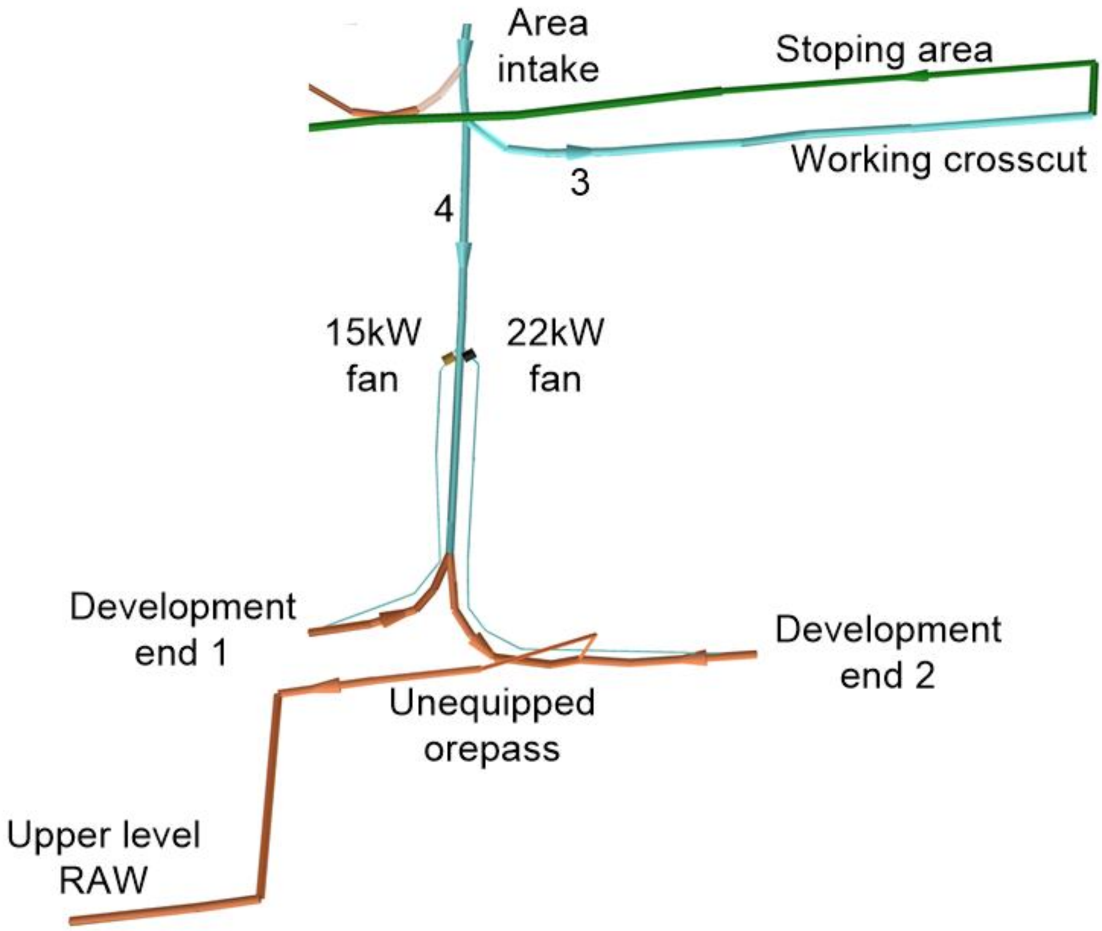


Figure 3-25: Scenario 2 - Unequipped ore pass.

The results from the simulation model with Scenario 1 implemented are shown in Figure 3-26 compared to the baseline. The figure shows the T_{wb} and $\dot{m}$ of the air for both scenarios and measurement points. Points 3 and 4 represent the measuring point for the working crosscut and haulage leading towards the development ends, respectively.

Figure 3-26 compares the simulated baseline and Scenario 2 simulation results.

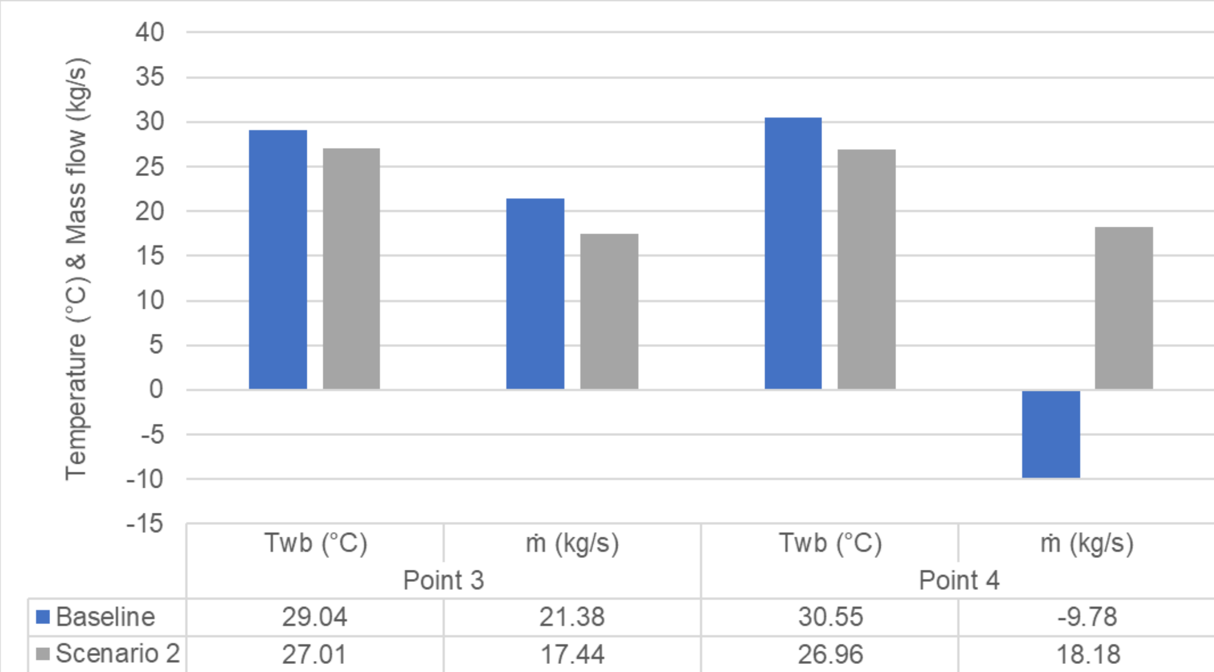


Figure 3-26: Baseline in comparison to Scenario 2.

Figure 3-26 shows that introducing an unequipped ore pass at the specified location has a desirable effect on the system. Scenario 2 resulted in a 2 °C decrease in T_{wb} at Point 3 and a 3.6 °C decrease in T_{wb} at Point 4. Furthermore, a slight reduction in airflow at point 3 was observed, with the airflow still above the limit set by the MHS [38]. Most notably, a flow reversal was achieved at Point 4. The flow reversal observed at Point 4 indicates that no air mixing will occur at the intake of the working crosscut.

Ore pass development is part of the mine plan thus no additional development time or capital is required. No production delays are expected as crews that would use the ore pass will be relocated to panels that have access to another ore pass on the same raise. Due to no additional time or cost required and no production delays expected. The scenario can be incorporated into the mine plan to reduce the temperature and dust concentrations of the last working crosscut.

Table 3-7 lists the results and outcomes of each scenario in terms of the KPI's discussed in section 2.5.2 (Table 2-6).

Table 3-7: Scenario summary

KPI		Description	
		Scenario 1	**Scenario 2**
Primary	Temperature	Decreased T_{wb} by 2 °C and 3.5 °C ate point 1 and 2	Decreased T_{wb} by 2 °C and 3.5 °C at point 3 and 4
	Dust	Diverted air/dust from dev end to RAW	Diverted air/dust from dev end to RAW
	Airflow	• Airflow direction reversal at point 2 mitigates air mixing • Airflow quantity at point 2 is above the legal limit.	• Airflow direction reversal at point 4 mitigates air mixing • Airflow quantity at point 4 is above the legal limit.
Secondary	Additional development time	The RBH can be developed parallel to the production/development teams. (Development time = 16.6 months)	No additional development time is required.
	Cost	Parallel development requires additional crews and will require R 6 Mil to develop an RBH.	Production rocks are diverted to other ore passes no production delays are experienced.
	Sustainability & Repeatability	New RBH location planning and development is required every 3-4 crosscuts	Crews will be allocated so that the unequipped ore pass is not required for production purposes. This ventilation method can be incorporated into the mine plan for the development of each crosscut, as no time or production delays are experienced.

Table 3-7 will be used to score each scenario using the evaluation matrix provided in section 2.5.2 (Table 2-7). The evaluation matrix will be populated in the next section and used for the solution selection.

B. Solution selection

The Section 3.2.5-A provided results for the two scenarios identified as possible solutions in Section 3.2.4. This section aims to select the best solution by evaluating the results and parameters of the solutions with an evaluation matrix. Table 3-8 evaluates Scenarios 1 and 2 with the evaluation matrix, Table 2-7, provided in Section 2.5.2. The KPI parameters listed in Table 3-8 are discussed in Table 2-6, Section 2.5.2. The result from Table 3-8 will be chosen as the final solution and implemented underground to mitigate the increased temperatures and dust concentrations.

Table 3-8: Case study scenarios evaluation

KPI		Weight	Scenario 1		Scenario 2	
			Score	Total	Score	Total
Primary	Temperature	2	1	2	1	2
	Dust	2	1	2	1	2
	Airflow	2	1	2	1	2
Secondary	Additional development time	1	0	0	1	1
	Cost	1	0	0	1	1
	Sustainability & Repeatability	1	0	0	1	1
Total				6		9

Table 3-8 shows that both scenarios meet the criteria for the primary KPIs, thus meeting the study's objectives. Therefore, the final solution was chosen based on the secondary KPIs. Compared to Scenario 1, Scenario 2 requires no additional time or capital for implementation and offers a more sustainable and repeatable solution. Thus, Scenario 2 was chosen as the final solution.

3.2.6. Step 5: Implementation and validation

Section 3.2.5 evaluated different scenarios through simulation and concluded with Scenario 2 as the final solution. Scenario 2's implementation is discussed, and the validation of the simulation results is discussed in Section A. B. This section will provide the results of the implemented solution and compare the actual measurements before and after implementation. Figure 3-27 shows the two sections to complete in Step 5 of the methodology discussed in Section 2.6.

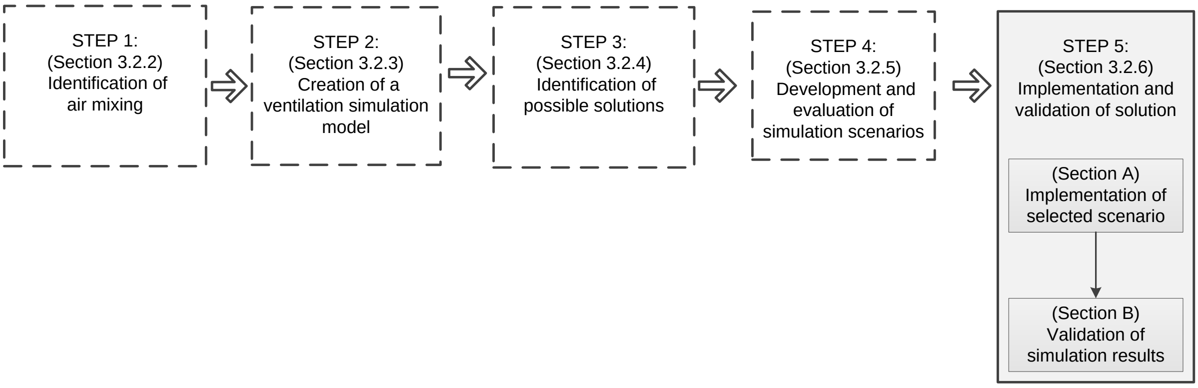


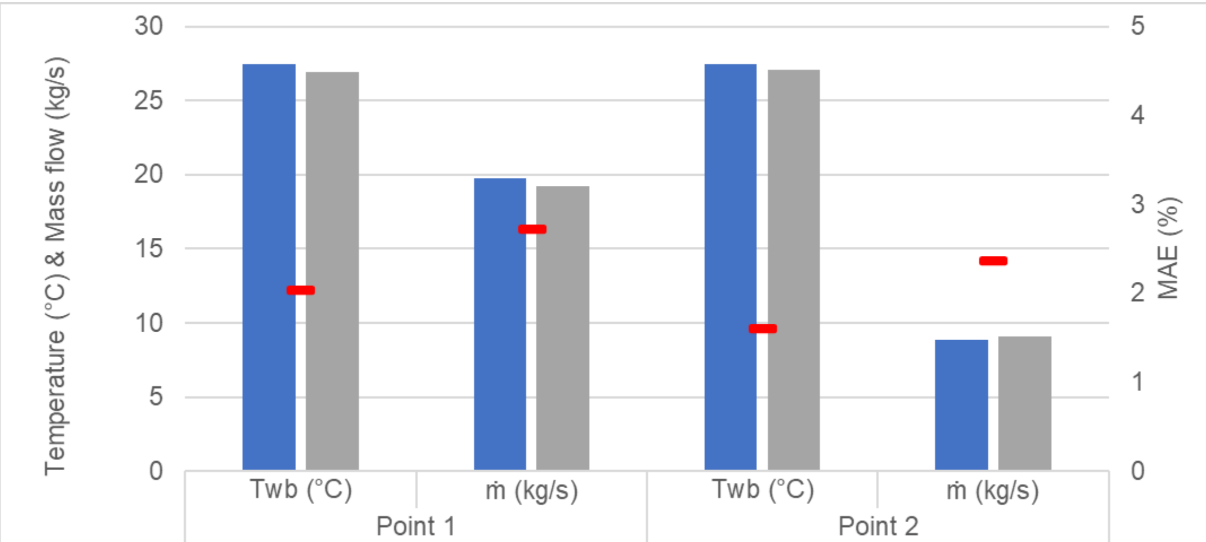
Figure 3-27: Application of Step 5 of the proposed method.

A. Implementation of selected scenario

Scenario 2 was implemented in the ventilation network. The implementation steps included changes to the AVS in the ventilation network to resemble the AVS described in Figure 3-25. Furthermore, the box front installation at the base of the ore pass was postponed to allow the ore pass to serve as a RAW. This configuration will stay in place until the raise and development end is connected, creating a through-ventilated crosscut.

B. Validation of simulation results

Figure 3-28 compares the simulated results for Scenario 2 with the actual measurements after Scenario 2 was implemented in the ventilation network. The figure includes the T_{wb} and ṁ of the two KPI locations identified in Section 3.2.5. At the same time, the MAE of the simulated vs actual results is plotted for the different parameters and locations.

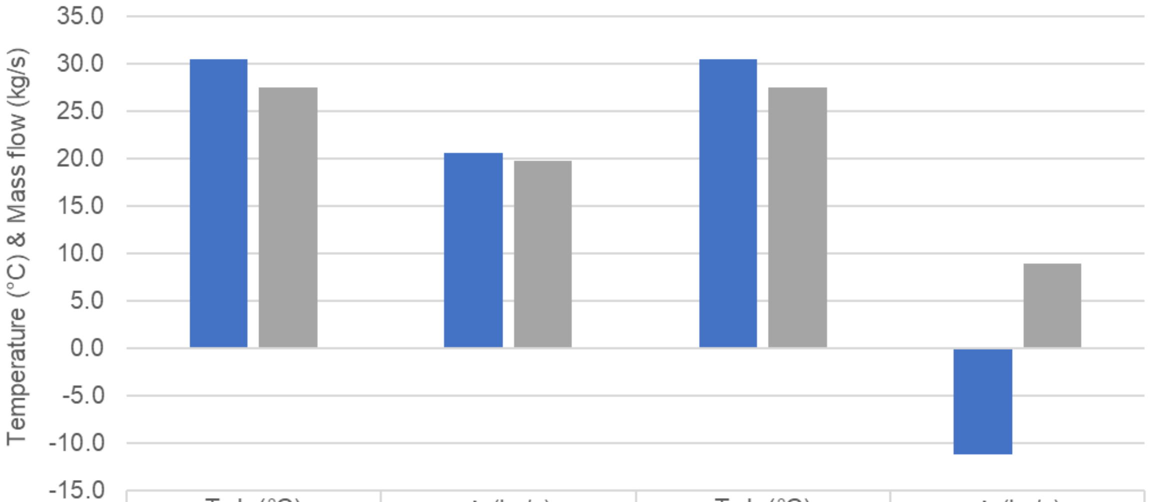


	Point 1 Twb (°C)	Point 1 ṁ (kg/s)	Point 2 Twb (°C)	Point 2 ṁ (kg/s)
Actual	27.50	19.80	27.50	8.89
Simulation	26.94	19.26	27.06	9.1
MAE	2.04	2.73	1.60	2.36

Figure 3-28: Simulation validation results.

From Figure 3-28, the average MAE is calculated as 2.2%. Therefore the solution developed using simulation software is validated by actual measurements.

The implemented solution met the study's objectives. Figure 3-29 shows the impact on the T_{wb} and ṁ at Points 1 and 2 after implementation.



	Point 1		Point 2	
	Twb (°C)	ṁ (kg/s)	Twb (°C)	ṁ (kg/s)
Before	30.50	20.53	30.50	-11.20
After	27.50	19.80	27.50	8.89

Figure 3-29: Actual measurements compared before and after implementation.

From Figure 3-29, the T_{wb} was decreased by 3 °C at Points 1 and 2. The flow reversal at Point 2 indicates that the air flows away from the working crosscut, preventing air mixing at the working crosscut intake. Furthermore, the air mass flow rate decreased by 0.7 kg/s but still managed to supply the working crosscut with a mass flow rate of 19.8 kg/s or a volume metric flow rate of 17.7 m^3/s of fresh intake air. Table 3-9 discusses how Objectives 2.1 to 3.1 outlined in Section 1.6 were met.

Table 3-9: Chapter 3.2 study objectives achieved

OBJ.	Description	Comment
2.1	Decrease the wet-bulb temperature of working crosscuts.	The intake T_{wb} for the working crosscut on level X was reduced by 3 °C.
2.2	Decrease dust concentrations of working crosscuts.	The airflow reversal at Point 2 indicates that the intake dust concentration was reduced with the dust produced at the development end.
2.3	Maintain the airflow requirements of working crosscuts as prescribed by the MHS Act.	Figure 3-29 shows that the working crosscut intake airflow at point one is 19.8 kg/s (17.7 m^3/s).
3.1	Is the MAE of the actual vs simulated results < 5%?	Figure 3-28 shows that the MAE of the T_{wb} and $\dot{m}$ are < 5%.

From Table 3-9, it is clear that the method proposed in Chapter 2 is valid to prevent air mixing at the intake of working crosscuts to decrease the air temperature and dust concentrations.

3.3. Case study 2

3.3.1. Background

Mine B is a deep-level gold mine in the Free State, South Africa, extracting 800 kt of rock annually through the narrow reef mining method as described in Section 1.3. The mine has 10 active levels and a life-of-mine of seven years.

Table 3-10: Legend for Figure 3-30

Symbol	Description
(grey)	No airflow
(dark green)	Production areas
(cyan)	Intake air
(orange)	Return air
(pink)	Old mined-out levels
(light green)	Active mining Levels

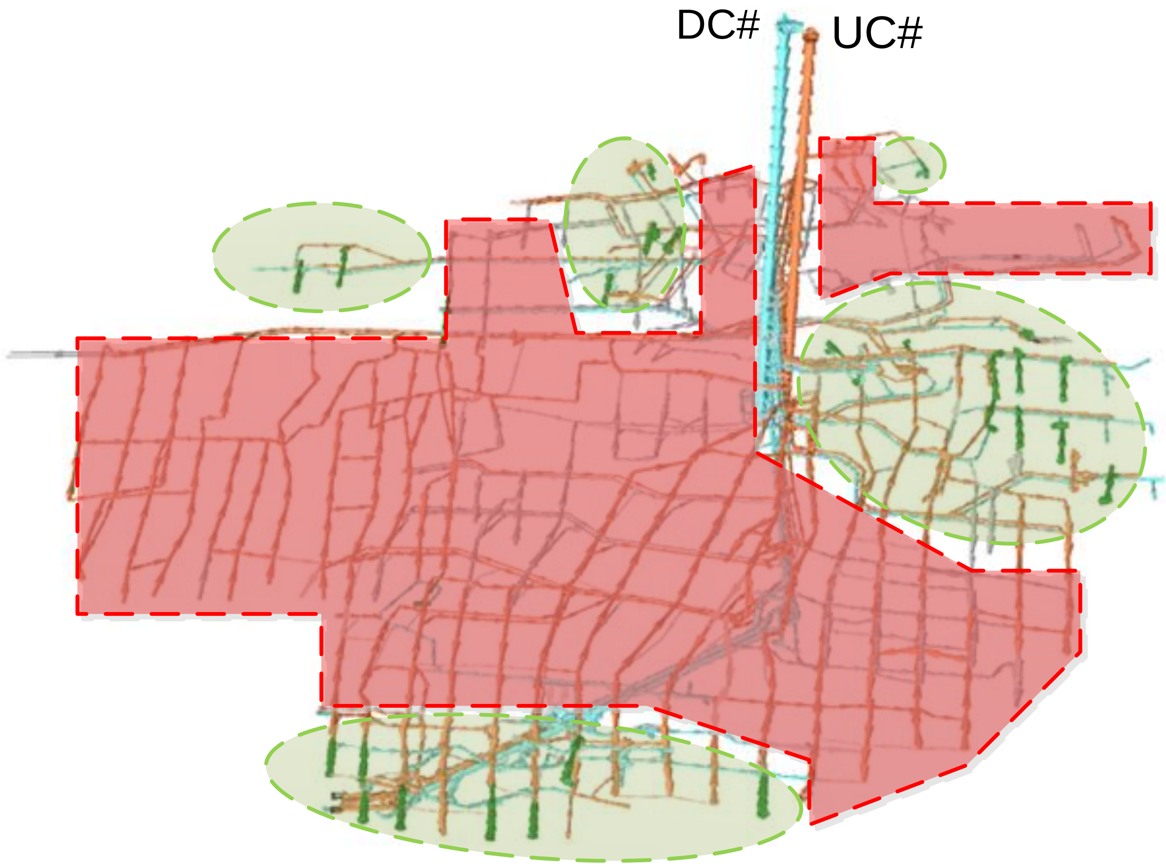


Figure 3-30: Mine B ventilation network generated using PTB.

Mine B Consists of two shafts, namely one down cast (DC#), and one upcast shaft (UC#). Three 2.25 MW centrifugal fans with VSDs are installed at UC# and all three fans are constantly running at reduced speed. The fans extract ±1 200 kg/s of air from the mine. The active areas spread across the 10 active levels are indicated by the green shaded areas, whereas the mined-out areas are indicated by the red shaded areas. The deepest levels (bottom left) are 2 286 m below the surface and an average mining depth of 1 880 m.

The mine has surface refrigeration plants with an installed cooling capacity of 28.8 MW. The refrigeration plants enable the mine to send ± 350 l/s @ 5 °C chilled water to the working areas. At the same time a surface bulk air cooler (BAC) is installed where chilled water is used to cool down ambient air and pumped directly into the DC#.

3.3.2. Step 1: Identification of air mixing

This section identifies air mixing underground by analysing the underground ventilation network. Figure 3-31 shows Step 1 as the starting point in the proposed method discussed in Section 2.2.

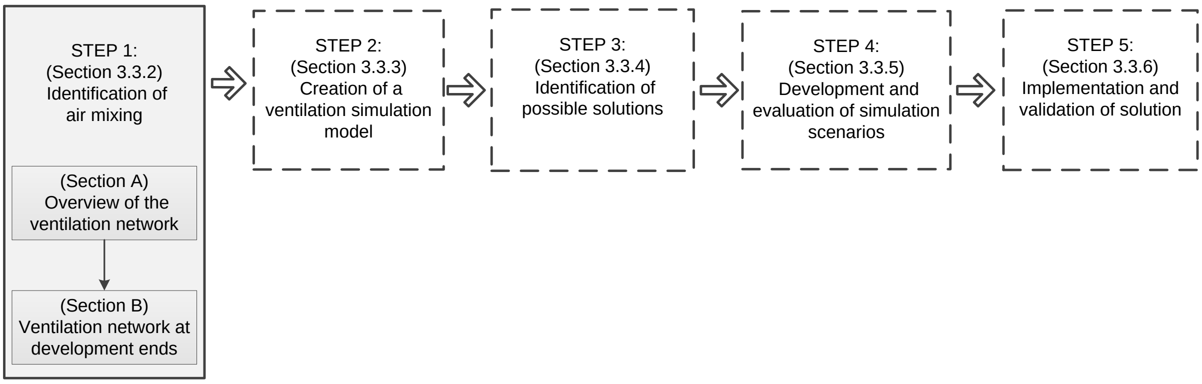


Figure 3-31: Application of Step 1 of the proposed method.

Step 1 will provide information about Mine B's underground ventilation network and aims to identify an area where air mixing is present.

A. Overview of the ventilation network

Primary ventilation fans

At the time of measurement all three fans were in operation as per the typical operation. The operating condition for the fans was measured. A pitot tube was used to measure the velocity of the air through the fans and the static pressure. The use and operation of the pitot tube is explained in Appendix A.

Figure 3-32 shows the characteristic curve for the three primary fans installed at Mine B. Where the fan static pressure (kPa), fan efficiency (%), and fan power (kW) are plotted against the volumetric flowrate (m³/s) at different guide vane angles. Furthermore, the operating points for Fan 1, 2 and 3 are represented by the light, darker grey, and circle dots, respectively.

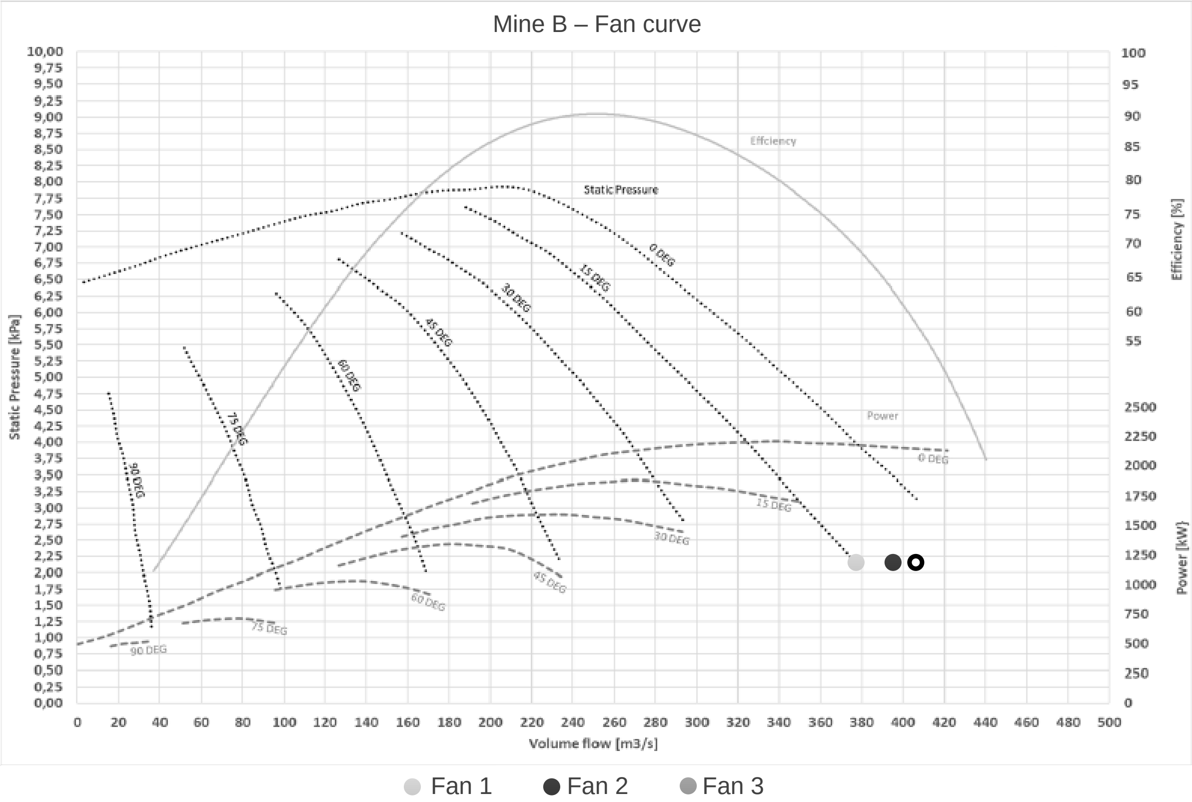


Figure 3-32: Primary fan curves for Mine B

Secondary cooling infrastructure

Mine B has refrigeration plants with an installed cooling capacity of 28.8 MW. The mine also has a three chamber counterflow direct water-to-air BAC. Each chamber is equipped with an axial fan, able to force up to 266 m³/s of air through the BAC. Combined, the three chambers can cool ± 800 m³/s of air to 11 °C in the summer (September to May) which mixes with additional ambient air before it is sent underground. There is instrumentation on the water and air system of the BAC.

DXF layout

The DFX layout in Figure 3 34 shows multiple levels overlayed in one image, with the deepest lower level in the figure at 2286 m and the shallowest upper level at 2 012 m.

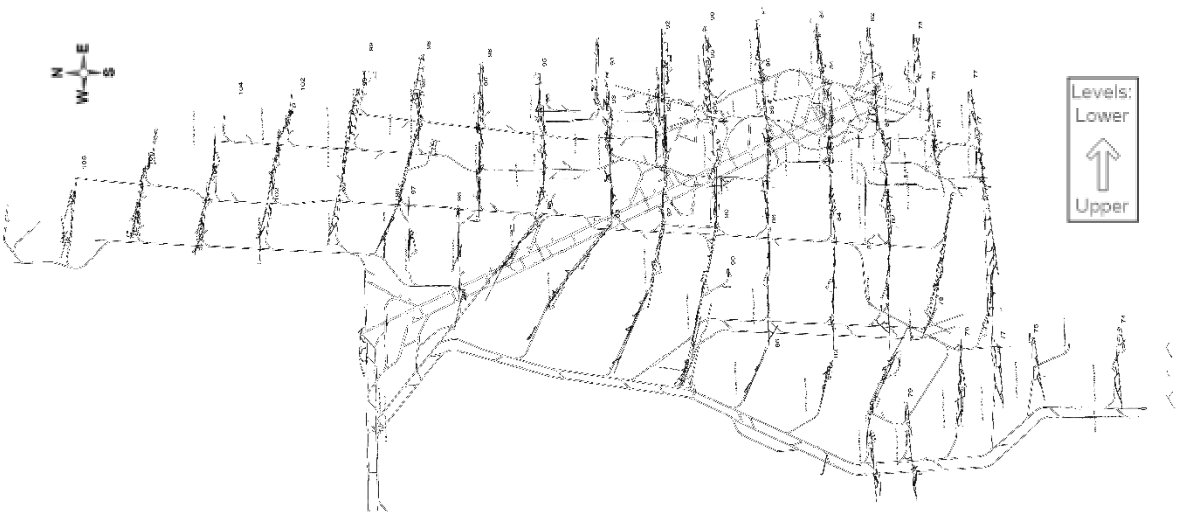


Figure 3-33: Top view of the DXF layouts of Mine B

Volume surveys & engage site personnel

Site staff provide volume surveys so that the ventilation system configuration may be understood. The ventilation control systems, the AVS locations, and ventilation measurements across the system are all included in the ventilation system layout. Underground visits are necessary to completely understand the ventilation system because volume surveys and conversations with site staff are insufficient.

Visit underground areas and conduct ventilation audits

A thorough grasp of the mine's underground ventilation system can be gained from volume surveys of the mine and discussions with site staff regarding the underground environment. However, to fully comprehend the ventilation system and create an accurate ventilation simulation model, it is imperative that one visit the underground areas and perform ventilation measurements.

Figure 3-34 and Table 3-11 are the result of a ventilation audit. The figure shows a DXF layout of the deepest level in the mine, where a working crosscut and a development end is located. The numbers indicate the locations where measurements were taken to record the conditions of the ventilation system at that point. At the same time the airflow directions are indicated by the arrows.

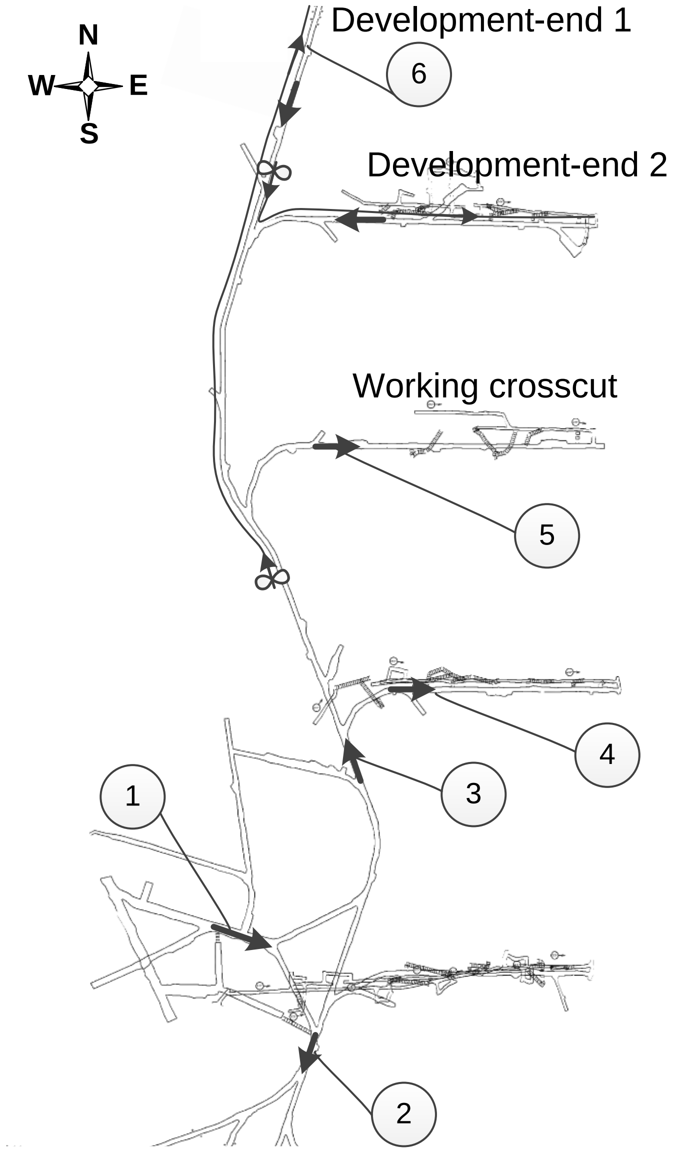


Figure 3-34: Ventilation audit of Level Z of Mine B.

The parameters recorded at the measurement points indicated in Figure 3-34, are listed in Table 3-11.

Table 3-11: Ventilation audit of Level Z of Mine B

Point	T_{wb} (°C)	T_{db} (°C)	Barometric Pressure (kPa)	Area (m^2)	Quantity (m^3/s)	Mass flow (kg/s)	Dust concentration (mg/m^3)
1	24.5	26.1	112.4	21.56	15.8	19.9	-
2	27.0	28.7	112.4	10.50	5.4	6.8	-
3	26.0	27.4	112.4	11.56	10.4	13.1	-
4	27.0	30.0	112.4	10.60	3.1	4.2	-
5	31.1	33.3	112.4	11.56	8.2	10.4	-
6	30.0	32.5	112.4	10.60	5.2	6.6	0.03

The instruments described in Section 2.2.1 were used to obtain most of the measurements in Table 3-11. The dust concentration measurements were obtained using a gravimetric dust sampler described in Appendix A. Elevated temperatures at Points 5 and 6 require further investigation. This area will be the focus, where the objective is to decrease the temperature at Point 5. At the same time, the airflow should be maintained or increased.

B. Ventilation network at the development end

From Table 3-11, Points 5 and 6 have the highest temperatures with high airflow. Here the airflow sources of the working crosscut (point 5) will be investigated to determine the cause of the increased temperatures at point 5. In Figure 3-35, Point 6 is a development end and forms part of the localised ventilation system, Points A, 5 and 6, where Point A is the intake and Point 5 is the system's return.

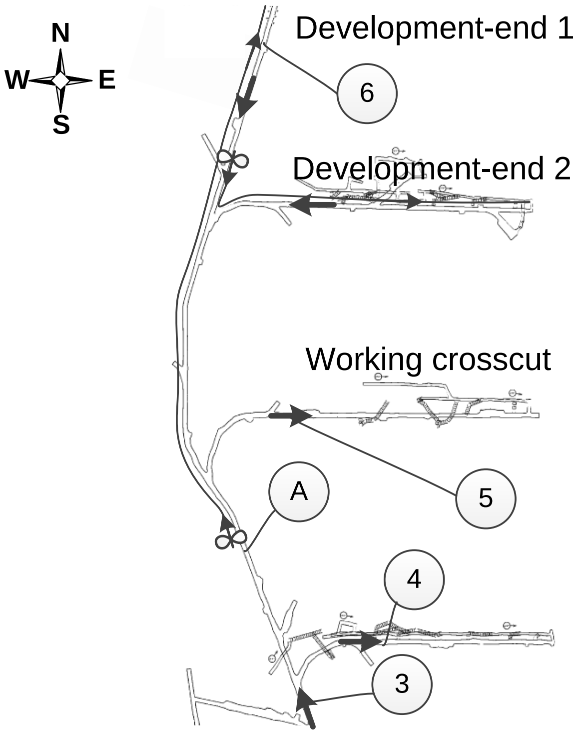


Figure 3-35: Schematic of Level Z of Mine B development end.

Fresh intake air enters the localised ventilation system, where the bulk is picked up at Point A and delivers the air to the development end face at Point 6 via the ducting system. On the way back the air is once again picked up by a fan and directed to the 2nd development-end. After the air is used at the 2nd face the return air flows to the working crosscut (Point 5). The return air from the development-ends mixes with the air flowing from Point A to Point 5. The mixing of air streams from Points A and 6 causes an increase in temperatures and dust concentration at Point 5.

3.3.3. Step 2: Creation of a ventilation simulation

Section 3.3.2 provided information on the underground environment and identified the air mixing. This section is Step 2 of the methodology discussed in Section 2.3.

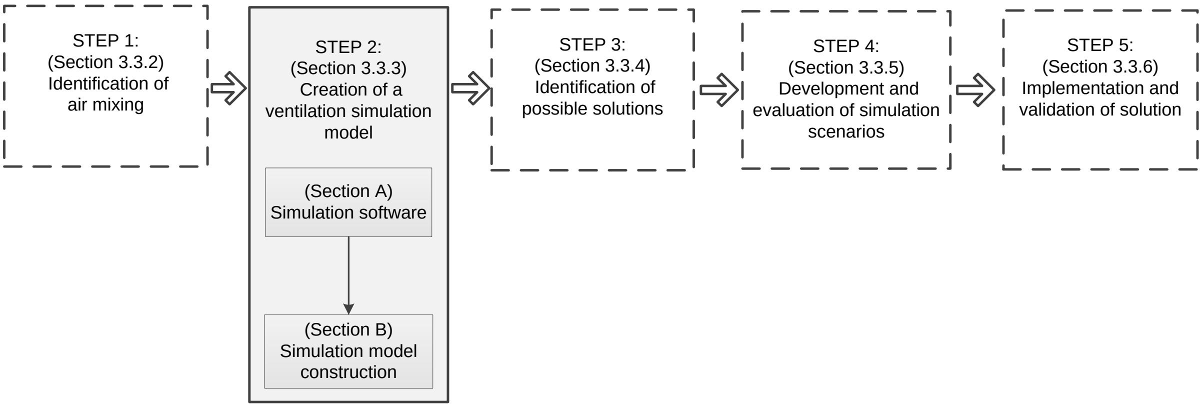


Figure 3-36: Application of Step 2 of the proposed method.

A. Simulation software

The software used to create the simulation model is Process Toolbox (PTB), a mass flow solver with a built-in thermal-hydraulic solver. The data gathered in Section A is sufficient to construct a PTB ventilation simulation model.

B. Simulation model construction

The construction of a simulation model can be categorised into skeleton, and calibration and verification. These two parts are the focus of this section.

Skeleton

The process followed to build the skeleton of Mine B is the same as Mine A in Section 3.2.3.

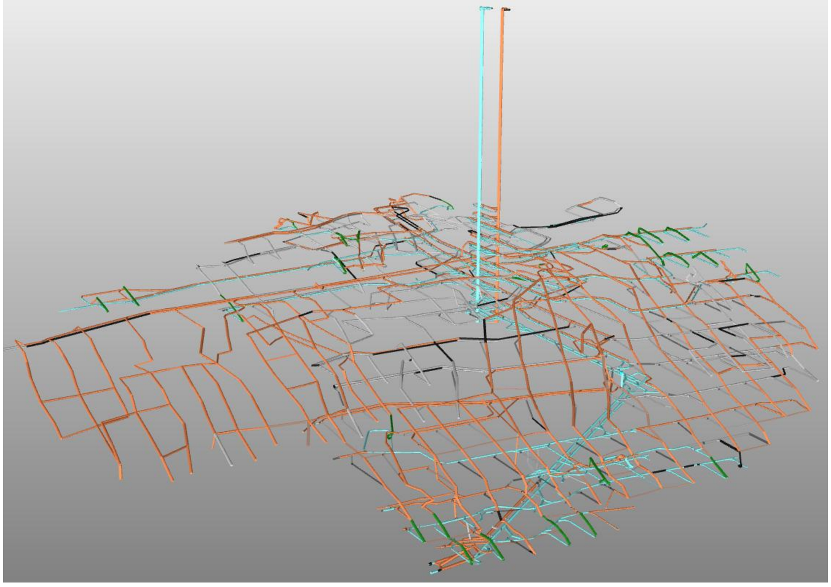


Figure 3-37: A 3D image of the ventilation skeleton model of Mine B.

The airflow in the model resembles the airflow indicated on the volume surveys and the colour assignment is complete. The model will be calibrated and verified with actual measurements in the next section.

Calibration and verification

The process followed to calibrate and verify the simulation model of Mine B is the same as Mine A in Section 3.2.3. This section will provide evidence that the simulation model of Mine A is calibrated and verified.

Figure 3-38 and Figure 3-39 show 14 measurement points close to the identified air mixing area. Figure 3-38 compares the simulated results with the actual measurements of the T_{wb} and plots the MAE of the measurements at each location.

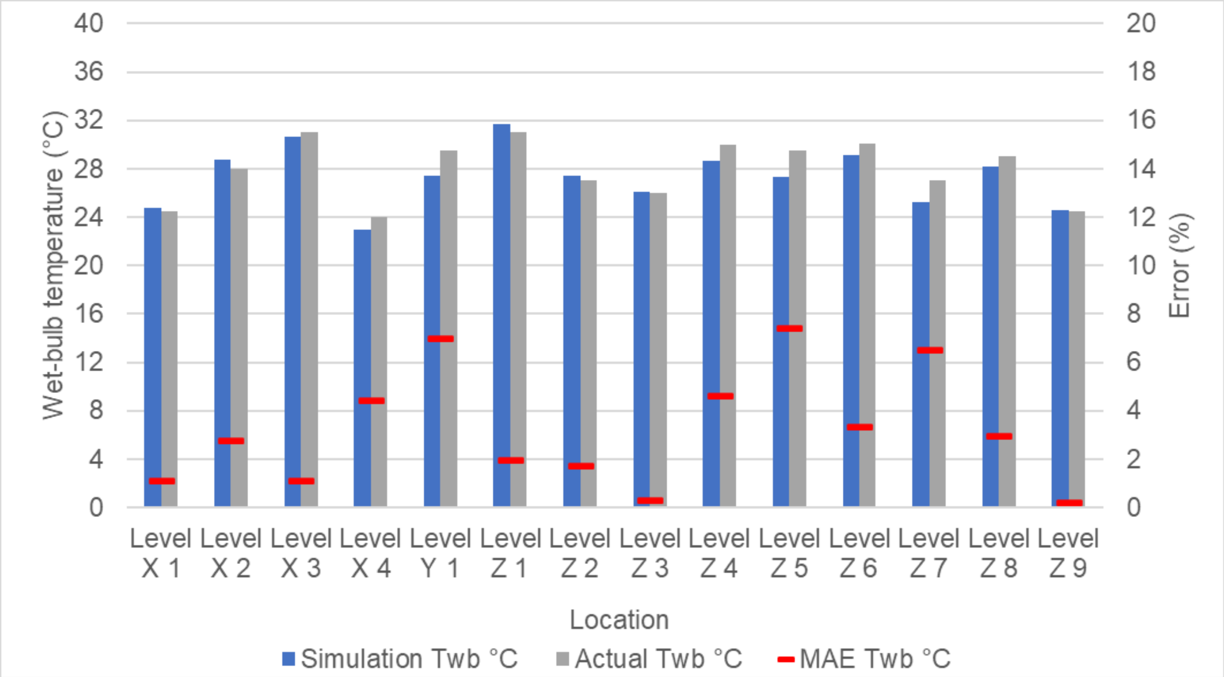


Figure 3-38: Simulation vs Actual comparison of T_{wb} and MAE of Mine B

Figure 3-39 compares the simulated results with the actual T_{db} measurements and plots the MAE of the measurements at each location.

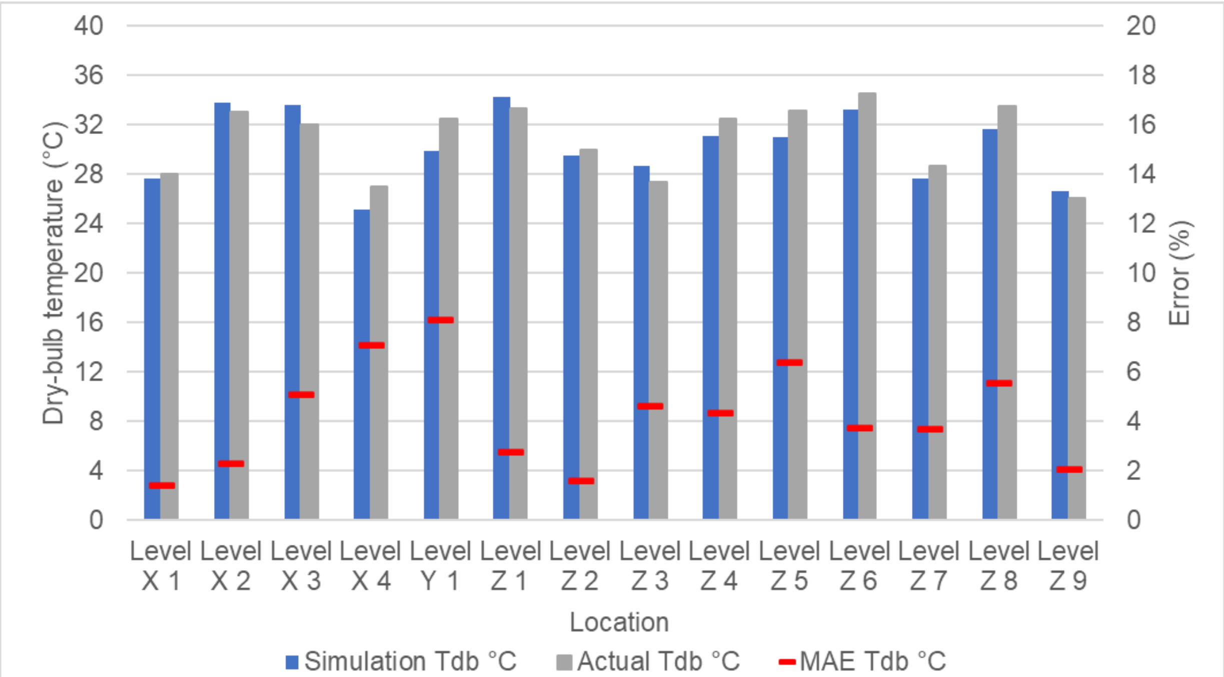


Figure 3-39: Simulation vs Actual comparison of Tdb and MAE of Mine B

Figure 3-40 compares the simulated results with the actual T_{db} measurements and plots the MAE of the measurements at each location.

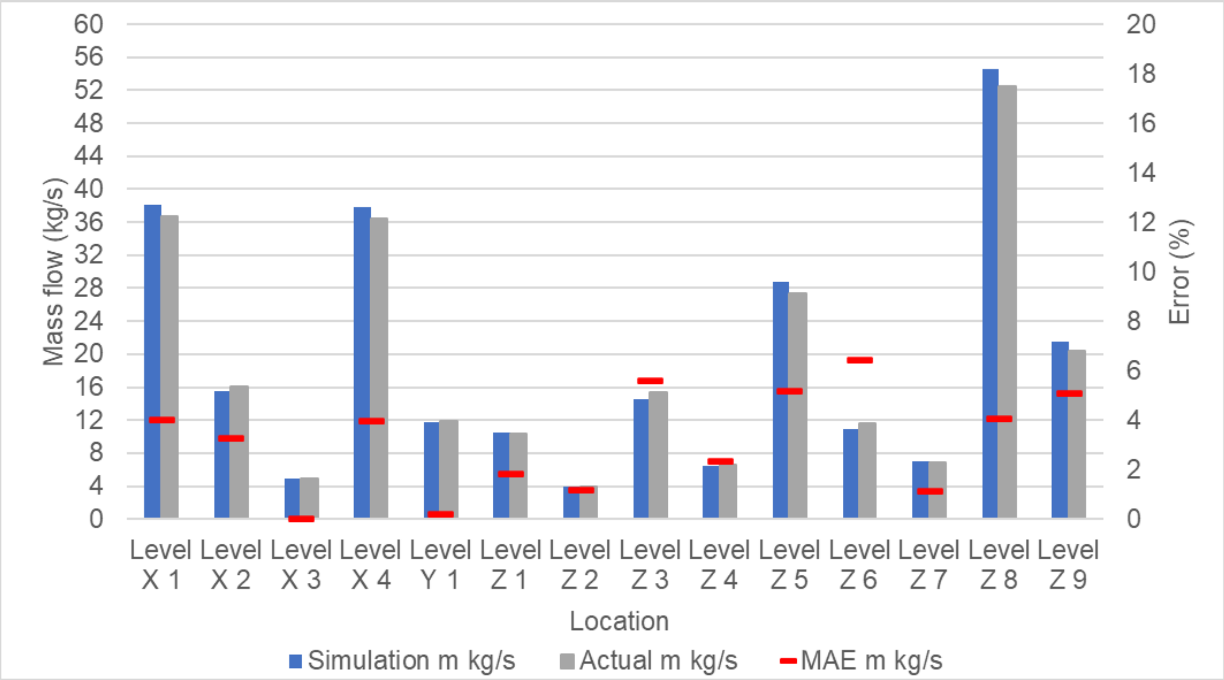


Figure 3-40: Simulation vs Actual comparison of air mass flow and MAE of Mine B

Figure 3-41 shows the MAE as < 5% for the three parameters of the simulated results and the actual measurements.

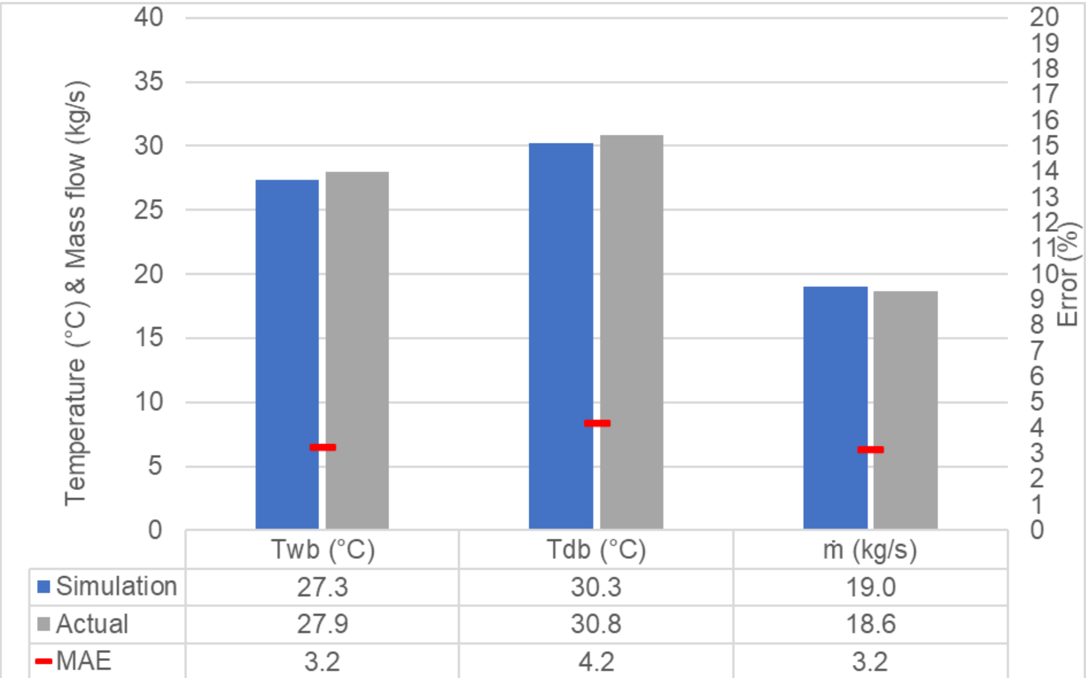


Figure 3-41: Average values of simulation vs actual comparison and error of Mine B

Once the MAE for the parameters is calculated as < 5%, the simulation model is considered accurate and calibrated [92].

After calibration, the simulation results need to be verified. The verification process of a simulation model is when a calibrated simulation model is subjected to the same input changes as the actual underground environment. The simulated results and actual measurements are compared after the input changes are implemented.

A baseline is established to verify the simulation model, to which any change can be compared. The baseline used for the verification is the results, as presented in Figure 3-38 - Figure 3-40. The input change to the actual mine and the simulations was adding a 300 kW MCU. The MCU will receive 6 l/s of water @ 15 °C and force 9.53 m³/s of air over the coils with an axial fan. Figure 3-42 shows the location of the MCU and the key locations to be used for verification.

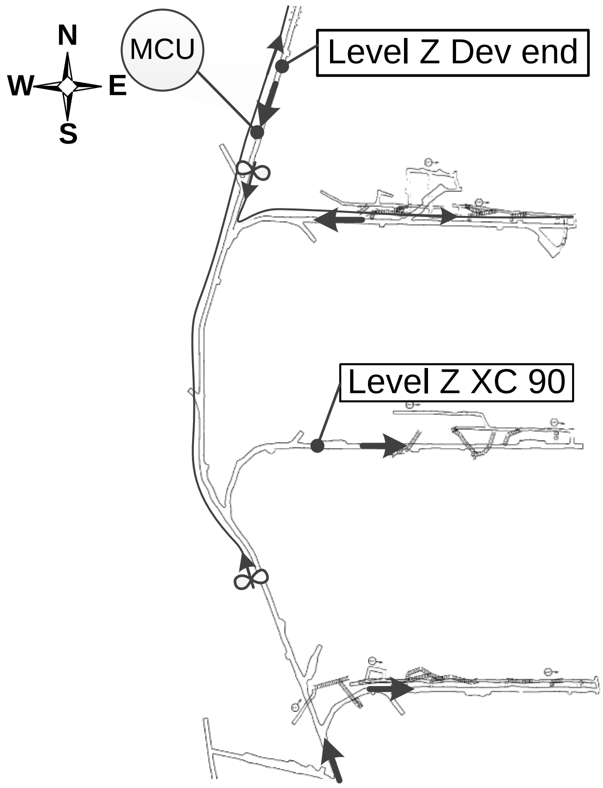


Figure 3-42: Schematic of Level Z of Mine B development end

Two locations were identified and used as KPIs to verify the simulation model: The working crosscut (Level Z XC 90) where the air mixing was identified, and development-end 1 (Level Z Dev end) upstream of the MCU.

Figure 3-43 shows monthly averages of the T_{db}, T_{wb}, and $\dot{m}$ of Level Z XC 90. Furthermore the graph highlights two points. Point 1 the averages for September 2021 and point 2 averages for October 2021.

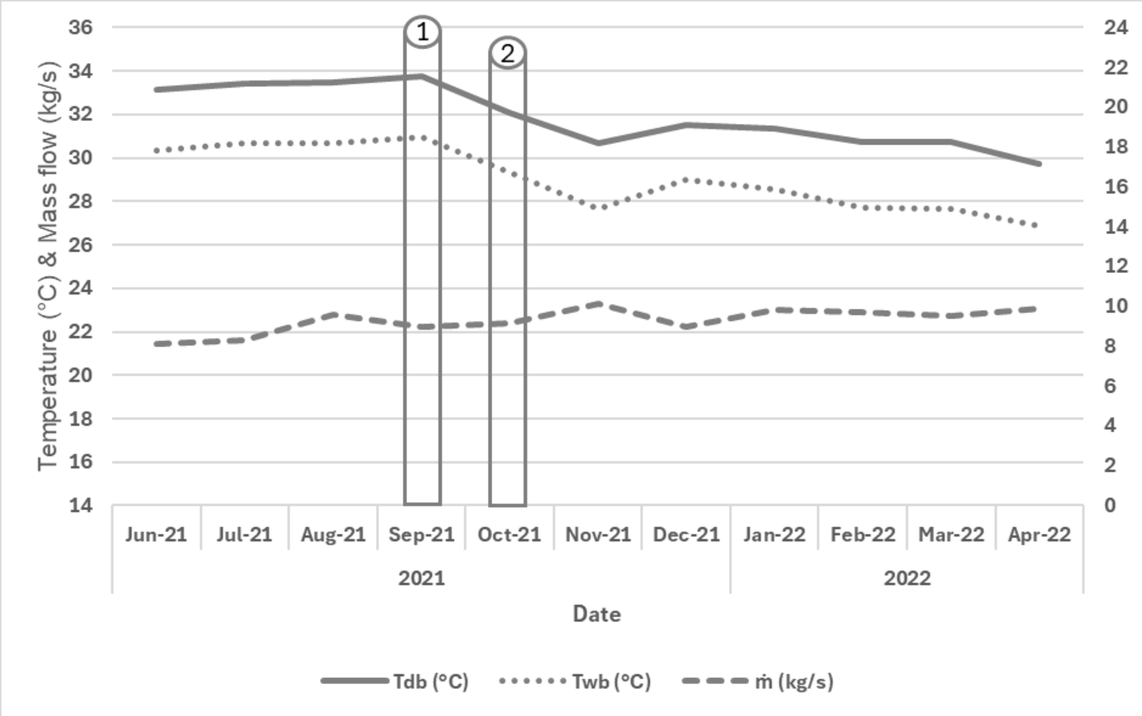


Figure 3-43: Monthly average of XC 90 Intake data

Figure 3-44 shows the baseline simulation results and compares the simulated results with the actual measurements for T_{wb}, T_{db} and ṁ for the identified KPI locations. Where Point 1 in Figure 3-43 is used as the actual measurements.

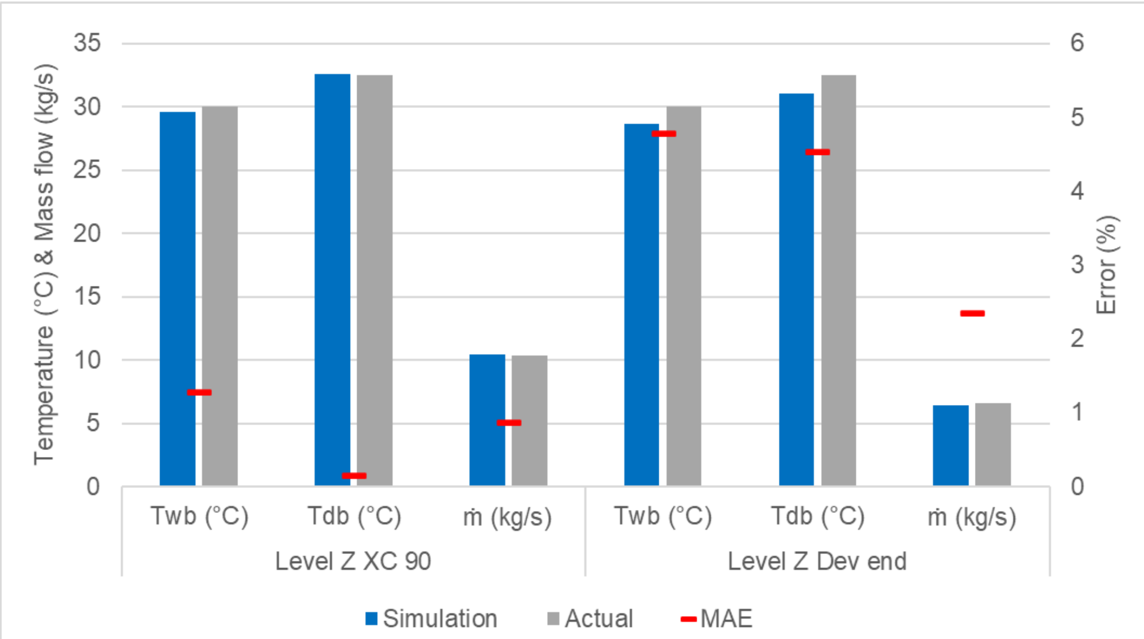


Figure 3-44: Baseline simulation results of Mine B

The addition of the MCU at the indicated locations yielded the results shown in Figure 3-45. Where Point 2 in Figure 3-43 is used as the actual measurements.

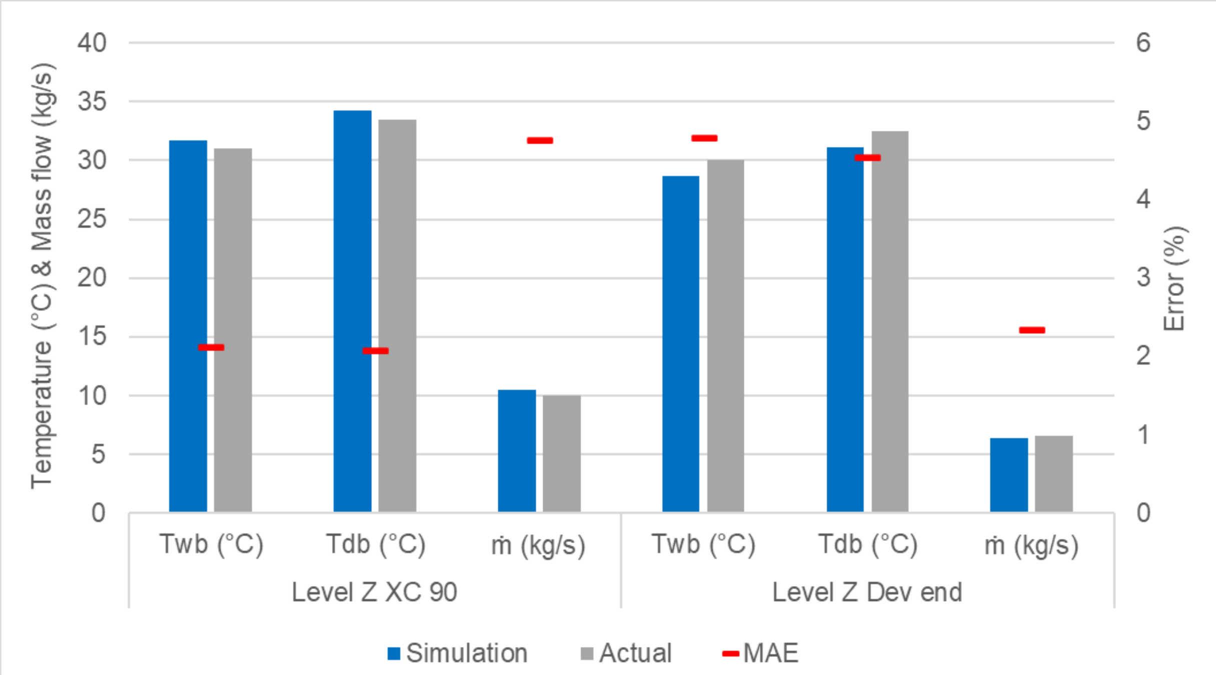


Figure 3-45: Input change simulation verification of Mine B

The MAE between the simulated and actual results for all three parameters is <5%. Therefore the simulation model can be considered accurate and, thus, verified [92]. Table 3-12 provides a comment on how this section has satisfied part of Objective 1.

Table 3-12: Section 3.3.3 satisfies Objective 1.1 of case study 2

OBJ.	Description	Comment
1.1	Build a calibrated ventilation simulation model.	The outcome of Section 3.3.3 is a calibrated ventilation simulation model.

After verification, Step 2 is complete. The various ventilation and cooling methods identified in Section 2.4 will be subject to a decision matrix in the next section.

3.3.4. Step 3: Identification of possible solutions

Section 3.3.3 produced an accurate ventilation simulation model that can be used to test different scenarios to optimise the mine ventilation network. The methods identified in Sections 2.4.1 and 2.4.2 will be evaluated using the tree diagram, Figure 2-22, discussed in Section 2.4.3. The section aims to create a short list of applicable scenarios of which simulations will be constructed to mitigate the air mixing at the working crosscut.

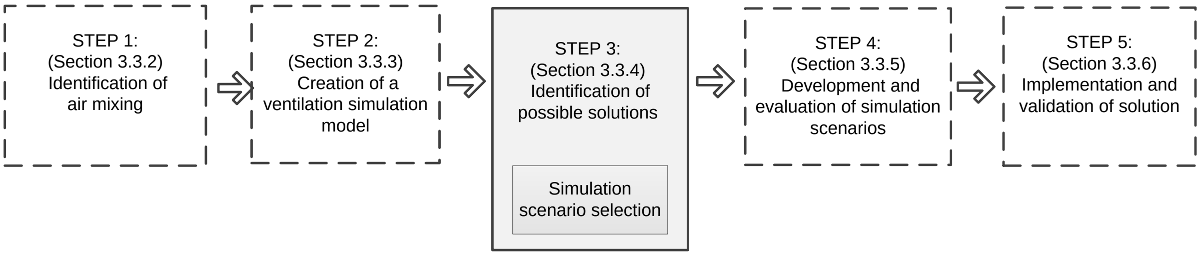


Figure 3-46: Application of Step 3 of the proposed method.

Figure 3-47 was created by following the line of questioning set out in Figure 2-22. The path formed by the coloured blocks results from applying the decision diagram to the case study. The objectives of the study are to decrease the T_{wb} and dust concentrations in working crosscuts while maintaining the airflow at the working crosscut within the legal limits set out by the MHS Act [38].

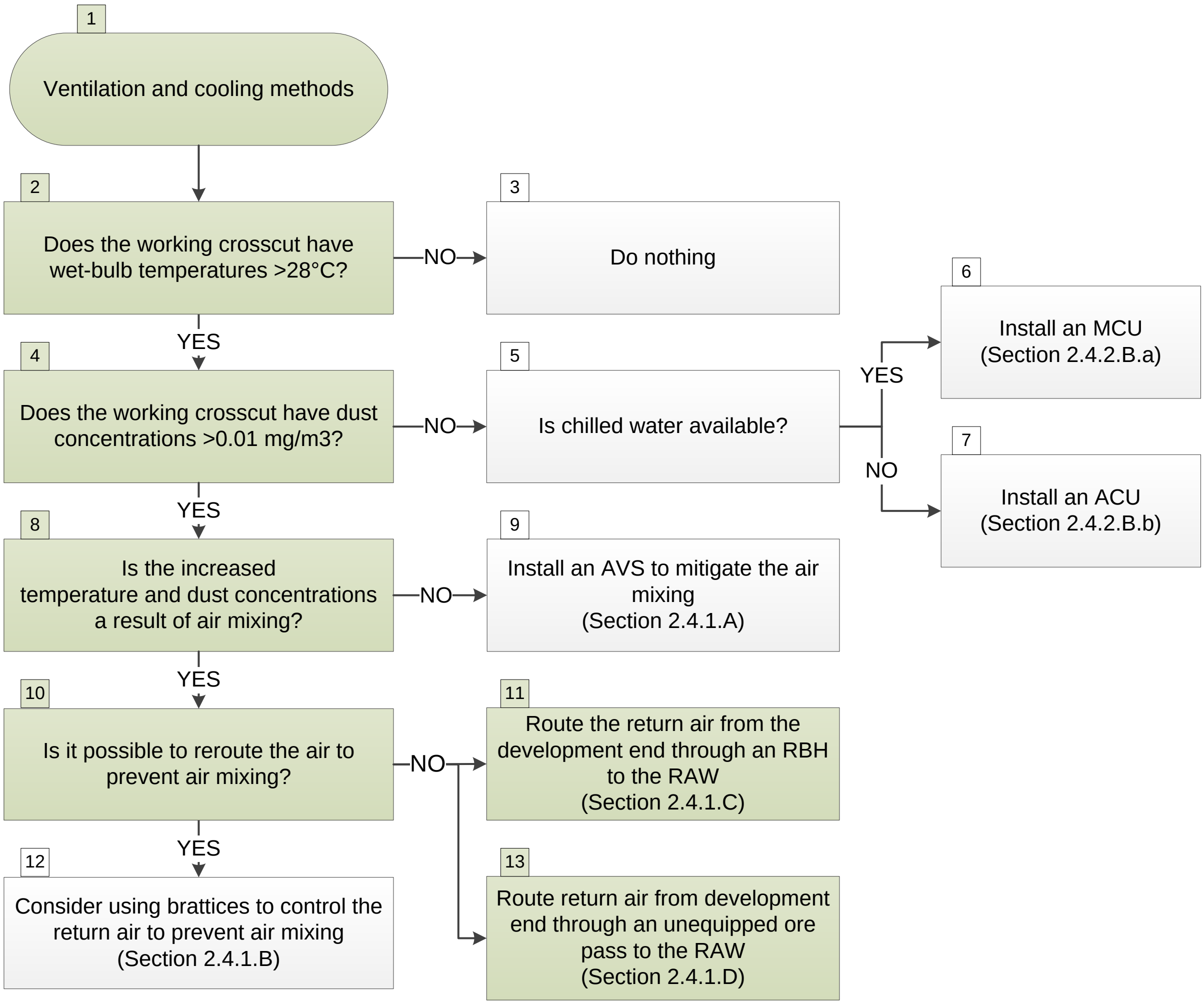


Figure 3-47: Decision diagram applied to case study 2

After the study's objectives were applied to the decision diagram, Figure 3-47 was produced. The figure indicates the possible solutions that satisfy the study's objectives are RBH and unequipped ore pass, as described in Sections 2.4.1.C and 2.4.1.D, respectively.

Table 3-13: Section 3.3.4 satisfies Objective 1.3

OBJ.	Description	Comment
1.3	Provide a decision diagram that will aid in choosing the optimal solution.	Section 3.3.4 used the decision diagram provided in Section 2.4.3 to identify 2 solutions.

The possible solutions identified in this step will be implemented into the ventilation simulation model, built in Section 3.3.3, to develop and evaluate scenarios in Section 3.3.5.

3.3.5. Step 4: Development of evaluation of simulation solutions

This section will focus on developing simulation scenarios for the possible solution identified in Section 3.2.4. Figure 3-48 shows the subsections required to complete Step 4 of the methodology discussed in Section 2.5.

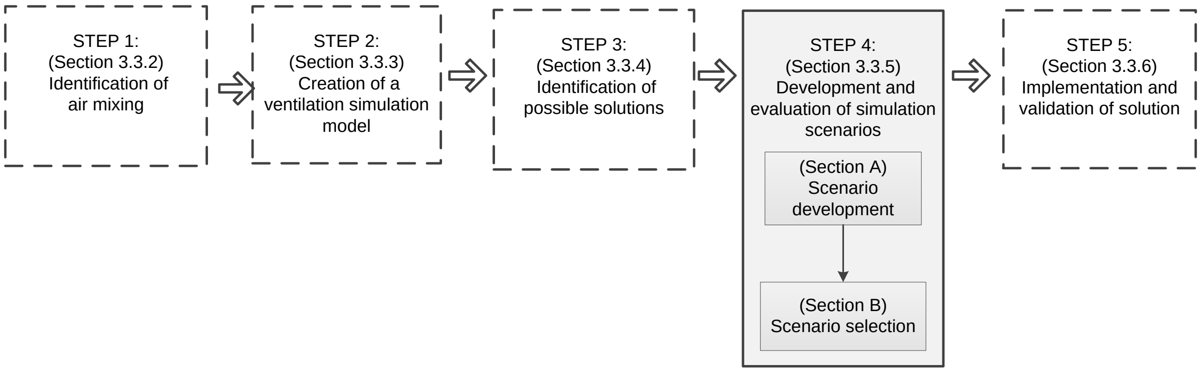


Figure 3-48: Application of Step 4 of the proposed method.

The locations chosen for the comparison were selected to determine which scenario satisfies the objective. One of the locations (point 1) corresponds with the intake of Level Z XC 90. The objectives are to decrease the T_{wb}, decrease the dust concentration, and ensure the airflow meets MHS standards. Air mixing was identified as the cause of the increased T_{wb} and dust concentrations at the working crosscut.

The ventilation methods proposed in Section 3.3.4 aim to mitigate the increased T_{wb} and high dust concentrations at the working crosscut. The one scenario will include a solution to discard the hot return air from the development ends to the RAW before it mixes with the fresh intake air of the working crosscut. The other was deemed impractical due to the mine layout and no solution was developed for the.

A. Scenario development

Scenario 1 – RBH

Scenario 1 features an RBH connecting the working level to the RAW on the level above. The RBH is connected from the haulage on the working level to an old crosscut on the level above. The old crosscut is converted to a RAW.

This case study has two development ends and requires AVS to supply the development faces with sufficient airflow. Firstly, a 45-kW fan was placed in the haulage leading to the development end to pick up the fresh air and introduce the fresh air directly onto the face. Then the air needed to reach the second development end, and another AVS delivered air to the 2nd development face.

An RBH requires additional development, however this RBH will serve as a main return for all future crosscuts on the level. The location of the RBH is critical to ensure ventilation standards are met, as described in Section 1.2.2 A. It will serve as a RAW for multiple development ends on the level discarding the hot return air to the level above (Upper level). Figure 3-49 depicts the area's layout where hot return air from the development ends and the fresh intake air of the working crosscut mixed.

The figure indicates the area intake, working crosscut, stoping area, measurement points, the proposed fan and ducting placement, the location of the RBH. The blue coloured lines indicate fresh intake air, with the orange line representing hot return air. At the same time, the green lines show the stoping area where the drilling and blasting of the gold mining process occur, as described in Section 1.3.

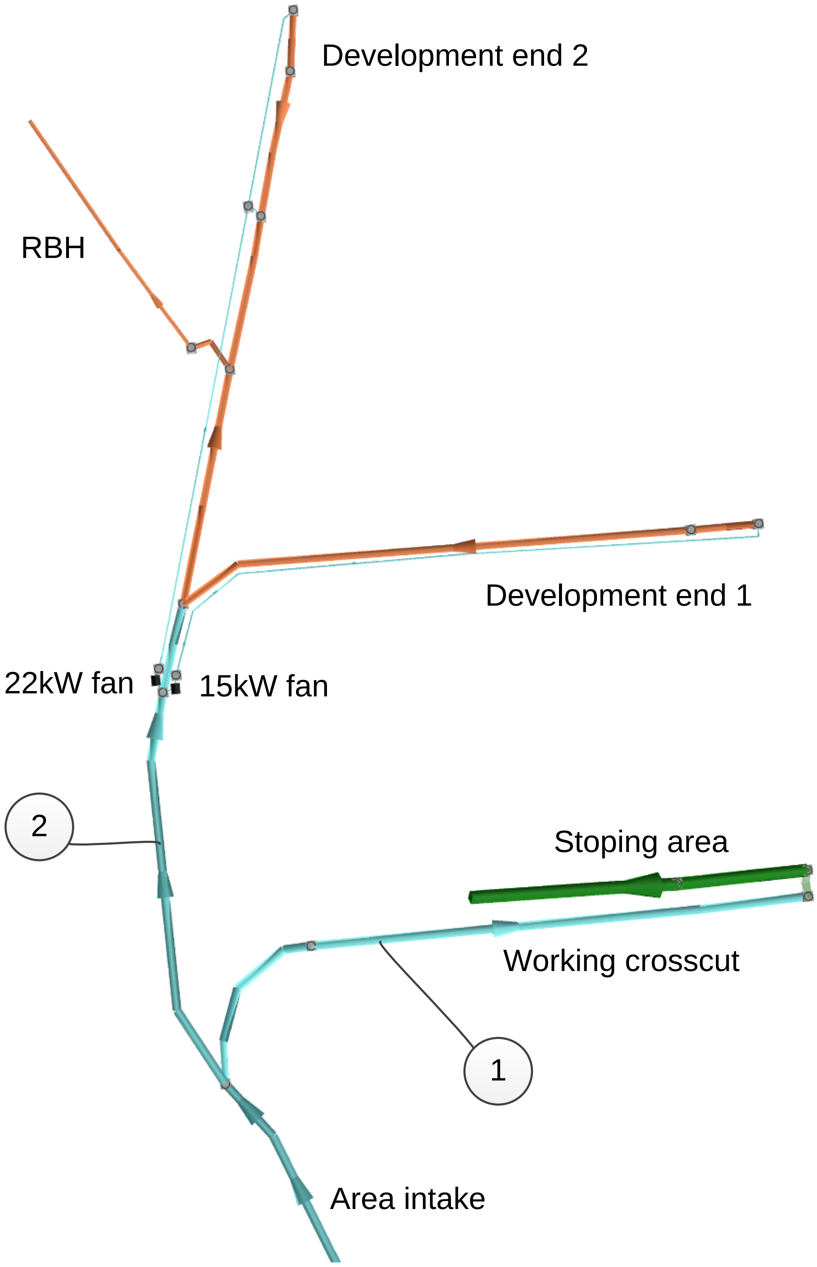


Figure 3-49: Scenario 1 – RBH of case study 2

The results from the simulation model with Scenario 1 implemented are shown in Figure 3-50 compared to the baseline. The figure shows the T_{wb} and $\dot{m}$ of the air for both scenarios and measurement points. Points 1 and 2 represent the measuring point for the working crosscut and haulage leading towards the development ends, respectively.

Figure 3-50 compares the simulated results of the baseline simulation and Scenario 1 simulation.

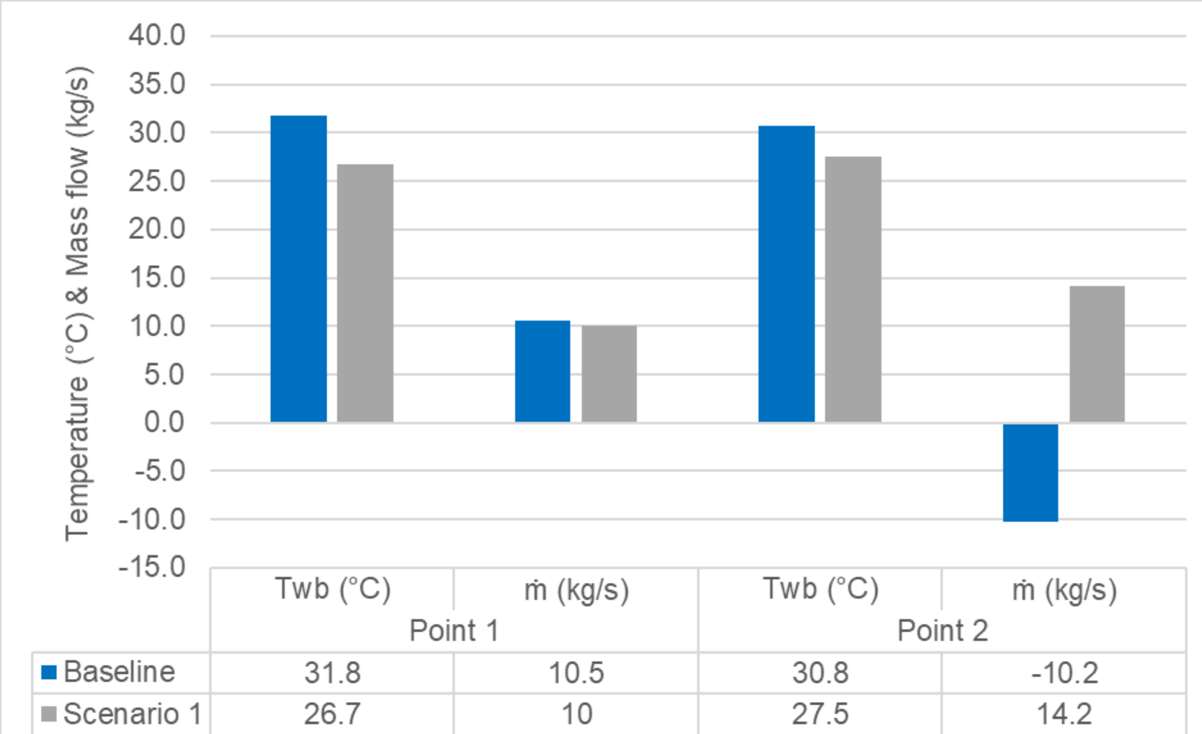


Figure 3-50: Baseline in comparison to Scenario 1 of case study 2

Figure 3-50 shows that introducing an RBH at the specified location has a desirable effect on the system. Scenario 1 resulted in a 5.1 °C decrease in T_{wb} at Point 1 and a 3.3 °C decrease in T_{wb} at Point 2. Furthermore, a slight reduction in airflow at Point 1 was observed. Most notably, a flow reversal was achieved at Point 2. The flow reversal observed at Point 2 indicates that no air mixing will occur at the intake of the working crosscut.

The RBH is an additional piece of ventilation infrastructure. Additional costs will be required to develop the RBH. The projected development cost for the proposed RBH is R 5.7 Mil (RBH = R 4.8 Mil and Break away from haulage to base of RBH = R 0.9 Mil[9]). The effect on production time will depend on whether a third party will develop the RBH or will the mine use its personnel. The use of a third party will have no impact on the production, whereas pulling personnel from another project could affect the other project's timeline.

Table 3-6 shows a breakdown of the development time for an RBH. (conventional blasting not reaming)

Table 3-14: Development time for scenario 1 of case study 2

Description	Advance per blast (m)	Blasts per month	Length (m)	Development time (months)
RBH development	0.9	16	130	9.0
Flat development	2.0	16	30	0.9
		Total development time (months)		10.0

[9] Costs derived from other projects, costs may vary if a third party is used for the development.

This RBH will serve as a RAW for all the future development ends on the level.

Scenario 2 – Unequipped ore pass

As discussed in Section 2.4.1-D, it is essential to have an existing winze from the level above to consider using an unequipped ore pass as an RAW. In this case, the crosscut from the level above does not have an existing winze. Thus, to develop an ore pass and a centre gully to connect to the level above's raise will not be feasible due to a large amount of rock in the haulage.

Table 3-15: Scenario summary of case study 2

KPI		Description	
		Scenario 1	**Scenario 2**
Primary	Temperature	Decreased T_{wb} by 5.1 °C and 3.3 °C ate point 1 and 2	-
	Dust	Diverted air/dust from dev end to RAW	-
	Airflow	• Airflow direction reversal at point 2 mitigates air mixing • Airflow quantity at point 2 is above the legal limit.	-
Secondary	Additional development time	The RBH can be developed parallel to the production/development teams. (Development time = 10.0 months)	-
	Cost	Parallel development requires additional crews and will require R 5.7 Mil to develop an RBH.	-
	Sustainability & Repeatability	The RBH will be the only RBH required for the entire remaining life-of-mine of the level.	-

Table 3-15 will be used to score each scenario using the evaluation matrix provided in section 2.5.2 (Table 2-7). The evaluation matrix will be populated in the next section and used for the solution selection.

B. Solution selection

Sections 3.3.5.A provided results for one of the two scenarios identified as possible solutions in Section 3.3.4. This section will not be completed as described in Section 2.5.2 as only one scenario was developed. The next section will discuss the implementation of the scenario, and the simulation validation.

3.3.6. Step 5: Implementation and validation

Section 3.3.5 evaluated different scenarios through simulation and concluded with Scenario 1 as the final solution. Scenario 1's implementation is discussed, and the validation of the simulation results is discussed in Section 3.3.6. B. This section will provide the results of the implemented solution and compare the actual measurements before and after implementation. Figure 3-51 shows the two sections to complete in Step 5 of the methodology discussed in Section 2.6.

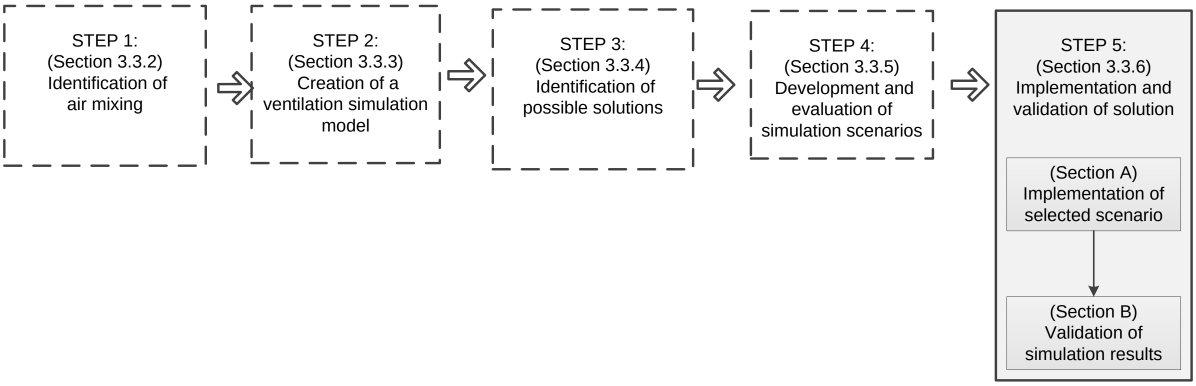


Figure 3-51: Application of Step 5 of the proposed method.

A. Implementation of selected scenario

Scenario 1 was implemented in the ventilation network in the middle of November 2021. The implementation steps included changes to the AVS in the ventilation network to resemble the AVS described in Figure 3-49. The RBH will serve as a return for the rest of the half level development.

In Section 3.3.3, Figure 3-43 showed the average values of each month where point 1 was used calibrate and point 2 to verify the simulation model. Following this it would make sense to use point 3 shown in Figure 3-52. However, the average of the whole month would be an incorrect value as the implementation only occurred in the middle of November. Therefore, the correct average value to use is the second half of November as indicated by the green block on the left-hand side of the graph in Figure 3-53.

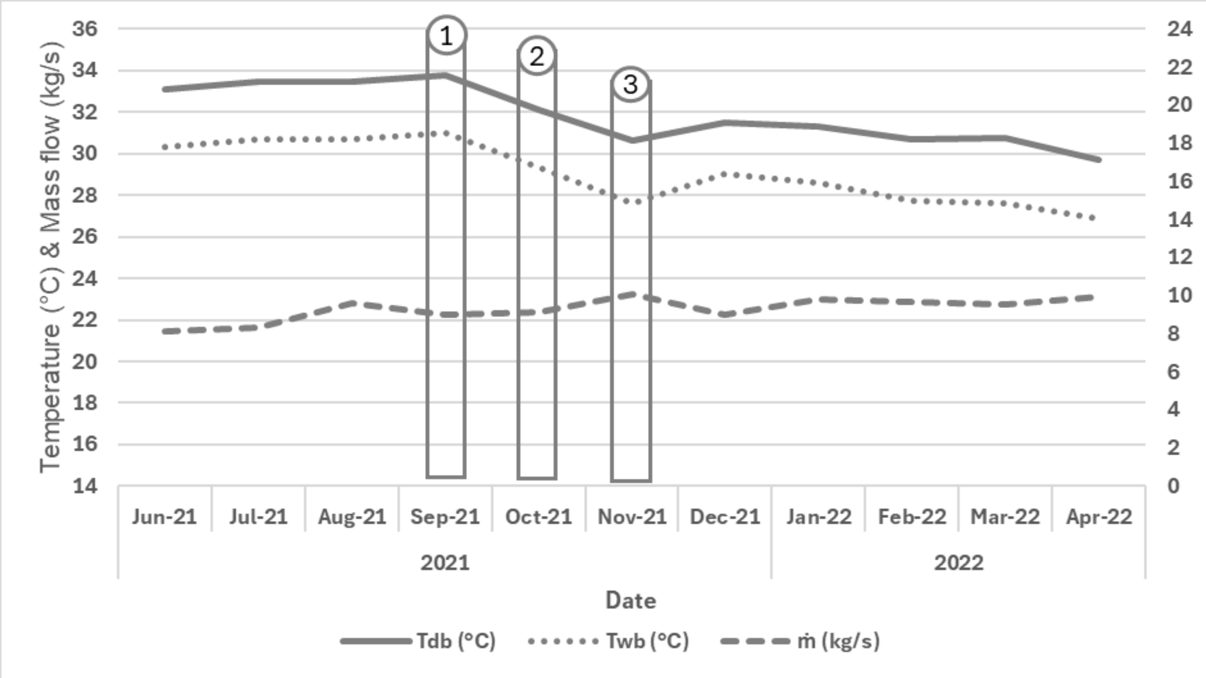


Figure 3-52: Monthly averages of XC 90 data

Figure 3-53 shows the daily average values for XC 90 intake. The graph has four shaded areas. Firstly, the white area is the period of November before implementation, where the first green block is when implementation started. The grey third block, the whole of December, is excluded from the study as irregular air flows were seen greatly affecting the temperatures. The fourth block shows the whole of January where the airflows have stabilised as well as the temperatures. The average T_{db}, T_{wb}, and $\dot{m}$ were calculated for both green blocks as actual measurements for the validation section.

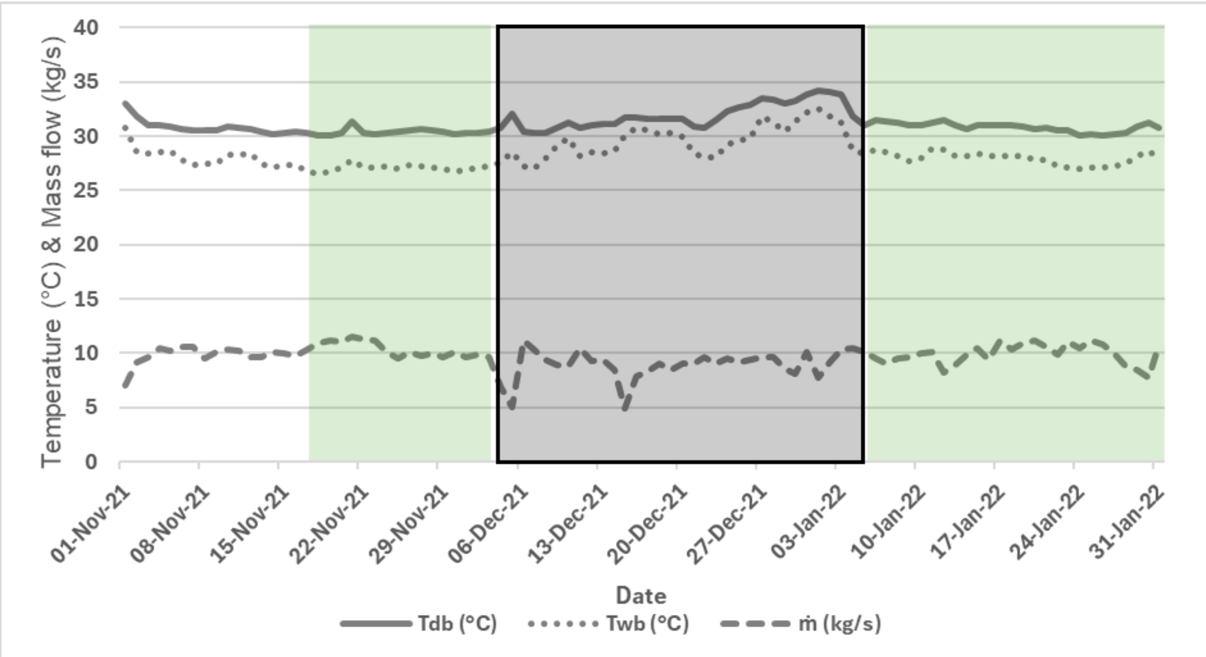


Figure 3-53: 3-months daily average XC 90 intake data

Although Figure 3-53 does not show much change in airflow after the implementation, Figure 3-54, shows a significant jump in airflow. Figure 3-54, is the daily average half level intake data, and provides evidence (grey block) of the irregular airflow to this area.

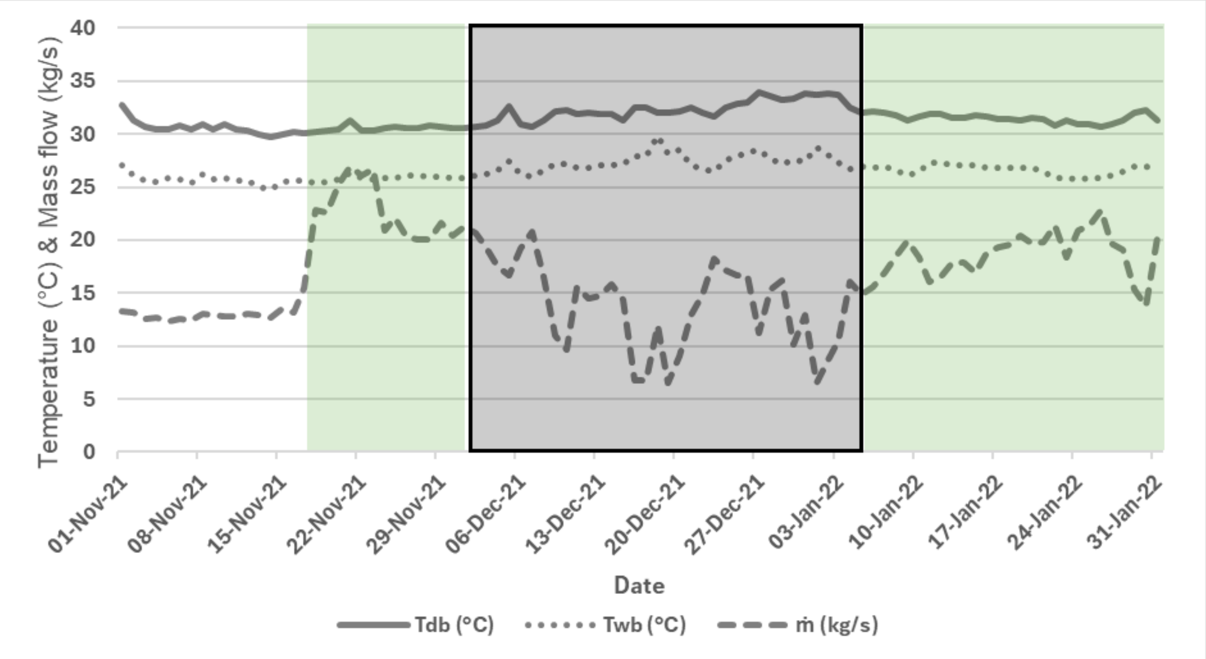


Figure 3-54: 3 month daily average half-level intake data

The averaged values for XC 90 in the green block in Figure 3-53 will be used as the actual measurements for the validation of simulation results.

B. Validation of simulation results

Figure 3-28 compares the simulated results for Scenario 2 with the actual measurements after Scenario 2 was implemented in the ventilation network. The figure includes the T_{wb} and ṁ of the two KPI locations identified in Section 3.2.5. At the same time, the MAE of the simulated vs actual results is plotted for the different parameters and locations.

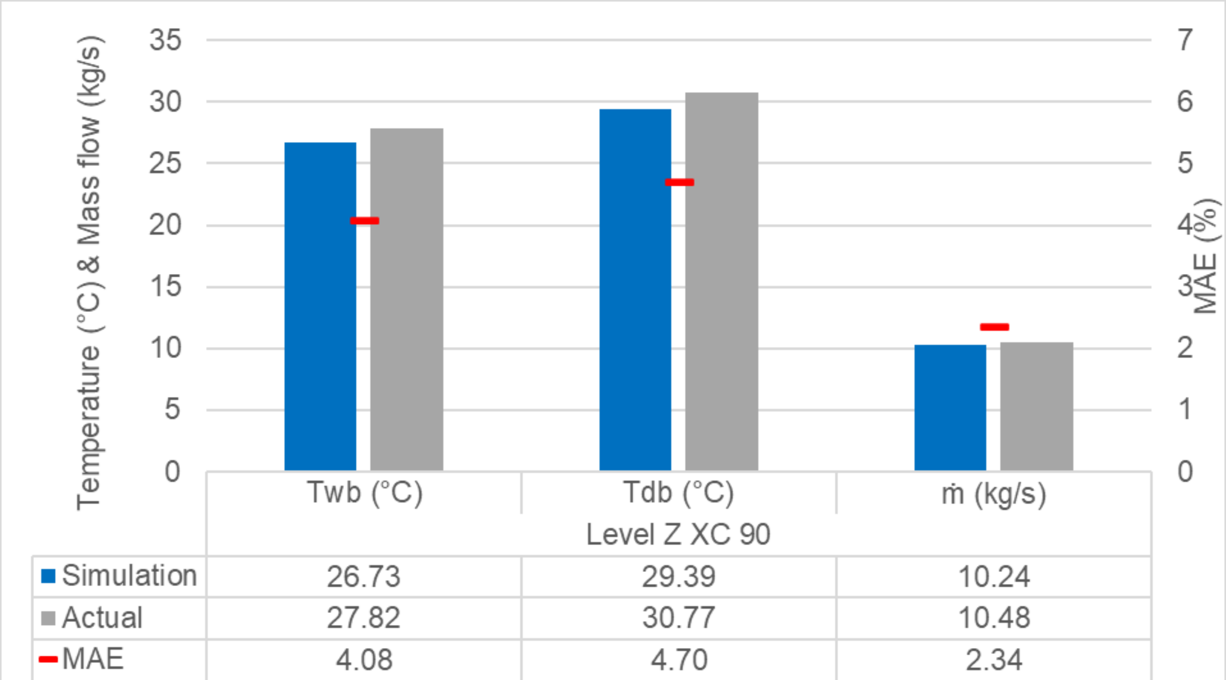


Figure 3-55: Simulation validation results of case study 2

From Figure 3-55, the average MAE is calculated as 3.7%. Therefore, the solution developed using simulation software is validated by actual measurements.

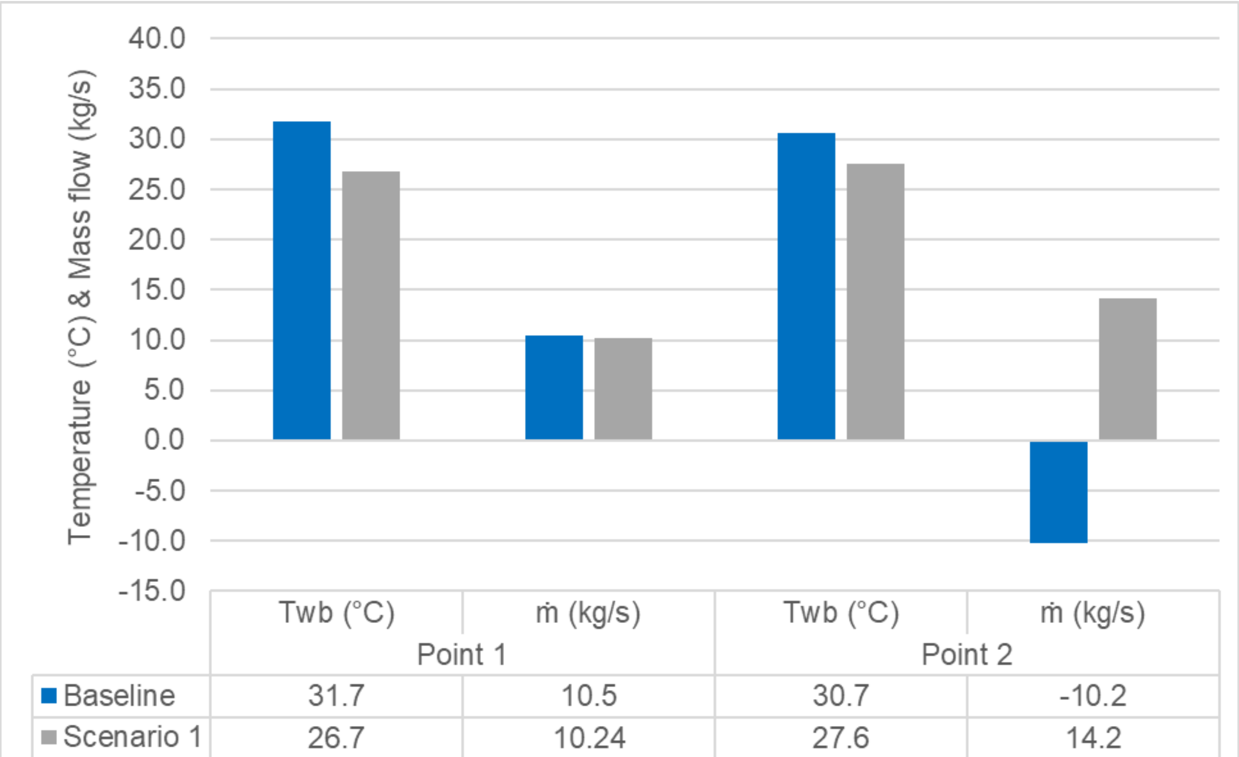


Figure 3-56: Actual measurements compared before and after implementation of case study 2

From Figure 3-29, the T_{wb} decreased by 5.0 °C and 3.1 °C at Point 1 and 2, respectively. The flow reversal at Point 2 indicates that the air flows away from the working crosscut, preventing air mixing at the working crosscut intake. Furthermore, the air mass flow rate decreased by 0.26 kg/s but still managed to supply the working crosscut with a mass flow rate of 10.24 kg/s of fresh intake air. Table 3-16 discusses how this section satisfied Objectives 2.1 to 3.1 outlined in Section 1.6.

Table 3-16: Chapter 3.3 study objectives achieved

OBJ.	**Description**	**Comment**
2.1	Decrease the wet-bulb temperature of working crosscuts.	The intake T_{wb} for the working crosscut on level Z was reduced by 5 °C.
2.2	Decrease dust concentrations of working crosscuts.	The airflow reversal at Point 2 indicates that the intake dust concentration was reduced with the dust produced at the development end.
2.3	Maintain the airflow requirements of working crosscuts as prescribed by the MHS Act.	Figure 3-56 shows that the working crosscut intake airflow at point one is 10.24 kg/s
3.1	Is the MAE of the actual vs simulated results < 5%?	Figure 3-55 shows that the MAE of the T_{wb} and $\dot{m}$ are < 5%.

From Table 3-16, it is clear that the method proposed in Chapter 2 is valid to prevent air mixing at the intake of working crosscuts to decrease the air temperature and dust concentrations.

3.4. Summary

In this Chapter, the method provided in Chapter 2 was applied to two different mines and is discussed as two separate case studies. The method addressed the following objectives outlined in Section 1.6:

2. Apply the method provided to improve the ventilation conditions.
   2.1. Decrease the wet-bulb temperature of working crosscuts.
   2.2. Decrease dust concentrations of working crosscuts.
   2.3. Maintain the airflow requirements of working crosscuts as the MHS Act prescribes [38].
3. Validate the simulation results after the optimal solution has been implemented (Section B).
   3.1. Is the MAE of the actual vs simulated results < 5%?

Figure 3-57 shows an overview of the study method provided in Chapter 2.

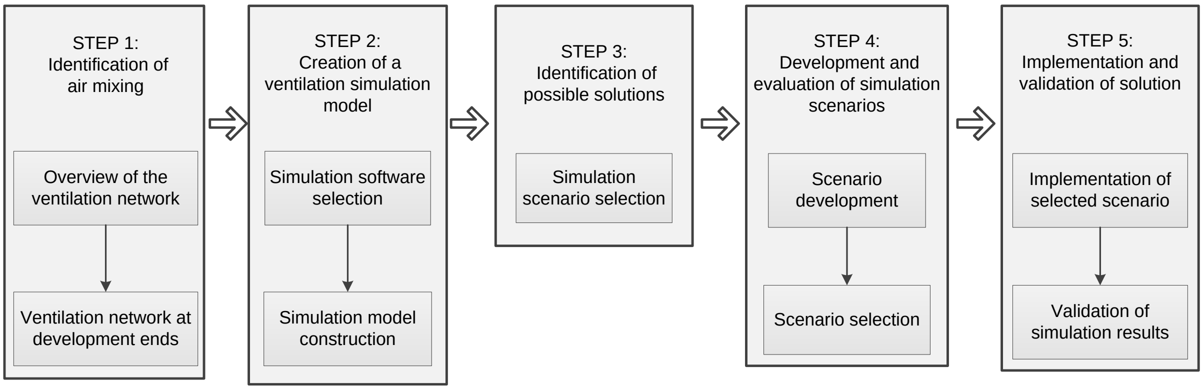


Figure 3-57: Study method overview

Steps 1, 2, and 3 does not directly satisfy any of the objectives mentioned but is necessary for Step 4 and 5. Where Step 4 and 5 satisfies objective 2 and respectively. Brief discussions of Steps 1 to 5 are provided to summaries how the steps were applied to each case study.

Steps 1, 2, and 3 are similar for case study 1 and 2 as the processes of air mixing identification, ventilation simulation model creation, and possible solution identification are followed as described in Sections 2.2-2.4.

Step 1 – Identification of air mixing focussed on gathering information on the underground ventilation network, including primary fan curves, secondary cooling infrastructure (only Case study 2), DXF layouts, volume surveys, and minutes of discussions with the mine personnel.

After thoroughly analysing the volume surveys, the air mixing was identified on Level X (Mine A) and Level Z (Mine B), where the hot development end air returned to the RAW through the working crosscut. The levels identified are the deepest of the respective mines.

Step 2 – Creation of a ventilation simulation model focused on creating a verified ventilation simulation model of the underground ventilation network, with which different scenarios can be simulated and evaluated. Firstly, a simulation software package was selected, after which DXF layouts were imported. A skeleton model was created by adding ventilation components along the DXF layouts in the simulation environment. The simulation model was calibrated and verified using measurements recorded throughout the underground ventilation network.

Step 3 – Identification of possible solutions provided the reader with possible solutions to mitigate various ventilation problems in an underground ventilation network. The solutions were categorised into ventilation methods and cooling methods. Ventilation methods focused on improving air quantity and quality and decreasing air temperatures. At the same time, cooling methods were solely used for reducing air temperatures. A decision diagram was used to decrease the number of possible solutions to only those satisfying the study's objectives. The problems for the case studies were similar where the intake T_{wb} of the working crosscuts exceeded 28 °C and the dust concentrations of the at the development ends were >0.03 mg/m^3. The decision diagram yielded the same possible solutions for both case studies due to the problem similarities. The two possible solutions highlighted by the decision diagram were using an RBH as a RAW and an unequipped ore pass as a RAW.

The similarities between the cases end at Step 4. Both possible solutions identified for case study 1 were developed and evaluated as scenario 1 and 2. Whereas only one possible solution was developed an evaluated as scenario 1, as the underground excavations in the area did not meet the solution requirements.

Step 4 – Development and evaluation of simulation scenarios provided two scenarios with simulated results for case study 1 and one for case study 2.

Case study 1 provided two scenarios with simulated results for case study 1. The simulated results of each scenario were compared to the baseline simulation to determine which scenario would satisfy the study's objectives. The scenarios were subject to a decision matrix for further analysis, where other parameters were introduced and compared. The two scenarios, in case study 1, yielded similar and favourable results as both decreased the T_{wb} by 3 °C and dust concentrations by inducing a flow reversal. At the same time, maintained the air flow rate to the last working crosscut. Scenario 2 – Unequipped ore pass was selected as the final solution as this scenario satisfied the study's objectives discussed in Section 1.6 and did not require additional development time or capital compared to scenario 1.

Case study 2 only provided one scenario with simulated results. The simulated results of the scenario were compared to the baseline simulation to determine whether the scenario would satisfy the study's objectives. The scenario was subject to a decision matrix for further analysis, where other parameters were introduced and compared. The scenario decreased the working crosscut intake T_{wb} by 5 °C and dust concentrations by inducing a flow reversal. At the same time, maintained the air flow rate to the last working crosscut. The scenario satisfied the study's objectives discussed in Section 1.6 and was therefore chosen as the final solution.

Step 5 – Implementation and validation of solution focused on the results after the implementation of the final solution. Furthermore, the section provided a comparison between the simulated results and the actual results after the solution was implemented.

Case study 1 saw the successful implementation of the proposed scenario. Where an ore pass was left unequipped to serve as a dedicated RAW until through ventilation was realised in the development end. Mine A does not have continuous measurement equipment. The measurements used in the comparison to validate the simulation model was spot measurements. The comparison results validated the simulation model by yielding an average MAE of 2.2%.

Case study 2 implemented the RBH as this was a one-time development which will serve as an RAW for the entire life of the half level. Mine B does have continuous measurement devices at the working crosscut intake and the half level intake. The devices have a resolution of 30 minutes but was averaged to daily values to determine the day of implementation. After which, monthly averages were used to calibrate, verify, and ultimately validate the ventilation simulation model. The comparison results validated the simulation model by yielding an average MAE of 3.7%.

4. CONCLUSION AND RECOMMENDATIONS

4.1. Summary

Underground mines have complex and constantly expanding ventilation networks. Applying AVS at the points of expansion usually result in an inefficient ventilation network with increased air temperatures and dust concentrations.

Deep-level mines are constantly expanding laterally and increasing in depth. While the lateral expansion makes the ventilation network more complex, the deepening increases the heat that is added to ventilation air as a result of auto compression. Less air can reach the workings further from the shaft due to the network's increased resistance caused by longer airways with smaller widths. Therefore, it is increasingly difficult to follow ventilation regulations, such as deep-level mine temperature and dust exposure regulations.

When secondary cooling is not available to reduce elevated air temperatures, special attention is given to maintain airflow throughout the mine. Especially while operating crosscuts at higher temperatures near development ends. The fresh air flowing to the working crosscut deteriorates as it mixes with the return air from the development end. The return air of the development end is returned to the nearest working crosscut with through-ventilation. In the long run, eliminating air mixing will raise the temperature of the air going to the workspaces and enhance air quality because no dust created at the development end will enter the workspaces.

Chapter 1 provided an overview of ventilation networks in deep-levels mines, after which a literature review was conducted on simulation, optimisation, contamination, improvement techniques, and methods, all regarding the improvement of ventilation networks in deep-level mines, particularly to decrease T_{wb} and dust concentrations of fresh intake air.

The study aimed to develop a method to reduce the air temperatures and dust concentrations of fresh intake air flowing to working crosscuts. Section 1.6 provided objectives to achieve the study’s aim.

Chapter 2 provided a method to mitigate increased air temperatures and dust concentrations in deep-level gold mines.

Chapter 3 provided two case studies where the method discussed in Chapter 2 was applied to two deep-level gold mines. In both mines increased air temperatures and dust concentrations were recorded.

Case study 1 was done at Mine A, a South African gold mine, has an average mining depth of 1 290 m and a maximum depth of 1 370 m. The mine has no chilled water or dedicated RAWs on the active working levels.

Air mixing on the deepest level of the mine resulted in increased temperatures and dust concentrations at the intake of the working crosscut. The air mixing was identified in Step 1.

Step 2 delivered a calibrated and verified ventilation simulation model capable of predicting air conditions due to modifications in the underground ventilation network.

Step 3 provided two possible solutions out of the initial nine identified from the literature in Sections 2.4.1 and 2.4.2. The two possible solutions were to: develop an RBH and use it as a RAW or use an unequipped ore pass as a RAW.

Step 4 developed and evaluated scenarios from the two possible solutions selected in Step 3. Furthermore, a selection process was followed to select the solution where an unequipped ore pass is used as a RAW.

Step 5 discussed the implementation process of the solution in the mine and provided results which validated the study's methodology. The implementation resulted in the mitigation of the air mixing at the crosscut intake which led to a T_{wb} decrease of 3 °C at the intake of the working crosscut.

Case study 2 was done at Mine B, a South African gold mine, has an average mining depth of 1 880 m and a maximum depth of 2 286 m. The mine does have refrigeration plants which supplies chilled water to a surface BAC and underground.

Air mixing on the deepest level of the mine resulted in increased temperatures and dust concentrations at the intake of the working crosscut. The air mixing was identified in Step 1.

Step 2 delivered a calibrated and verified ventilation simulation model capable of predicting air conditions due to modifications in the underground ventilation network.

Step 3 provided two possible solutions out of the initial nine identified from the literature in Sections 2.4.1 and 2.4.2. The two possible solutions were to: develop an RBH and use it as a RAW or use an unequipped ore pass as a RAW.

Step 4 developed and evaluated scenarios from the two possible solutions selected in Step 3. Furthermore, a selection process was followed to select the solution where an RBH was developed and used as a RAW.

Step 5 discussed the implementation process of the solution in the mine and provided results which validated the study's methodology. The implementation resulted in the mitigation of the air mixing at the crosscut intake which led to a T_{wb} decrease of 5 °C at the intake of the working crosscut.

The study's objectives were met by following the steps outlined above. Section 4.2 will provide more details as to how both case studies satisfied its objective.

4.2. Study objectives achieved

The literature review conducted in Section 1.5 led to the problem statement provided in Section 1.6. Table 4-1 explains how the case studies satisfied each of the relevant objectives provided in Section 1.6.

Table 4-1: Study's objectives achieved

OBJ.	Case study 1	Case study 2
1.1	The outcome of Section 3.2.3 is a calibrated ventilation simulation model.	The outcome of Section 3.3.3 is a calibrated ventilation simulation model.
1.2	Sections 2.4.1 and 2.4.2 identified ventilation and cooling methods used in industry to improve ventilation conditions.	
1.3	Section 2.4.3 provided a decision diagram, and in Section 3.2.4, the decision diagram was used to identify two solutions.	Section 3.3.4 used the decision diagram provided in Section 2.4.3 to identify 2 solutions.
2.1	The intake T_{wb} for the working crosscut on Level X was reduced by 3 °C.	The intake T_{wb} for the working crosscut on level Z was reduced by 5 °C.
2.2	The airflow reversal at Point 2 indicates that the intake dust concentration was reduced, with the dust produced at the development end.	The airflow reversal at Point 2 indicates that the intake dust concentration was reduced with the dust produced at the development end.

2.3	Figure 3-29 shows that the working crosscut intake airflow at Point one is 19.8 kg/s (17.7 m^3/s).	Figure 3-56 shows that the working crosscut intake airflow at point one is 10.24 kg/s
3.1	Figure 3-28 shows that the MAE of the T_{wb} and $\dot{m}$ are < 5%.	Figure 3-55 shows that the MAE of the T_{wb} and $\dot{m}$ are < 5%.

The comments listed for each objective prove that applying the study's methodology to Mine A and Mine B satisfied the study's objectives.

4.3. Recommendations

Recommendations for future work in ventilation optimisation are as follows:

- Portable measuring stations can be developed and used in mines that do not have continuous measurement devices. The equipment should be able to measure T_{db} and relative humidity, air velocity, and barometric pressure. Table 4-2 lists the various measuring devices used to measure each of the ventilation parameters.

Table 4-2: Devices used to measure ventilation parameters.

Parameter	Device	Comments
T_{db}	Thermocouple	The instrument should be exposed to the air stream, but it must be protected from solar radiation and moisture.
Relative humidity	• Capacitive humidity sensor • Resistive humidity sensor	Capacitive humidity sensors comprise approximately 75% of the market.[10]
Air velocity	• Ultrasonic anemometer • Thermal anemometer • Pitot tube • Vane anemometer	Record the cross-sectional area at the measurement point to calculate the airflow quantity.
Barometric pressure	Atmospheric pressure sensor	Where vacuum is the reference pressure

The values collected from the equipment can be used to calculate daily profiles or averages as inputs to a simulation model.

- Developing a simulation model with a 24-hour profile output can be used to implement ventilation-on-demand systems in deep-level mines.

[10] https://www.andivi.com/humidity-sensor-what-type-should-you-choose/ [Accessed: 30/09/2024]

- An in-depth cost analysis of each scenario developed and evaluated in Section 3.2.5.A will aid in refining the scenario selection process described in Section 3.2.5.B.

Exploring the possibility of applying the methodology to other mining operations and using different simulation software will increase confidence in the method.

5. REFERENCES

[1] D. J. Brake and T. Nixon, “Correctly estimating primary airflow requirements for underground metalliferous mines,” in *Australian Institute of Mining and Metallurgy Publication Series*, R. Brake, Ed., Launceston, Apr. 2008, pp. 199–204.

[2] I. J. Duckworth and I. S. Lowndes, “Modelling of auxiliary ventilation systems,” *Institution of Mining and Metallurgy. Transactions. Section A: Mining Technology*, vol. 112, no. 2, pp. 105–113, 2003, doi: 10.1179/037178403225001665.

[3] M. J. Mcpherson, *Subsurface Ventilation Engineering*. 2009.

[4] H. Hamrin, “Underground Mining Methods,” in *Underground mining methods*, N. Imam, Ed., 2001, pp. 1–14.

[5] A. Widiatmojo *et al.*, “Assessment of air dispersion characteristic in underground mine ventilation: Field measurement and numerical evaluation,” *Process Safety and Environmental Protection*, vol. 93, pp. 173–181, 2015, doi: 10.1016/j.psep.2014.04.001.

[6] X. Zhang, Y. Zhang, and J. C. Tien, “The Efficiency Study of the Push-pull Ventilation System in Underground Mine,” in *Coal Operators’ Conference*, Feb. 2011, pp. 225–230.

[7] P. Roghanchi, C. Kocsis, P. Roghanchi, and C. Kocsis, “Optimizing Auxiliary Ventilation Systems to Mitigate Heat and Gases in Underground Metal Mines,” in *16th North American Mine Ventilation Symposium*, 2017, pp. 1–6.

[8] A. J. Schutte, M. Kleingeld, and L. Van Der Zee, “An integrated energy efficiency strategy for deep mine ventilation and refrigeration,” in *International Conference on the Eleventh industrial and Commercial Use of Energy, ICUE*, Aug. 2014, pp. 1–9. doi: 10.1109/ICUE.2014.6904168.

[9] L. J. Gardner and N. D. Fernandes, “Ore pass rehabilitation - Case studies from Impala Platinum Limited,” *Journal of the South African Institute of Mining and Metallurgy*, vol. 106, no. 1, pp. 17–23, 2006.

[10] M. B. Teixeira, “Assessing surface and underground cooling methods , coupled to efficient ventilation systems to improve the climatic conditions in deep and hot mines,” Master of Science in Mining Engineering, University of Nevada, Reno, 2019.

[11] S. Bluhm and M. Biffi, “Variations in ultra-deep, narrow reef stoping configurations,” *The South African Institute of Mining and Metallurgy*, pp. 127–134, 2001.

[12] E. I. Acuña and I. S. Lowndes, "A review of primary mine ventilation system optimization," in *Interfaces*, 2014, pp. 163–175. doi: 10.1287/inte.2014.0736.

[13] R. Grau, T. Mucho, S. Robertson, A. Smith, and F. Garcia, "Practical techniques to improve the air quality in underground stone mines," in *The North America/Ninth US Mine Ventilation Symposium*, E. De Souza, Ed., Ontario: A.A. Balkema Publishers, Jun. 2002, pp. 123–129. doi: 10.1201/9781439833742.ch19.

[14] M. Peltier, A. F. Rotta Loria, L. Lepage, E. Garin, and L. Laloui, "Numerical investigation of the convection heat transfer driven by airflows in underground tunnels," *Applied Thermal Engineering*, vol. 159, 2019, doi: https://doi.org/10.1016/j.applthermaleng.2019.113844.

[15] B. Heriyadi and R. Salia Zakri, "Evaluation and Analysis of Needs for Air Ventilation Systems in Underground Coal Mine (Case Study in Underground Coal Mine, Sawahlunto City)," in *Journal of Physics: Conference Series*, 2021. doi: 10.1088/1742-6596/1940/1/012077.

[16] D. J. de Villiers, M. J. Mathews, P. Maré, M. Kleingeld, and D. Arndt, "Evaluating the impact of auxiliary fan practices on localised subsurface ventilation," *International Journal of Mining Science and Technology*, vol. 29, no. 6, pp. 933–941, 2019, doi: 10.1016/j.ijmst.2019.02.008.

[17] G. Wendel, "Radioactivity in mines and mine water - Sources and mechanisms," *Journal of The South African Institute of Mining and Metallurgy*, vol. 98, no. 2, pp. 87–92, 1998.

[18] G. Barakos, H. Mischo, and J. Gutzmer, "Rare Earth Underground Mining Approaches with Respect to Radioactivity Control and Monitoring Strategies," *Rare Earths Industry: Technological, Economic, and Environmental Implications*, pp. 121–138, 2015, doi: 10.1016/B978-0-12-802328-0.00008-5.

[19] J. N. Middleton, R. C. Burton, and K. Walker, "Monitoring and Control in the Recirculation of Underground Ventilation Air," in *IFAC Automation for Mineral Resource Development*, Elsevier, 1985, pp. 95–102. doi: 10.1016/s1474-6670(17)60495-6.

[20] S. Chong, K. S. Lee, M. J. Chung, J. Han, O. J. Kwon, and T. S. Kim, "Pneumoconiosis: Comparison of imaging and pathologic findings," *Radiographics*, vol. 26, no. 1, pp. 59–77, 2006, doi: 10.1148/rg.261055070.

[21] M. I. Greenberg, J. Waksman, and J. Curtis, "Silicosis: A Review," *Disease-a-Month*, vol. 53, no. 8, pp. 394–416, 2007, doi: 10.1016/j.disamonth.2007.09.020.

[22] J. J. L. Du Plessis, *Ventilation and occupational environment engineering in mines*. Johannesburg: Mine Ventilation Society of South Africa, 2014.

[23] M. Q. W. Jones, "Virgin rock temperatures and geothermal gradients in the Bushveld Complex," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 118, no. 7, pp. 671–680, 2018, doi: 10.17159/2411-9717/2018/v118n7a1.

[24] H. Wagner, "The management of heat flow in deep mines," *Geomechanik und Tunnelbau*, vol. 4, no. 2, pp. 157–163, 2011, doi: 10.1002/geot.201100006.

[25] L. J. Robb and F. M. Meyer, "The Witwatersrand Basin, South Africa: Geological framework and mineralization processes," 1995.

[26] M. Q. W. Jones, "Thermal properties of stratified rocks from Witwatersrand gold mining areas," *Journal of The South African Institute of Mining and Metallurgy*, vol. 103, no. 3, pp. 173–185, 2003.

[27] S. Kakac, Y. Yener, and A. Pramuanjaroenkij, *Convective heat transfer*, vol. 3, no. April. 2015.

[28] D. T. Crane and G. S. Jackson, "Optimization of cross flow heat exchangers for thermoelectric waste heat recovery," *Energy Conversion and Management*, vol. 45, no. 9–10, pp. 1565–1582, 2004, doi: 10.1016/j.enconman.2003.09.003.

[29] A. P. Sasmito, J. C. Kurnia, E. Birgersson, and A. S. Mujumdar, "Computational evaluation of thermal management strategies in an underground mine," *Applied Thermal Engineering*, vol. 90, pp. 1144–1150, 2015, doi: 10.1016/j.applthermaleng.2015.01.062.

[30] T. H. Benzinger, A. W. Pratt, and C. Kitzinger, "The Thermostatic Control of Human Metabolic Heat Production," *Proceedings of the National Academy of Sciences*, vol. 47, no. 5, pp. 730–739, 1961, doi: 10.1073/pnas.47.5.730.

[31] R. Venter, "Reconfiguring deep-level mine dewatering systems for increased water volumes."

[32] D. G. Shepherd, "Historical Development of the Windmill," New York, 1990.

[33] H. Manchao *et al.*, "Principles and technology for stepwise utilization of resources for mitigating deep mine heat hazards," *Mining Science and Technology*, vol. 20, no. 1, pp. 20–27, 2010, doi: 10.1016/S1674-5264(09)60155-1.

[34] D. Mishra and N. Dr Sahay, “Effect of Auto Compression on Ventilation System of Deep Shaft Coal Mines in Jharia Coal Field - A Case Study,” *Innovative Surface and Underground Mining Technology for Performance Enhancement*, pp. 1–11, 2015.

[35] H. J. van Staden, J. F. van Rensburg, and H. J. Groenewald, “Optimal use of mobile cooling units in a deep-level gold mine,” *International Journal of Mining Science and Technology*, vol. 30, no. 4, pp. 547–553, 2020, doi: 10.1016/j.ijmst.2020.03.004.

[36] R. C. W. Webber-Youngman, “An integrated Approach Towards the Optimisation of Ventilation, Air cooling and Pumping Requirements for Hot Mines,” PhD, North-West University, Potchefstroom, 2005. Accessed: Jul. 30, 2023. [Online]. Available: http://hdl.handle.net/10394/467

[37] Z. gui Su, Z. an Jiang, and Z. qiang Sun, “Study on the heat hazard of deep exploitation in high-temperature mines and its evaluation index,” *Procedia Earth and Planetary Science*, vol. 1, no. 1, pp. 414–419, 2009, doi: 10.1016/j.proeps.2009.09.066.

[38] Mine Health and Safety Council, “Mine Health and Safety Act 29 of 1996 and Regulations,” *Mine Healthy and Safety Council*, no. 29, p. 588, 2018, [Online]. Available: http://www.mhsc.org.za/site/sites/default/files/public/publications/Mine Health and Safety Act 29 of 1996 and Regulations Final Booklet.pdf%0Ahttps://www.mhsc.org.za/sites/default/files/public/publications/Mine Health and Safety Act 29 of 1996 and Regulat

[39] D. Mitchell and A. Whillier, “Cooling power of underground environments,” *Journal of the Mine Ventilation Society of South Africa*, vol. 52, no. 4, pp. 161–168, 1999.

[40] M. Jacobson and J. A. Lamonica, *Personal respirable dust sampler*, vol. 17, no. 1. US Department of the Interior, Bureau of Mines, 1969.

[41] K. Balt and R. L. Goosen, “MSAHP: An approach to mining method selection,” *The Journal of the Southern African Institute of Mining and Metallurgy*, vol. 120, 2020, doi: 10.17159/2411.

[42] “A review of the sequential grid mining method employed at Elandsrand Gold Mine.”

[43] G. N. Phillips and J. D. M. Law, “Chapter 14 Witwatersrand Gold Fields: Geology, Genesis, and Exploration,” 2000.

[44] R. Pickering, "Stoping Systems and Technology," *The Journal of The South African Institute of Mining and Metallurgy*, pp. 289–291, 1999.

[45] Y. Jooste and D. F. Malan, "Rock engineering aspects of a modified mining sequence in a dip pillar layout at a deep gold mine," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 115, no. 11, pp. 1097–1112, Nov. 2015, doi: 10.17159/2411-9717/2015/v115n11a14.

[46] I. T. Tshabalala, M. Rsa, P. H. Ferreira, and P. Eng, "FUTURE AND POTENTIAL IN-STOPE ROCK SUPPORT SYSTEMS IN CONVENTIONAL NARROW VEIN STOPING OPERATIONS TO REDUCE SAFETY RISKS AND ENHANCE PRODUCTIVITY."

[47] H. G. Mosenthal, "Presidential Address: Stoping in Witwatersrand gold mines during the past forty years," 1990.

[48] D. R. Jacobs, J. H. Laar, and C. S. L. Schutte, "Strategy To Identify and Mitigate Hazards in Deep-Level Mine Ventilation Systems Using a Calibrated Digital Twin," *South African Journal of Industrial Engineering*, vol. 33, no. 3, pp. 204–217, 2022, doi: 10.7166/33-3-2795.

[49] C. A. Monteiro, J. H. van Laar, and C. S. L. Schutte, "A Simulation-Based Water Management Strategy for Life-of-Mine Water Planning," *South African Journal of Industrial Engineering*, vol. 33, no. 3, pp. 248–261, 2022, doi: 10.7166/33-3-2787.

[50] B. van der Heijde *et al.*, "Dynamic Equation-Based Thermo-Hydraulic Pipe Model for District Heating and Cooling Systems," *Energy Conversion and Management*, vol. 151, pp. 158–169, 2017, doi: 10.1016/j.enconman.2017.08.072.

[51] W. Wang *et al.*, "In Situ Measurements and CFD Numerical Simulations of Thermal Environment in Blind Headings of Underground Mines," *Processes*, vol. 7, no. 5, pp. 313–334, 2019, doi: 10.3390/pr7050313.

[52] C. K. Kocsis, R. Hall, and S. G. Hardcastle, "The integration of mine simulation and ventilation simulation to develop a ' Life-Cycle ' mine ventilation system," *Application of computers and operations research in the minerals industries*, pp. 223–230, 2003.

[53] Y. Shen and H. N. Wang, "Study and application on simulation and optimization system for the mine ventilation network," *Procedia Engineering*, vol. 26, pp. 236–242, 2011, doi: 10.1016/j.proeng.2011.11.2163.

[54] R. Fair, J. H. van Laar, K. Nell, D. Nell, and E. H. Mathews, "Simulating the Sensitivity of Underground Ventilation Networks to Fluctuating Ambient Conditions," *South African Journal of Industrial Engineering November 2021*, vol. 32, no. 3, pp. 42–51, 2021, doi: http://dx.doi.org/10.7166/32-3-2616.

[55] A. Kamyar, S. M. Aminossadati, C. Leonardi, and A. P. Sasmito, "Current Developments and Challenges of Underground Mine Ventilation and Cooling Methods," in *Coal Operator's Conference*, Wollongong: Research Online, 2016, pp. 18–20. [Online]. Available: https://ro.uow.edu.au/coal/615

[56] P. Roghanchi and K. C. Kocsis, "Improving the climatic conditions in development and production workings of hot underground mines by re-designing the auxiliary ventilation system - A case study," *International Journal of Mining and Mineral Engineering*, vol. 8, no. 4, pp. 280–293, 2017, doi: 10.1504/IJMME.2017.087965.

[57] M. Butterworth, "Controlled Recirculation in Deep South African Gold Mines," in *8th US Mine Ventilation Symposium*, 1999, pp. 697–704.

[58] A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "Evaluating complex mine ventilation operational changes through simulations," *Journal of Energy in Southern Africa*, vol. 29, no. 3, pp. 22–32, 2018, doi: 10.17159/2413-3051/2018/v29i3a4445.

[59] M. Bascompta, A. M. Castañón, L. Sanmiquel, and J. Oliva, "A GIS-based approach: Influence of the ventilation layout to the environmental conditions in an underground mine," *Journal of Environmental Management*, vol. 182, pp. 525–530, 2016, doi: 10.1016/j.jenvman.2016.08.013.

[60] A. Ryan and D. S. Euler, "Heat stress management in underground mines," *International Journal of Mining Science and Technology*, vol. 27, no. 4, pp. 651–655, 2017, doi: 10.1016/j.ijmst.2017.05.020.

[61] W. Feng, F. Zhu, and H. Lv, "The Use of 3D Simulation System in Mine Ventilation Management," *Procedia Engineering*, vol. 26, pp. 1370–1379, 2011, doi: 10.1016/j.proeng.2011.11.2313.

[62] K. Kolobe, C. Rutter, and N. Shea, "Evolution of the Henderson Mine Ventilation System," in *18th North American Mine Ventilation Symposium*, P. Tukkaraja, Ed., Rapid city, 2021, pp. 538–547. doi: 10.1201/9781003188476-55.

[63] P. Wang, K. Zhu, Y. Zhou, J. Liu, and C. Shi, "Research and application of controlled circulating ventilation in deep mining," *Procedia Engineering*, vol. 84, pp. 758–763, 2014, doi: 10.1016/j.proeng.2014.10.493.

[64] S. Teegavarapu and J. D. Summers, "CASE STUDY METHOD FOR DESIGN RESEARCH," 2007.

[65] M. Singh, M. Jradi, and H. R. Shaker, "Monitoring and evaluation of building ventilation system fans operation using performance curves," *Energy and Built Environment*, vol. 1, no. 3, pp. 307–318, Jul. 2020, doi: 10.1016/j.enbenv.2020.04.001.

[66] X. Nie, X. Wei, X. Li, and C. Lu, "Heat Treatment and Ventilation Optimization in a Deep Mine," *Advances in Civil Engineering*, vol. 2018, 2018, doi: 10.1155/2018/1529490.

[67] H. Wagner, "The management of heat flow in deep mines," *Geomechanik und Tunnelbau*, vol. 4, no. 2, pp. 157–163, Apr. 2011, doi: 10.1002/geot.201100006.

[68] *AutoCAD 2012 - DXF*. California: Autodesk, Inc., 2007. [Online]. Available: http://images.autodesk.com/adsk/files/autocad_2012_pdf_dxf-reference_enu.pdf%0Ahttp://images.autodesk.com/adsk/files/acad_dxf0.pdf

[69] M. J. McPherson, "Ventilation surveys," *Subsurface Ventilation and Environmental Engineering*, pp. 175–208, 1993, doi: 10.1007/978-94-011-1550-6_6.

[70] P. Roghanchi and K. C. Kocsis, "Quantifying the thermal damping effect in underground vertical shafts using the nonlinear autoregressive with external input (NARX) algorithm," *International Journal of Mining Science and Technology*, vol. 29, no. 2, pp. 255–262, 2019, doi: 10.1016/j.ijmst.2018.06.002.

[71] W. A. Olosunde, J. C. Igbeka, and T. O. Olurin, "Performance evaluation of absorbent materials in evaporative cooling system for the storage of fruits and vegetables," *International Journal of Food Engineering*, vol. 5, no. 3, 2009, doi: 10.2202/1556-3758.1376.

[72] A. L. Martikainen, H. N. Dougherty, C. D. Taylor, and A. L. Mazzella, "Sonic anemometer airflow monitoring technique for use in underground mines."

[73] L. P. Purtell, "Low Velocity Performance of a High Speed Vane Anemometer," Washington, D.C., 1978.

[74] A. E. Pearse, K. T. Weber, and D. Wu, “Military Applications of Wind Characterization Models Relative to Army Sniper Operations,” Idaho, 1999.

[75] Z. Kalab, M. Lednicka, J. Knejzlik, and L. Telesca, “First Results from Long-Term Monitoring of Distance Using a Laser Distance Meter in Shallow Medieval Mine,” *Acta Geodynamica et Geomaterialia (AGG)*, vol. 7, no. 4, pp. 469–473, 2010.

[76] L. Xu, X. Lin, J. Amen, K. Welding, and D. McDermitt, “Impact of changes in barometric pressure on landfill methane emission,” *Global biogeochemical cycles*, pp. 679–695, 2014, doi: 10.1111/1462-2920.13280.

[77] E. De Souza, “Optimization of Complex Mine Ventilation Systems with Computer Network Modelling,” *IFAC Proceedings Volumes*, vol. 40, no. 11, pp. 323–329, 2007, doi: 10.3182/20070821-3-CA-2919.00049.

[78] N. Szlązak, D. Obracaj, and M. Korzec, “Analysis of connecting a forcing fan to a multiple fan ventilation network of a real-life mine,” *Process Safety and Environmental Protection*, vol. 107, pp. 468–479, 2017, doi: 10.1016/j.psep.2017.03.001.

[79] C. H. Oosthuizen, “Evaluating Localised Ventilation Improvements on Deep-Level Mines Using Simulation Models,” Masters, North West University, Potchefstroom, 2019.

[80] P. H. Oosthuizen and W. E. Carscallen, *Introduction to Compressible Fluid Flow.*, 2nd ed. CRC Press, 2013.

[81] F. Allard and Y. Utsumi, “Airflow through large openings,” *Energy and Buildings*, vol. 18, no. 2, pp. 133–145, 1992, doi: 10.1016/0378-7788(92)90042-F.

[82] J.-A. Watkins, “Trade-Off Between Simulation Accuracy and Complexity for Mine Compressed Air Systems,” Masters, North West University, Potchefstroom, 2018.

[83] H. Wang, C. Wang, and D. Wang, “The influence of forced ventilation airflow on water spray for dust suppression on heading face in underground coal mine,” *Powder Technology*, vol. 320, pp. 498–510, 2017, doi: https://doi.org/10.1016/j.powtec.2017.07.069.

[84] Y. Cho, H. B. Awbi, and T. Karimipanah, “Theoretical and experimental investigation of wall confluent jets ventilation and comparison with wall displacement ventilation,” *Building and Environment*, vol. 43, no. 6, pp. 1091–1100, 2008, doi: 10.1016/j.buildenv.2007.02.006.

[85] M. T. Parra, J. M. Villafruela, F. Castro, and C. Méndez, “Numerical and experimental analysis of different ventilation systems in deep mines,” *Building and Environment*, vol. 41, no. 2. pp. 87–93, 2006. doi: 10.1016/j.buildenv.2005.01.002.

[86] J. P. R. J. M. L. J. A. O. A. L. W. J. F. Colinet, “Best Practices for Dust Control in Coal Mining,” *National Institute for Occupational Safety and Health*, vol. 1, pp. 17–36, 2010, [Online]. Available: http://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2010-110.pdf

[87] K. Wallace, B. Prosser, and J. D. Stinnette, “The practice of mine ventilation engineering,” *International Journal of Mining Science and Technology*, vol. 25, no. 2, pp. 165–169, 2015, doi: 10.1016/j.ijmst.2015.02.001.

[88] B. Rahimi, M. Sharifzadeh, and X. T. Feng, “Ground behaviour analysis, support system design and construction strategies in deep hard rock mining – Justified in Western Australian’s mines,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 12, no. 1, pp. 1–20, 2020, doi: 10.1016/j.jrmge.2019.01.006.

[89] J. de V. Lambrechts, “An emperical study of heat flow in stopes in South African gold mines,” *Journal of the South African Institute of Mining and Metallurgy*, pp. 285–316, 1959.

[90] S. M. Aminossadati and K. Hooman, “Numerical Simulation of Ventilation Air Flow in Underground Mine Workings,” *12th US/North American Mine Ventilation Symposium*, no. 1974, pp. 253–260, 2008.

[91] A. J. Starfield, A. M., & Dickson, “A study of heat transfer and moisture pick-up in mine airways,” *Journal of the South Africa Institute of Mining and Metallurgy*, vol. 68, no. 5, pp. 211–234, 1967, [Online]. Available: https://hdl.handle.net/10520/AJA0038223X_4137

[92] B. M. Friedenstein, C. Cilliers, and J. van Rensburg, “Simulating operational improvements on mine compressed air systems#,” *South African Journal of Industrial Engineering*, vol. 29, no. 3 Special Edition, pp. 69–81, 2018, doi: 10.7166/29-3-2049.

[93] B. Belle, “Evaluation of gravimetric sampler bias, effect on measured concentration, and proposal for the use of harmonised performance based dust sampler for exposure assessment,” *International Journal of Mining Science and Technology*, vol. 29, no. 3, pp. 445–452, 2019, doi: 10.1016/j.ijmst.2018.07.009.

[94] D. J. Brake, “Mine ventilation: a practitioner’s manual,” *Mine Ventilation Australia, Brisbane*, 2012.

[95] W. Dziurzyński and J. Kruczkowski, “Variability of the volumetric air flow rate in a mine fan channel for various damper positions,” *Archives of Mining Sciences*, vol. 56, no. 4, pp. 641–650, 2011.

[96] P. Du Toit, *Intermediate certificate in mine environmental control*. Mine Ventilation Society of South Africa, 2008.

[97] O. G. Clark, J. C. Segura, J. J. R. Feddes, and C. Ouellette, “Multiport averaging pitot tube to measure airflow rates from exhaust fans,” *Canadian Biosystems Engineering*, vol. 50, 2008.

A. APPENDIX A: VENTILATION MEASURING EQUIPMENT

Gravimetric dust sampler

Figure A-1 shows a mobile gravimetric dust sampler with a writing pen for size comparison. This device measures the amount of dust in a cubic metre of air [86].

Figure A-1: Gravimetric dust sampler [86].

The device comprises an air pump and dust filter. A worker will wear this device during a work shift, and it will collect dust. The air pump takes in ambient air and delivers a continuous air flow rate to the dust filter. The dust filter collects dust particles in the air throughout a work shift. The filter is weighed before and after the work shift to determine the amount of dust collected in grams (g). A dust concentration (g/m^3) is calculated by dividing the weight of dust collected (g) by the volume of air pumped during the work shift (m^3) [93].

Whirling hygrometer

A whirling hygrometer, shown in Figure A-2, measures the T_{wb} and T_{db} of the ambient air.

Figure A-2: AMS Haden whirling hygrometer [11].

The device features two alcohol thermometers, one where the alcohol reservoir is covered with a muslin sock, and the other is uncovered. The device has a water reservoir used to keep the muslin sock moist, and the manufacturer recommends using distilled water. The thermometer with the muslin sock records the T_{wb} of the air, whereas the thermometer with no sock records the T_{db} of the air.

According to McPherson, [3], the operation instructions of the device are as follows:

1. Grip the device on the handle with the dominant hand.
2. Hold the device at arm's length and away from other heat sources.
3. Swing the device at roughly 3 m/s for a minimum of 30 seconds.
4. Extend the index finger to stop the device.
5. Immediately record the values from both thermometers.

[11] *Haden, A.M.S. (2022) Mining Services - environmental monitoring, AMS Haden. Available at: https://amshaden.co.za/wp-content/uploads/2021/11/whirlinghydrometer.png/ (Accessed: February 19, 2023).*

Vane anemometer and stopwatch

Figure A-3 shows a Davis vane anemometer (vane). This device is a rotating mechanical vane anemometer measuring the air passed in meters (m) [3].

Figure A-3: Davis vane anemometer[12].

The vane connects to a pole, allowing the user to perform the traversing action to obtain the average air passed. This device has two levers, one to zero the dials and one to engage (Start) and disengage (Stop) the clutch. A stopwatch records the time of the vane operation. Thus the combination of the two devices produces a value of meters of air passed per second, also the air velocity (m/s) in the haulage.

According to McPherson, [3] and Drake, [94], the operation instructions of the devices are as follows:

1. Attach the vane to the pole while in its protective bag.
2. Remove the protective bag with the device parallel to the airflow allowing the rotor to spin.
3. Ensure the clutch mechanism is working, then reset the dial to zero.
4. Simultaneously start the vane and stopwatch, and traverse the haulage. Figure A-4 shows a cross-section of a haulage and the path to follow with the vane when performing the traverse measuring technique.

[12] Tektronix (2022) *Davis Vane anemometers*, *Tektronix*. Available at: https://www.tek.com/en/calibration-services/davis-vane-anemometer (Accessed: February 19, 2023).

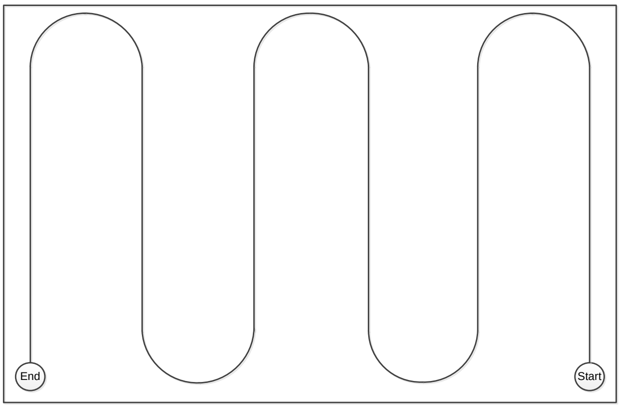


Figure A-4: A cross-section of a haulage and suggested traverse path.

5. Stop the vane and stopwatch simultaneously at the end of the path shown in Figure A-3.
6. Record the reading on the vane in meters and the reading on the stopwatch in seconds.
7. Use (Eq. A-1) to calculate the air velocity.

$$v = \frac{d}{t} \quad \text{(Eq. A-1)}$$

Where v – air velocity (m/s), d – distance travelled (m), and t– time (s).

Digital anemometer

Figure A-5 shows a digital anemometer, which measures air velocity.

Figure A-5: Kestrel digital anemometer[13]

Operation instructions for the digital anemometer [3]:

1. Switch the device on.

[13] *Kestrel 1000 wind meter - kestrelmeters.com* (2023) *Kestrelmeters*. Available at: https://kestrelmeters.com/products/kestrel-1000-wind-meter (Accessed: February 24, 2023).

2. Ensure the device output is set to average air velocity.
3. Hold the device at arm's length at the nine points in the cross-section of a haulage shown in Figure A-6 [95]. Hold the device stationary at each point for a minimum of 10 seconds.

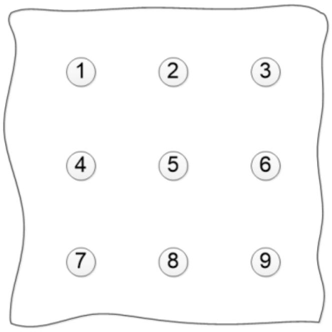


Figure A-6: Digital anemometer measurement guide.

4. Record the average air velocity shown on the device screen.

Laser distance meter

Figure A-7 shows a laser distance meter measuring distance in meters (m). This device is essential for measuring the height and width of a haulage.

Figure A-7: Bosch laser distance meter[14].

Three height and width measurements are required to document the average area of the haulage successfully. Figure A-8 shows the location of each measurement.

[14] *GLM 20 laser measure: Bosch professional* (2021) *GLM 20 Laser Measure | Bosch Professional*. Available at: https://www.bosch-professional.com/za/en/products/glm-20-0601072EG0 (Accessed: February 24, 2023).

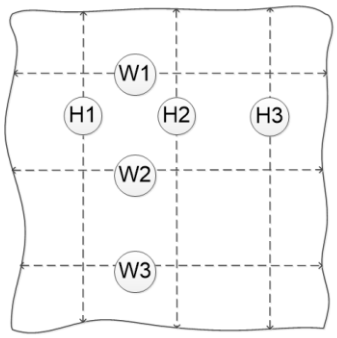


Figure A-8: Height and width measure guide.

W1, W2, and W3 represent the locations for the width measurements and H1, H2, and H3 the height. Average height (H_{ave}) and width (W_{ave}) are calculated by applying (Eq. A-2) and (Eq. A-3), respectively:

$$H_{ave} = \frac{H1 + H2 + H3}{3} \quad \text{(Eq. A-2)}$$

$$W_{ave} = \frac{W1 + W2 + W3}{3} \quad \text{(Eq. A-3)}$$

Digital Barometer

Figure A-9 shows a digital barometer. The typical measurement of barometric pressure is millibar (mbar).

Figure A-9: Digital barometer.

Follow the steps to record the barometric pressure of an area underground:

1. Switch the device on.
2. Wait a minimum of 10 seconds after the device displays a value.
3. Record the barometric pressure.

Pitot tube and manometer

Figure A-10 shows a pitot tube, and Figure A-11 shows a vertical manometer. Together these devices measure either the static pressure, total pressure or the difference between the static pressure and the total pressure.

Figure A-10: Dwyer pitot tube[15].

Figure A-11: AMS Haden vertical manometer.

The vertical manometer consists of a U-tube with the open ends at the top, and a ruler. The ruler has intervals measured in pascals (Pa). The pitot tube has two concentric tubes, an outer and inner tube. The outer tube has holes around its perimeter, and the inside tube has a hole at the tip. The two devices are connected with rubber pipes. The outer tube and the vertical manometer measure static pressure, while the inner tube measures total pressure. The pressure difference is vital in calculating the air velocity of a duct [96].

(Eq. A-4) is a form of Bernoulli's equation adapted to solve for air velocity [97].

$$P_v = P_t - P_s = \frac{\rho v^2}{2} \qquad \textit{(Eq. A-4)}$$

Where P_v – velocity pressure (Pa), P_t – total pressure (Pa), P_s – static pressure (Pa), ρ – fluid density (kg/m^3), v - air velocity (m/s).

[15] Dwyer 160 series single point pitot tubes (2019) Process Instrumentation. Available at: https://fluidic-ltd.co.uk/product/dwyer-160-pitot-tubes/ (Accessed: February 23, 2023).

(Eq. A-4) can be rewritten so that the air velocity is the subject, and (Eq. A-5) is obtained.

$$v = \sqrt{\frac{2(P_t - P_s)}{\rho}} \qquad \textit{(Eq. A-5)}$$